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Date: February 25, 2013

Subject: NorthMet Mining Project GoldSim Water Quality Model - Phase 3 Quality Assurance

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INTRODUCTION

This technical memorandum summarizes a series of Quality Assurance (QA) evaluations that were performed on two water quality models used to estimate environmental impacts associated with the proposed NorthMet Mining Project. The two models, one for the Mine Site and one for the Plant Site, were programmed using GoldSim®, a commercially available "systems" model. The models were developed by Barr Engineering Company (Barr) to estimate potential effects from the proposed mine on the quality and quantity of water resources. The QA audits were conducted by members of the ERM Project Team to provide technical support to the State of Minnesota in preparation of the NorthMet Mining Project and Land Exchange Supplemental Draft Environmental Impact Statement (SDEIS).

SUMMARY OF WORK AND CONCLUSIONS REGARDING THE GOLDSIM MINE SITE MODEL

The Phase 3 QA audit was performed on the version 4 (v4) NorthMet Project Mine Site GoldSim water-quality model that was run during January 2013. The current (v5) version of the model is not substantially different from the v4 version that was evaluated. Previously, the ERM Team conducted an audit of the version 3 (v3) GoldSim model that was run during September 2012. Results of the v3 audit are summarized in an ERM memorandum dated October 30, 2012 (Appendix A of this memorandum). The October 2012 audit was not a 100-percent verification of model calculations, but instead focused on select model components that are critical in the estimates of solute release/transport. A QA update conducted during January 2013 (Appendix B of this memorandum) provided a supplementary audit of additional model components at the Plant Site that were not evaluated previously or had changed due to modified inputs or GoldSim programming.

The January 2013 audit confirmed that model changes were appropriately incorporated into the v4 GoldSim model and the changes did not raise any QA concerns. The following evaluations were performed using a deterministic run of the v4 GoldSim model with P50 inputs:

- Re-evaluation of water quality in the West and East Pits.
- Evaluation of chemical migration in surficial groundwater flowpaths.
- Evaluation of chemical loading to the Partridge River caused by groundwater discharge from the surficial groundwater flowpaths.

Each of these evaluations is described in Appendix B.

Overall, the results of this audit provide good evidence that the v5 Mine Site GoldSim model has appropriate and mathematically correct algorithms for (1) estimating flows and chemical concentrations of impacted water leaving the Mine Site facilities, (2) simulating chemical migration in the surficial groundwater flowpaths, and (3) estimating Partridge River chemical concentrations caused by mixing of background and human-affected water sources to the river.

SUMMARY OF WORK AND CONCLUSIONS REGARDING THE GOLDSIM PLANT SITE MODEL

The Phase 3 QA audit was performed on the version 5 (v5) NorthMet Project Plant Site GoldSim water-quality model that was run during February 2013. Previously, the ERM Team conducted an audit of the version 3 (v3) GoldSim model that was run during September 2012. Results of the v3 audit are summarized in an ERM memorandum dated October 30, 2012 (Appendix A of this memorandum). The October 2012 audit was not a 100-percent verification of model calculations, but instead focused on select model components that are critical in the estimates of solute release/transport. A QA update conducted during February 2013 (Appendix C of this memorandum) provided a supplementary audit of additional model components at the Plant Site that were not evaluated previously or had changed due to modified inputs or GoldSim programming. The most important model changes that were made in going from v3 to v5 are the following:

- Revised chemical concentrations in the WWTP effluent based on pilot testing.
- Revised calibration factors for release of sulfate from fine and coarse LTVSMC tailings to provide consistency with previously agreed upon vanGenuchten parameters (CDF055).
- New GoldSim programming that effectively increased the flow rate of tailings-impacted groundwater that by-passes the containment system and enters surficial groundwater flowpaths (CDF061)
- Use of water from Colby Lake to augment streamflow in tributaries to the Embarrass River (CDF069 and CDF062).
- Modified watershed areas (CDF051).

The February 2013 audit confirmed that these model changes were appropriately incorporated into the v5 GoldSim model and the changes did not raise any QA concerns. The following evaluations were performed using a deterministic run of the v5 GoldSim model with P50 inputs:

- Re-evaluation of chemical release from subareas of the Flotation Tailings Basin (FTB).

- Evaluation of containment system bypass and associated chemical migration in surficial groundwater flowpaths.
- Evaluation of chemical loading to the Embarrass River caused by discharge of WWTP effluent, Colby Lake augmentation water, and discharge from the surficial groundwater flowpaths.

Each of these evaluations is described in Appendix C.

Overall, the results of this audit provide good evidence that the v5 Plant Site GoldSim model has appropriate and mathematically correct algorithms for (1) estimating flows and chemical concentrations of impacted water leaving the FTB, (2) simulating chemical migration in the surficial groundwater flowpaths, and (3) estimating Embarrass River chemical concentrations caused by mixing of background and human-affected water sources to the river.

OVERALL CONCLUSIONS

The Mine Site and Plant Site GoldSim models are very complex and contain thousands of lines of custom programming. It was not feasible to validate and check every line of code contain in the models. The approach taken by the ERM Team in the QA evaluations was to use a combination of independent calculations and profession judgment to identify potential problems with the codes and work with Barr to correct these issues.

There is good evidence that the v5 GoldSim models are functionally accurate and have addressed all issues identified by the ERM Team. The Team concludes that the v5 GoldSim models have acceptable reliability and can be used as a basis for assessing environmental impacts in the SDEIS.

Appendix A
NorthMet Quality Assurance Memo October 29, 2012

Memorandum

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Date: October 30, 2012

Subject: Quality Assurance

INTRODUCTION

This memorandum summarizes the Quality Assurance (QA) evaluation of two models developed by Barr Engineering Company (Barr) for the proposed NorthMet Mining Project (Project), located in northern Minnesota. One model performs calculations for the Mine Site and the other for the Plant Site. The models are connected in that excess water from the Mine Site will be pumped to the Plant Site during operations (for use as process water), and chemically affected water from the Plant Site tailings collection system will be pumped to the West Pit component of the Mine Site during the first twenty years of closure. The models are designed to estimate chemical mass release rates from the various mine facilities and track water constituent migration from the facilities to evaluation locations in the groundwater flow system and at surface water features. The models are programmed using the commercially available GoldSim® software, which provides a platform for performing Monte Carlo simulations. The primary model output is the probabilistic prediction of chemical concentrations in surface water and groundwater.

Previous QA efforts were performed to verify that the models used the input values specified in the Mine Site and Plant Site Water Modeling Workplans. The objective of the subsequent QA evaluation was to provide independent verification that the models are correctly using formulas and algorithms presented in the Mine Site and Plant Site Water Modeling Data Packages. The inputs and equations presented in the Work Plans and Data Packages were previously agreed upon by Barr and the Minnesota Department of Natural Resources (MDNR). This QA evaluation did not assess their scientific validity or reliability.

This QA audit does not represent a complete verification of all model calculations. Instead, emphasis was placed on model components having the potential to generate the greatest amounts of chemical mass. At the Plant Site, the major components are the subareas of the Flotation Tailings Basin (FTB). At the Mine Site, the major components are the Cat 1 Stockpile, East Pit, Plant Site water pumped to the West Pit, and ore wall rock in the West Pit. Of these, water pumped from the Plant Site to the West Pit is the greatest source of chemical loading to the Mine

Site. If one considers the Plant and Mine Sites collectively, the FTB is the primary chemical source for the Project.

This model QA effort placed more emphasis on the closure period than the operations period. This is because mechanical Waste Water Treatment Plants (WWTPs) will be in operation during mining and for at least 20 years after mining. If unanticipated site conditions occur during this 40 year period (e.g., chemical concentrations higher than expected), the mine permit will likely require that the site operator upgrade the WWTPs as necessary to mitigate the situation. However, it is during longer-term closure that decisions will be made to scale-down operation of mechanical WWTPs or to replace them with non-mechanical treatment systems.

The primary method applied in this audit was to develop independent calculations that generally reproduce the GoldSim® model estimates for the load and/or concentration of chemicals released from selected NorthMet facilities. Examples include calculations to reproduce model-predicted water flows from various facilities, release rates for chemical mass generated through oxygen diffusion into tailings material, and kinetically-limited reaction rates of the pit wall rock.

There was minimal assessment of chemical release from facilities that are highly engineered to reduce mass loads and/or meet water quality criteria in discharge, such as wastewater treatment facilities or the temporary lined facilities for reactive rock. These do not contain significant uncertainty, and the designs could, if necessary, be modified to meet future unanticipated site conditions.

This evaluation focused on the release and transport of sulfate, which is the primary product of sulfide mineral oxidation and is the basis for estimating the release of most other chemicals. Other chemicals evaluated included 5 of the 28 water-quality constituents tracked in the GoldSim® models: arsenic, cobalt, copper, nickel, and zinc. These six constituents were selected because preliminary assessments indicated a possibility that they could be released from mine rock at rates high enough to exceed surface water and/or groundwater regulatory standards.

This evaluation did not focus on pathways that connect the chemical-generating components to the groundwater and surface water compliance points. As currently proposed, the Project will use mechanical water treatment and discharge for as long as necessary to meet water-quality objectives. If necessary, the mechanical treatment plants will be modified during operations and closure to ensure that applicable discharge requirements are met. Because site-wide mine water treatment will not rely on hydrologic or geochemical processes occurring in groundwater or surface water pathways, the modeling of these pathways is not of critical importance to regulatory decision making.

PRINCIPAL FINDINGS

The Review Team identified a number of calculation issues early in the QA process and these were resolved with Barr. With one exception, the Review Team did not identify any new issues that would potentially require a major model modification and new model output. The excepted issue pertains to sulfate generation below bentonite-amended subareas of the FTB. This issue is discussed in a subsequent section of this memorandum. A complete log of all model issues identified by either the model development team or the Review Team is included as Attachment 3.

In the Review Team's opinion, the current models are a reasonable platform for assessing design concepts and closure strategies. However, the Review Team has concerns regarding use of the models to make regulatory decisions that need to be based on the models' absolute predictive accuracy. The Review Team questions whether these models (or any other model) could provide accurate predictions of what will happen at a very complicated site 50 or 100 years into the future.

The above issue becomes more apparent when one recognizes the numerous assumptions and calibration/correction factors contained in the models. For example, a suite of factors are applied to the LTVSMC humidity test results that reduce the model-simulated leach rates to a fraction of what was observed during the tests. For sulfate, the reduction ranges from 94 to 97 percent, but for some metals, the reduction is many orders of magnitude. Many of these factors were determined by calibrating the existing-conditions model to measured chemical concentrations in groundwater and surface water, but it is uncertain how well these factors will apply to future conditions. In addition, each calibration factor is treated as deterministic input, so its scientific uncertainty is not incorporated into the Monte Carlo (probabilistic) analyses. Conversely, no calibration factors are applied to the humidity cell results for NorthMet tailings, although it would be consistent to reduce the model-simulated leaching rates for these materials as well.

With regard to the model components that have been checked, the Review Team did not identify any components that appear to be producing sulfur or other chemical constituents at rates significantly different than what the Review Team computed independently (using equations and inputs mutually agreed upon by Barr and MDNR) or in conflict with the Review Team's professional judgment. While this is a favorable outcome, it does not constitute a complete certification of the GoldSim® models.

SPECIFIC MODEL ISSUES

Cat 1 Stockpile Concentration Caps

Independent calculations show that seepage from the Cat 1 Stockpile will have chemical concentrations at maximum values mutually agreed upon by Barr and MDNR (referred to as concentration caps). Table 1 presents a MathCad® calculation worksheet showing concentration caps for five chemical constituents. The blue entries in the table are the 50% probability (P50) values extracted from the GoldSim® Mine Site model. As shown, there is good agreement between the GoldSim® model values and concentrations independently calculated using mutually agreed upon inputs.

Chemical Generation from FTB Tailings

For the FTB, independent calculations were performed by the Review Team to check chemical generation rates for both LTVSMC tailings and NorthMet tailings during closure. Each independent calculation was programmed into a MathCad® calculation worksheet that automatically performed unit conversions and provided a printed record. Based on P50 input values, examples of the independent chemical release calculations are provided in Attachment 2. On these worksheets, blue entries are values extracted from a deterministic GoldSim® model run using P50 inputs. As shown, there is generally very good agreement between the GoldSim® model values and the independent calculations made outside the model.

To assess the sulfate load to the Plant Site WWTP during closure, the independent calculations for each subarea of the Tailings Basin are summarized in Table 2. The blue entries in this table are values extracted from the deterministic GoldSim® Plant Site model using P50 inputs. As shown there is generally good agreement between the independent calculations and the GoldSim® model results. The independently estimated flow rate to the WWTP is 1795 gpm, which is very close to the GoldSim® model estimate of 1783 gpm. The independently estimated sulfate mass flux of 2511 kg/day to the WWTP is reasonably close to the GoldSim® model value of 2656 kg/day. The independently estimated sulfate concentration to the WWTP is 257 mg/L, which compares favorably to the GoldSim® model estimate of 273 mg/L.

Table 3 shows a similar comparison for copper. For input to the WWTP, the independent calculations give a mass flux of 1.34 kg/day and a copper concentration of 0.137 mg/L. These values are very close to the GoldSim® model estimates of 1.29 kg/day and 0.133 mg/L.

The relatively good agreement between the GoldSim® model results and independent calculations performed outside the model suggests that the FTB inputs and algorithms mutually agreed upon by Barr and MDNR have been properly incorporated into the GoldSim® model.

Table 1 Cat 1 Concentration Caps

Cat 1 seepage concentration from deterministic GoldSim model with P50 inputs at t = 500 years

Sulfate (solubility equation)

$Mg := \frac{0.235127}{24.305}$	P50 magnesium release rate in mmole/kg/week (Table 1-24 and GoldSim to compute P50 value)	$Mg = 9.674 \times 10^{-3}$	
$Ca := \frac{1.10426}{40.078}$	P50 calcium release rate in mmole/kg/week (Table 1-24 and GoldSim to compute P50 value)	$Ca = 0.028$	
$K := \frac{0.191692}{39.0983}$	P50 potassium release rate in mmole/kg/week (Table 1-24 and GoldSim to compute P50 value)	$K = 4.903 \times 10^{-3}$	
$Na := \frac{0.227726}{22.989}$	P50 sodium release rate in mmole/kg/week (Table 1-24 and GoldSim to compute P50 value)	$Na = 9.906 \times 10^{-3}$	
$CAP_{SO4} := \left[1294 \cdot \frac{(Mg + 0.5 \cdot Na + 0.5 \cdot K)}{Ca} + 1760\right] \cdot \frac{mg}{L}$	SO4 concentration cap computed from P50 values (equation in Table 1-30)	$CAP_{SO4} = 2562 \cdot \frac{mg}{L}$	2562

Copper (based on pH and AMAX data)

$pH := 7.25$	Assumed Cat 1 pH with geomembrane cover	$pH = 7.25$	
$CAP_{Cu} := \frac{(0.200 + 0.178 + 0.260 + 0.340)}{4} \cdot \frac{mg}{L}$	P50 copper concentration cap from pH based values (Table 1-30)	$CAP_{Cu} = 0.244 \cdot \frac{mg}{L}$	0.237

Zinc (based on pH and AMAX data)

$pH := 7.25$	Assumed Cat 1 pH with geomembrane cover	$pH = 7.25$	
$CAP_{Zn} := \frac{(0.133 + 0.170 + 0.230 + 0.230)}{4} \cdot \frac{mg}{L}$	P50 zinc concentration cap from pH based values (Table 1-30)	$CAP_{Zn} = 0.191 \cdot \frac{mg}{L}$	0.186

Nickel (based on pH and AMAX data)

$pH := 7.25$	Assumed Cat 1 pH with geomembrane cover	$pH = 7.25$	
$CAP_{Ni} := \frac{(1.62 + 2.08 + 2.29 + 3.42)}{4} \cdot \frac{mg}{L}$	P50 nickel concentration cap from pH based values (Table 1-30)	$CAP_{Ni} = 2.353 \cdot \frac{mg}{L}$	2.267

Cobalt (based on pH and AMAX data)

$pH := 7.25$	Assumed Cat 1 pH with geomembrane cover	$pH = 7.25$	
$CAP_{Co} := \frac{(0.093 + 0.1368 + 0.120 + 0.150)}{4} \cdot \frac{mg}{L}$	P50 cobalt concentration cap from pH based values (Table 1-30)	$CAP_{Co} = 0.125 \cdot \frac{mg}{L}$	0.123

Cat 1 seepage concentrations are at concentration caps at the end of simulation (t = 500 yrs)

Table 2. Sulfate - Plant Site During Closure

P50 rainfall = 27.818

Tailings Basin Sub-Area	Tailings Material	Bentonite Amended	Area acre	Perc in/yr	Flow gpm	Sulfur MRA mg/m2/week	Sulfate MR kg/day	Check GoldSim t≈100 yrs kg/day
North Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	249.00	6.07	78.08	24.22	10.44	10.10
East Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	40.00	6.07	12.54	24.22	1.68	1.68
South Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	91.00	6.07	28.54	24.22	3.82	3.81
North Beach	35% NM fine, 65% NM coarse	Closure only	75.67	6.07	23.73	233.99	30.66	30.53
East Beach	35% NM fine, 65% NM coarse	Closure only	45.61	6.07	14.30	233.99	18.48	15.41
South Beach	35% NM fine, 65% NM coarse	Closure only	103.08	6.07	32.32	233.99	41.77	34.79
Closure Beach	35% NM fine, 65% NM coarse	Closure only	188.64	6.07	59.15	233.99	76.44	64.79
Pond	n/a	Closure (after 30 years)	972.60	6.50	326.59		58.43	
1E coarse	LTV coarse	none	3.38	2.68	0.47	1167.29	6.83	4.59
1E fine	LTV fine	none	0.00	2.19				
2E coarse	LTV coarse	none	0.00	5.04				
2E fine	LTV fine	none	0.00	3.92				
2E other	LTV coarse	none	75.29	5.50	21.40	518.25	67.57	67.25
2W coarse	LTV coarse	none	220.08	13.27	150.86	1539.87	586.91	575.76
2W fine	LTV fine	none	748.07	15.93	615.75	727.95	943.09	940.79
2W banks	LTV coarse	none	339.18	7.82	136.97	1073.15	630.38	619.96
South Buttress banks	Assumed Cat 1 waste rock	none	15.00	13.24	10.26		7.53	
North Buttress banks	Assumed Cat 1 waste rock	none	45.00	13.24	30.78		26.51	

Tailings Basin Sub-Area	Flow Distribution				Flow Rate (Q)				Mass Rate (MR)			
	N %	NW %	W %	S %	N gpm	NW gpm	W gpm	S gpm	N kg/day	NW kg/day	W kg/day	S kg/day
North Dam banks (outer slopes)	100	0	0	0	78.08	0.00	0.00	0.00	10.44	0.00	0.00	0.00
East Dam banks (outer slopes)	100	0	0	0	12.54	0.00	0.00	0.00	1.68	0.00	0.00	0.00
South Dam banks (outer slopes)	0	0	0	100	0.00	0.00	0.00	28.54	0.00	0.00	0.00	3.82
North Beach	100	0	0	0	23.73	0.00	0.00	0.00	30.66	0.00	0.00	0.00
East Beach	100	0	0	0	14.30	0.00	0.00	0.00	18.48	0.00	0.00	0.00
South Beach	3.8	0	0	96.2	1.23	0.00	0.00	31.10	1.59	0.00	0.00	40.18
Closure Beach	84.8	0	0	15.2	50.16	0.00	0.00	8.99	64.82	0.00	0.00	11.62
Pond	81	0	0	19	264.54	0.00	0.00	62.05	47.33	0.00	0.00	11.10
1E coarse	0	0	0	100	0.00	0.00	0.00	0.47	0.00	0.00	0.00	6.83
1E fine	1.5	31.7	7	59.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2E coarse	1.5	98.5	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2E fine	100	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2E other	98.6	1.4	0	0	21.10	0.30	0.00	0.00	66.63	0.95	0.00	0.00
2W coarse	14.6	31.1	35.2	19.1	22.03	46.92	53.10	28.81	85.69	182.53	206.59	112.10
2W fine	8.9	55.5	35.4	0.2	54.80	341.74	217.97	1.23	83.94	523.42	333.85	1.89
2W banks	11.1	36.1	41.6	11.2	15.20	49.45	56.98	15.34	69.97	227.57	262.24	70.60
South Buttress banks	0.0	0.0	0.0	100.0	0.00	0.00	0.00	10.26	0.00	0.00	0.00	7.53
North Buttress banks	100.0	0.0	0.0	0.0	30.78	0.00	0.00	0.00	26.51	0.00	0.00	0.00

	N gpm	NW gpm	W gpm	S gpm	N kg/day	NW kg/day	W kg/day	S kg/day
GW to Individual Collection Systems	588.49	438.40	328.06	186.79	507.74	934.46	802.68	265.67
					637.80	927.10	804.00	286.80
GW to Combined Collection			Total -->	1541.73			Total -->	2510.55
SW Runoff to Combined Collection				253.47				0.00
Total Average to WWTP				**1795.20**				**2510.55**
			Check	1783.40			Check	2655.70

Total GW to Collection System
SW Runoff to Collection Systems
Total Average to WWTP

Concentration to WWTP (mg/L) **256.55**
Check 273.18

Blue entries are values extracted from the GoldSim model
Red entries from Mathcad worksheets
All values are independently calculated using inputs and equations mutually agreed upon by the Agencies and Barr.
Values in this table compare favorably to GoldSim output.

MRA Mass rate of chemical release per unit map area
MR Mass rate of chemical release

N North Toe
NW Northwest Toe
W West Toe
S South Toe

Table 3. Copper - Plant Site During Closure

Tailings Basin Sub-Area	Tailings Material	Bentonite Amended	Flow gpm	From Table 2 Sulfate MR kg/day	Sulfur MR kg/day	Ratio to Sulfur R mg/mg	Calib Factor C	Conc Cap if used Cap mg/L	Copper MR kg/day	Check GoldSim t≈100 yrs kg/day
North Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	78.08	10.44	3.49	3.10E-02	0.0005		5.40E-05	5.34E-05
East Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	12.54	1.68	0.56	3.10E-02	0.0005		8.68E-06	8.57E-06
South Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	28.54	3.82	1.27	3.10E-02	0.0005		1.97E-05	1.95E-05
North Beach	35% NM fine, 65% NM coarse	Closure only	23.73					0.5157	6.67E-02	
East Beach	35% NM fine, 65% NM coarse	Closure only	14.30					0.5157	4.02E-02	
South Beach	35% NM fine, 65% NM coarse	Closure only	32.32					0.5157	9.09E-02	
Closure Beach	35% NM fine, 65% NM coarse	Closure only	59.15					0.5157	1.66E-01	
Pond	LTV	Closure (after 30 years)	326.59					0.5157	9.18E-01	
1E coarse	LTV coarse	none	0.47	6.83	2.28	3.10E-02	0.0005		3.53E-05	3.49E-05
1E fine	LTV fine	none								
2E coarse	LTV coarse	none								
2E fine	LTV fine	none								
2E other	LTV coarse	none	21.40	67.57	22.56	3.10E-02	0.0005		3.49E-04	3.45E-04
2W coarse	LTV coarse	none	150.86	586.91	195.91	3.10E-02	0.0005		3.03E-03	3.00E-03
2W fine	LTV fine	none	615.75	943.09	314.80	3.10E-02	0.0005		4.87E-03	4.82E-03
2W banks	LTV coarse	none	136.97	630.38	210.42	3.10E-02	0.0005		3.26E-03	3.22E-03
South Buttress banks	Assumed Cat 1 waste rock	none	10.26						1.33E-02	1.33E-02
North Buttress banks	Assumed Cat 1 waste rock	none	30.78						3.44E-02	3.44E-02

Tailings Basin Sub-Area	Flow Distribution N %	Flow Distribution NW %	Flow Distribution W %	Flow Distribution S %	Flow Rate (Q) N gpm	Flow Rate (Q) NW gpm	Flow Rate (Q) W gpm	Flow Rate (Q) S gpm	Mass Rate (MR) N kg/day	Mass Rate (MR) NW kg/day	Mass Rate (MR) W kg/day	Mass Rate (MR) S kg/day
North Dam banks (outer slopes)	100	0	0	0	78.08	0.00	0.00	0.00	5.40E-05	0.00E+00	0.00E+00	0.00E+00
East Dam banks (outer slopes)	100	0	0	0	12.54	0.00	0.00	0.00	8.68E-06	0.00E+00	0.00E+00	0.00E+00
South Dam banks (outer slopes)	0	0	0	100	0.00	0.00	0.00	28.54	0.00E+00	0.00E+00	0.00E+00	1.97E-05
North Beach	100	0	0	0	23.73	0.00	0.00	0.00	6.67E-02	0.00E+00	0.00E+00	0.00E+00
East Beach	100	0	0	0	14.30	0.00	0.00	0.00	4.02E-02	0.00E+00	0.00E+00	0.00E+00
South Beach	3.8	0	0	96.2	1.23	0.00	0.00	31.10	3.45E-03	0.00E+00	0.00E+00	8.74E-02
Closure Beach	84.8	0	0	15.2	50.16	0.00	0.00	8.99	1.41E-01	0.00E+00	0.00E+00	2.53E-02
Pond	81	0	0	19	264.54	0.00	0.00	62.05	7.44E-01	0.00E+00	0.00E+00	1.74E-01
1E coarse	0	0	0	100	0.00	0.00	0.00	0.47	0.00E+00	0.00E+00	0.00E+00	3.53E-05
1E fine	1.5	31.7	7	59.8	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2E coarse	1.5	98.5	0	0	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2E fine	100	0	0	0	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2E other	98.6	1.4	0	0	21.10	0.30	0.00	0.00	3.44E-04	4.89E-06	0.00E+00	0.00E+00
2W coarse	14.6	31.1	35.2	19.1	22.03	46.92	53.10	28.81	4.43E-04	9.43E-04	1.07E-03	5.79E-04
2W fine	8.9	55.5	35.4	0.2	54.80	341.74	217.97	1.23	4.34E-04	2.70E-03	1.72E-03	9.75E-06
2W banks	11.1	36.1	41.6	11.2	15.20	49.45	56.98	15.34	3.62E-04	1.18E-03	1.35E-03	3.65E-04
South Buttress banks	0.0	0.0	0.0	100.0	0.00	0.00	0.00	10.26	0.00E+00	0.00E+00	0.00E+00	1.33E-02
North Buttress banks	100.0	0.0	0.0	0.0	30.78	0.00	0.00	0.00	3.44E-02	0.00E+00	0.00E+00	0.00E+00

🟦 Theoretical result over-ridden by concentration cap

		Flow N	Flow NW	Flow W	Flow S	MR N	MR NW	MR W	MR S
GW to Individual Collection Systems		588.49	438.40	328.06	186.79	1.0309	0.0048	0.0041	0.3014
						0.9996	0.0050	0.0044	0.2850
GW to Combined Collection				Total -->	1541.73			Total -->	1.3413
SW Runoff to Combined Collection					253.47				0.0000
Total Average to WWTP					**1795.20**				**1.3413**
				Check	1783.40				1.2939

Concentration to WWTP (mg/L) **0.1371**
Check 0.1330

Total GW to Collection System
SW Runoff to Collection Systems
Total Average to WWTP

Blue entries are values extracted from the GoldSim model

All values are independently calculated using inputs and equations mutually agreed upon by the Agencies and Barr.
Values in this table compare favorably to GoldSim output.

R Ratio of copper mass to sulfur mass
MR Mass rate of chemical release

N North Toe
NW Northwest Toe
W West Toe
S South Toe

Sulfate Generation in Bentonite-Amended Subareas of the FTB

The Review Team questioned the method used by the model to compute sulfur generation below bentonite-amended subareas of the FTB and proposed a different mathematical approach when the availability of oxygen is limited by diffusion through the bentonite-amended layer. In comparing the two methods, it was found that the Review Team's approach computed sulfur production rates similar to those computed by the model (within a factor of 2). The Review Team concluded that the current model could be improved with regard to sulfur generation below bentonite-amended subareas, but the potential errors are not large compared to the higher sulfur generation rates in other subareas of the FTB. Given these considerations, the Review Team did not recommend modifying the current model for this QA audit. However, the issue should be revisited at a later time when the model is modified for other reasons.

Chemical Generation from Wall Rock in the West Pit

The audit of West Pit water quality predictions used independent calculations to check the predicted chemical loads from wall-rock to the West Pit Lake and evaluated whether the concentration caps that impart limits on maximum solute concentrations in the lake were applied correctly.

Results indicate that the GoldSim® model successfully applied concentration caps to all of the evaluated constituents that were predicted to reach their caps (nickel, copper, cobalt, and arsenic). Concentrations reported by the GoldSim® model when these solutes were at their caps were slightly different from the 50th percentile cap values (e.g., relative percent differences <30%), but this may reflect the difference between median model results and results run using median values for all parameters. This discrepancy is small relative to the reported uncertainty in GoldSim predictions.

The audit matched well with the GoldSim® model estimates for cumulative solutes loads to the West Pit from the two wall rock units evaluated: the Cat 4 Duluth Complex (a reactive rock, but a minor source of metals due to its small surface area), and Ore (a dominant source of nickel, cobalt, and copper to the West Pit Lake due to its high reactivity, metal content, and pit-wall area). The audit analyzed the period during active mining (years 1 to 20) when solutes leached from wall rock will be captured in a sump, and the 25 years after mining (years 20 to 45) when the West Pit Lake is filling and wall-rock loading includes continued leaching by runoff plus the release of stored solutes in the wall rock that will be leached out when the rock is inundated. The audit provided a good match to cumulative loading predicted by the GoldSim® model for all evaluated solutes except copper, which indicated higher loading than predicted by the GoldSim® model. This difference is consistent with the prediction that modeled copper loading to the West Pit will be limited continuously by the copper solubility cap. The audit did not account for the reduction in wall-rock loading caused by solubility caps, and thus overestimated copper loading relative to the GoldSim® model. The audit of the West Pit is described in more detail in Attachment 1.

Chemical Generation in the East Pit

The East Pit is essentially an engineered system with runoff and inflow pumped and treated from a sump during operations. Eventually the pit is backfilled with acid-generating waste rock, flooded, and actively pumped and treated to reduce water solute concentrations to water-quality thresholds. In addition, mine plans retain an option to treat the rock backfilled to the East Pit to neutralize acidity which will reduce initial pore-water concentrations to the concentration caps for Category 1 rock, thereby further reducing the need for water treatment. As a result, the loading from wall rock and backfill was not replicated in detail as part of this audit. The audit instead evaluated whether the GoldSim® model predictions effectively limited pore-water concentrations to the values for neutral Cat 1 rock.

Results indicated that the GoldSim® model correctly applied the pore water concentration caps to all evaluated solutes when the backfilled rock is first flooded (year 11). The concentrations predicted in the GoldSim® model match the Cat 1 caps for sulfate, arsenic, and antimony. The caps applied in the GoldSim® model to cobalt, copper, and nickel exceed the neutral Cat 1 concentration caps, reflecting the use of intermediate caps for these metals (e.g., caps applicable to Cat 2/3/4 Duluth Complex rock under non-acidic conditions). More detailed information on the audit of the East Pit is provided in Attachment 1.

ATTACHMENT 1: AUDIT OF GOLDSIM® WATER QUALITY MODEL FOR WEST PIT AND EAST PIT, POLYMET NORTHMET PROJECT

Houston Kempton, Knight Piesold

Prepared in coordination with Interralogic, Inc.

29 October 2012

SCOPE OF THE GOLDSIM WATER QUALITY MODEL AUDIT FOR THE NORTHMET WEST AND EAST PITS

This audit is intended to confirm that the calculations used in the GoldSim model to estimate water quality in the West and East Pits of the NorthMet project have used the assumptions and parameter values presented in the supporting work plans and data packages and have been performed accurately. The audit is not a 100-percent verification of model calculations, but does focus on evaluating the model components that are most critical for estimating water management costs so that discharges meet regulatory thresholds during and after the NorthMet project. This audit is based on model parameter values and model results presented in the 26 September 2012 version of the NorthMet GoldSim water quality model provided by Barr Engineering.

This audit of the pit water quality included 6 of the 28 water-quality constituents included in the full GoldSim modeling: arsenic, antimony, copper, cobalt, nickel, and sulfate. These six were selected because preliminary assessments have indicated a reasonable possibility that they could be released from mine rock at rates high enough to exceed surface or groundwater thresholds at the NorthMet Mine. (Magnesium was not a primary target of this audit, but is included in some audit results because it is a required component in calculating the release of nickel from some mine rock).

The audit calculations are deterministic, using the 50th percentile (i.e., P50) value for model parameters. Audit results are then compared results to either deterministic GoldSim results that also used median parameter values, or to median results from probabilistic GoldSim runs. Uncertainty in model predictions is based on the probability distributions for specific model parameter, and the accuracy of these distributions was demonstrated in Task 1 of this audit, completed in February 2012.

West Pit

The audit of West Pit water quality predictions conducted independent calculations to check the predicted pollutant loads from wall-rock to the West Pit Lake, and evaluate whether the "concentration caps" that impart limits on maximum solute concentrations in the lake were applied correctly. The estimates of solute loads from the various sources were "Control Volume" file produced by running GoldSim in deterministic model using P50 values for model parameters. GoldSim considered loads from 11 different sources to the West Pit: Runoff, Groundwater, East Pit Wetland, East Pit Porewater, WWTF Return Water, In-pit Blast Ore, Cat

1 Stockpile, Cat 1 Wallrock, Cat 2/3 Wallrock, Cat 4 Wallrock, Ore Wallrock, Tailings Basin Water.

In keeping with the project's emphasis on using an adaptive management approach to meet water quality thresholds, the audit focused on the major uncontrolled sources of pollutants. Thus the external loads (i.e., sources delivered from other facilities to the West Pit, such as WWTF Return Water or Cat 1 Stockpile), were omitted from the West Pit Lake audit. The predicted external load to the West Pit is dominated by two facilities: Discharge from the Tailings Basin, which is evaluated separately in the main body of this audit report; and Waste Water Treatment Facility discharge, which will be engineered to meet discharge thresholds.

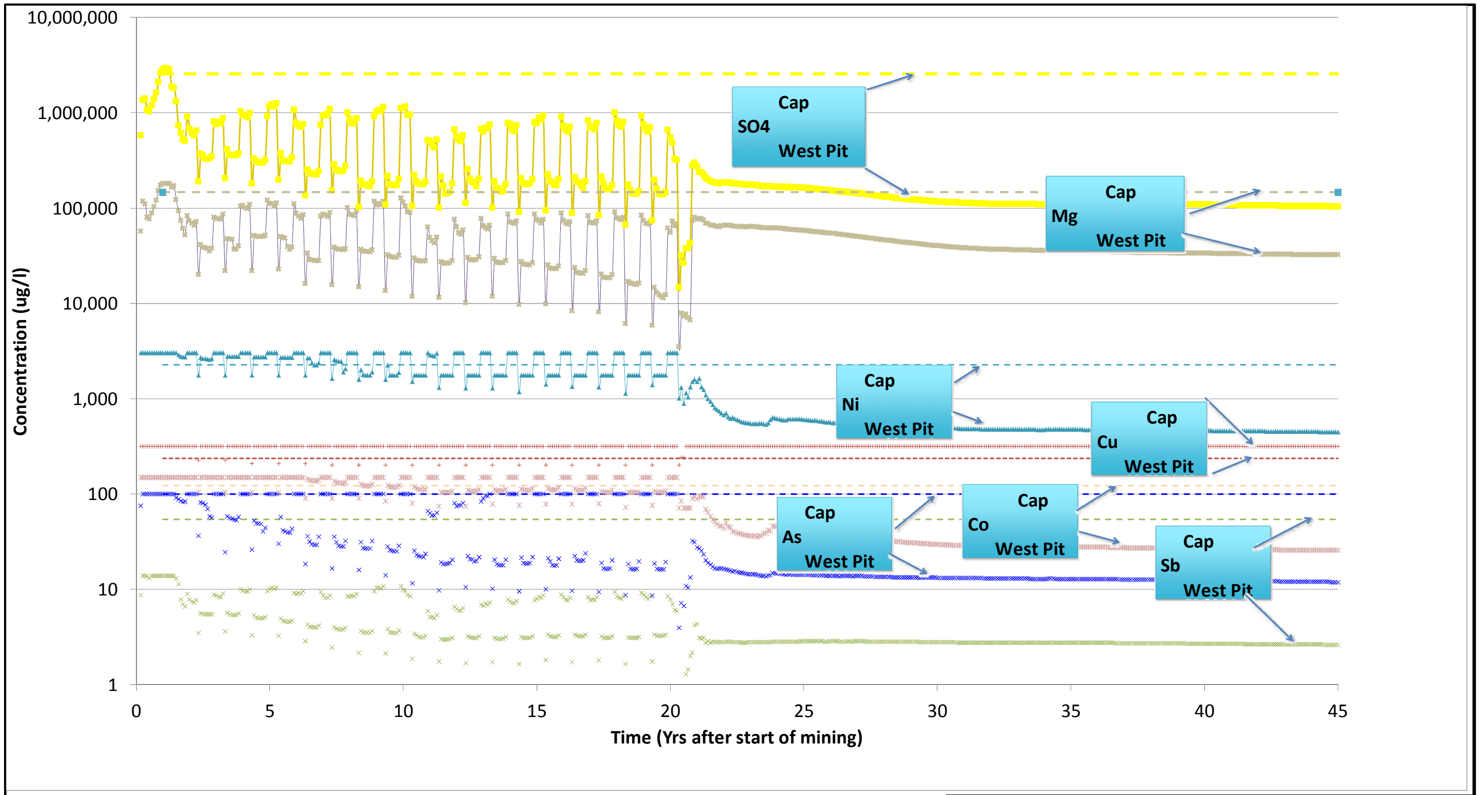
The West Pit Lake audit consisted of reproducing calculated loads for two in-pit sources: The Cat 4 Duluth Complex Wall rock, which is predicted to be a minor source of metals (included in the audit to confirm that it was in fact a minor contributor of pollutants), and the ore wall rock, which is predicted to be the dominant source of nickel, cobalt, and copper to the West Pit Lake. The Cat 4 Duluth Complex wall rock is a reactive acid-generating material, but is predicted to have a minor load due to the small are of this material in the pit walls. The Ore wall rock is a similarly reactive acid-generating material, but is a large contributor because of its large surface area in the pit walls and greater concentrations of metals. The estimates for wall rock loads to the West Pit were tracked in GoldSim as "Mine Site Control Volume 2," and were reported in spreadsheet files "MineSite_CV2.xlsx."

Application of Concentration Caps to West Pit Water

The predicted concentrations of the 6 evaluated solutes in the West Pit Lake indicate that GoldSim applied correctly the concentration caps for the evaluated solutes (Figure 1). Median solute concentrations in the West Pit Lake predicted by GoldSim between year 1 and 45 were drawn from reported output for the median concentrations (file provided by Barr Engineering = "WP_Concs_Output.txt"). Concentration caps were extracted from the Base Mine Site version 3.0 version of the NorthMet GoldSim model provided by Barr Engineering (Barr, 26 September 2012), and checked for consistency with the concentration cap values reported with model input (File = "Concentration_Caps.xlsx").

The GoldSim model of the West Pit Lake applies Cat 1 concentration caps to leachate from wall rock and to the pit lake itself. This application of concentration caps follows from the assumption that the West Pit Lake will have a near-neutral pH, either by natural buffering by rock and groundwater, or by active maintenance. The GoldSim algorithm for solutes loaded to the West Pit Lake is based on a conceptual model that assumes reversible precipitation of minerals, so that loads that would produce concentrations above the concentration cap are removed from solution, but are then allowed to precipitate back into solution later as soon as the lake concentration drops below the concentration cap. During active mining, GoldSim reflects the plan to capture groundwater inflow and wall-rock runoff in a small sump at the base of the West Pit that will be pumped out as necessary. As a result, predicted water quality during mining (year 1 to 20) has a strong seasonal signal (Figures 1), reflecting a large ratio in load: volume. Beyond year 20, the West Pit will be allowed to form a lake, so the seasonal effect is dampened as solutes leached from wall rock are added to an increasingly volume of water until the lake reaches its final elevation mine year 45.

Figure 1 ***Predicted concentrations of select solutes in the West Pit Lake, and their concentration caps. GoldSim NorthMet simulation 3.0 (26 Sept 2012).***



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PROJECT	
TITLE	**Predicted concentrations of select solutes in the West Pit Lake, and their concentration caps. GoldSim NorthMet simulation 3.0 (26 Sept 2012).**

Knight Piésold
CONSULTING

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Specific results for application of GoldSim concentration caps to the West Pit Lake (Figure 1) for evaluated analytes include:

- Sulfate (P50 cap = 2,562 mg/l) is never limited by its concentration cap.
- Nickel (P50 cap = 2.266 mg/l) exceeds its concentration cap for part of each season during mining, but is always below its cap once the lake begins to fill after year 20.
- Copper (P50 cap = 0.237 mg/l) exceeds its concentration cap for part of each season during mining, and remains at the concentration cap between end of mining and filling of the West Pit Lake at year 45.
- Cobalt (P50 cap = 0.123 mg/l) exceeds its concentration cap for part of each season during mining, but is always below its cap after the lake begins to fill at year 20.
- Magnesium (P50 cap = 142 mg/l) essentially never exceeds its concentration cap.
- Arsenic (P50 cap = 0.1 mg/l) exceeds its concentration cap for part of each season during mining, but is always below its cap after the lake begins to fill at year 20.
- Antimony (P50 cap = 0.54 mg/l) remains always below its concentration cap during and after filling of the West Pit.

These results indicate that wall-rock loading from copper should be limited by concentration caps during and after mining, but that most or all of the loads of the other 5 solutes evaluated in this audit should be transferred to the West Pit Lake.

Discrepancies in Model Audit Results

The concentration caps applied to several of the evaluated solutes in the GoldSim model (median values from model results) were slightly higher than the P50 value for the caps, including:

- Mg: 180 mg/l applied cap vs. 147 mg/l P50 cap value.
- Ni: 3.02 mg/l applied cap vs. 2.266 mg/l P50 cap value.
- Cu: 0.316 mg/l applied cap vs. 0.237 mg/l P50 cap value.
- Co: 0.15 mg/l applied cap vs. 0.12 mg/l P50 cap value.

These discrepancies in concentration-cap values may be explained by differences between P50 cap values and median model results, but they are, in any event, very small (<30% relative percent difference) relative to the total range in prediction uncertainty between the 10th and 90th percentile concentrations for these solutes.

Oxidation and Solute Release from West Pit Wall Rock

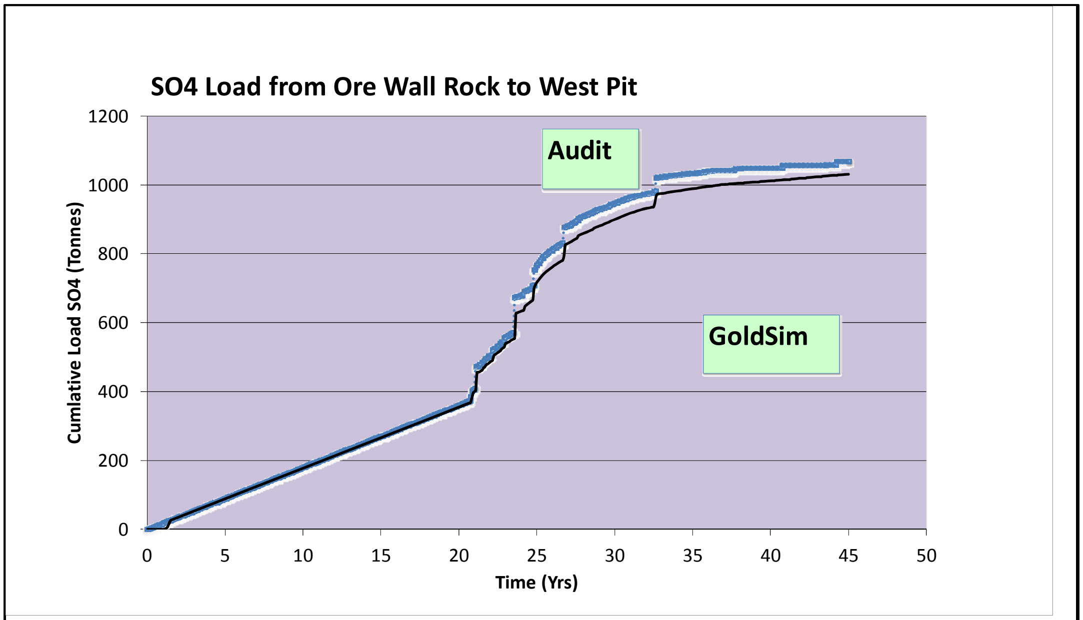
The audit of the West Pit Lake GoldSim model included independent calculation of cumulative loads of seven evaluated solutes from two wall rock units (Cat 4 Duluth Complex, and Ore) over the period between mine year 1 (start of mining) and year 45 (West Pit Lake reaches final elevation). The calculation of wall rock loads followed the algorithm presented in the Waste Characterization Data Package, v9 (Jul 2012).

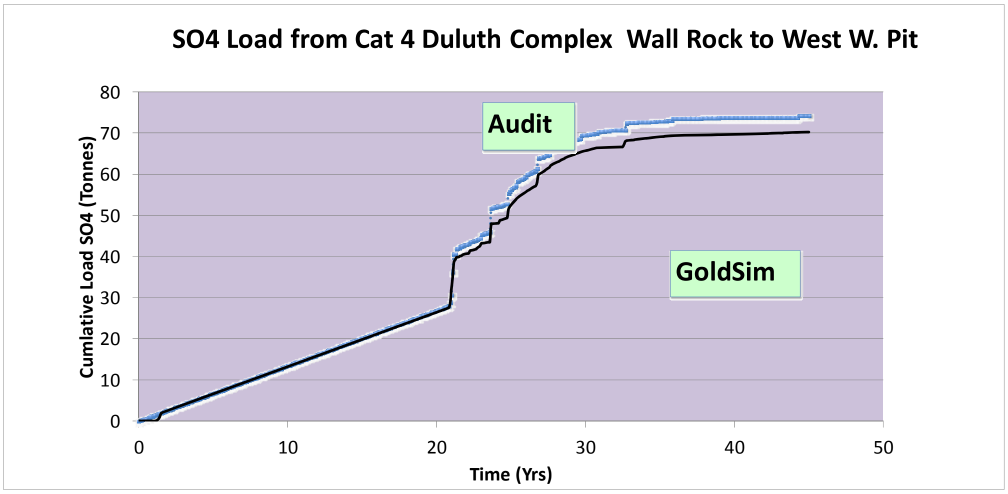
Parameters and effects included in these calculations, and thus evaluated by this audit, include:

- Area of wall rock exposed in pit wall;
- Thickness of reactive wall rock zone;
- Density of wall rock;
- Duration of exposure before wall rock is inundated with water given the predicted lake fill rate;
- Oxidation rate in the rock and associated rate of sulfate release;
- Rates of metal release from wall rock based on relation to sulfate release rates;
- Temperature factor (slows rate of field oxidation relative to laboratory rate based on field temperature and activation energy in oxidation);
- Size factor (on average, only 10% of the wall rock is small enough to appreciably oxidize);
- Contact Factor (on average, 50% of solutes in wall rock are assumed to be flushed to the pit each year by rain and snow);
- Latent release of solutes from flooded wall rock (the fraction of solutes in wall rock that are not released immediately by rain and snow melt but that are leached out when the rock is inundated by the lake);
- Duration of oxidation in sulfide-bearing wall rock before pore water becomes acidic;
- Spike in oxidation rate when pore water becomes acidic (occurs at ~mine-year 20 under field conditions), subsequent decay in rate as sulfide S is depleted in the wall rock; and.
- The effect of concentration caps, which in the GoldSim model will restrict the leaching of solutes from wall rock if the concentrations in the lake are above the concentration cap.

The audit of GoldSim’s load rate for Cat 4 Duluth Complex and Ore wall rock (Figures 2 through 8) to the West Pit show a similar trend for all 7 evaluated solutes. The audit calculation matches well to the load rates between start of mining and year 20, which is the period when solutes leached from wall rock are captured in a sump for active treatment. These results suggest that GoldSim is applying correctly the wall-rock-loading-model parameters agreed upon by PolyMet and the Co-Lead Agencies in preparation of the Model Work Plans. Also, the consistency indicates that the relative sources have been analyzed and reported by GoldSim in accordance with work plans, i.e., that the Cat 4 Duluth Complex wall rock is a minor source of solutes, and the that ore wall rock is predicted to be the major source of cobalt, copper, and nickel to the West Pit Lake. Finally, as expected, the load of copper to the West Pit Lake calculated by the audit (which did not explicitly include the effect of concentration caps) is greater than the values indicated by GoldSim (which did reduce solutes load rates that would have caused lake concentrations to exceed the cap threshold). Copper concentrations in the West Pit Lake are continuously limited by the application of the Cat 1 concentration caps, and this has reduced predicted load of copper in GoldSim relative to the Audit. In longer-term GoldSim simulations, the copper withheld from the West Pit to meet the concentration cap during the lake filling period will be available to re-dissolve at later times.

Figure 2 *Comparison of Sulfate Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation.*





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TITLE Comparison of Sulfate Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation.					
Knight Piésold CONSULTING					
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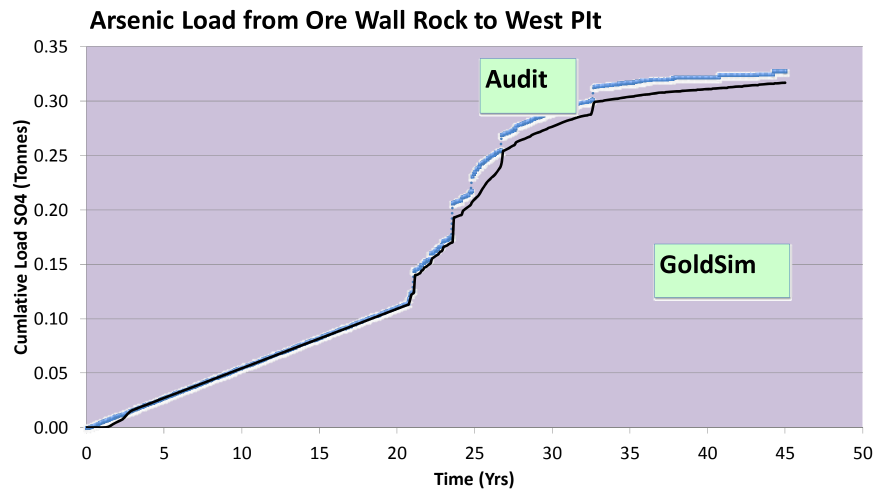
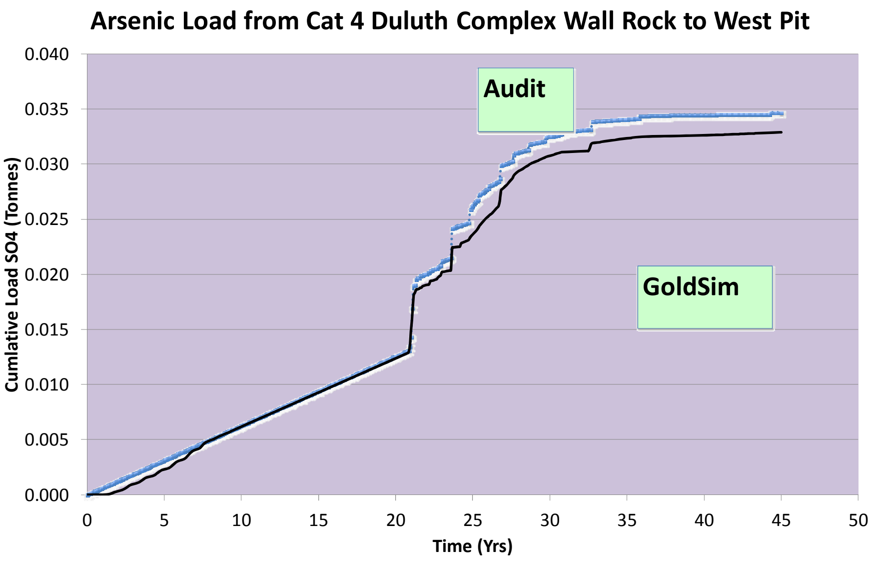
Figure 3 *Comparison of Arsenic Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation*





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Comparison of Arsenic Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation

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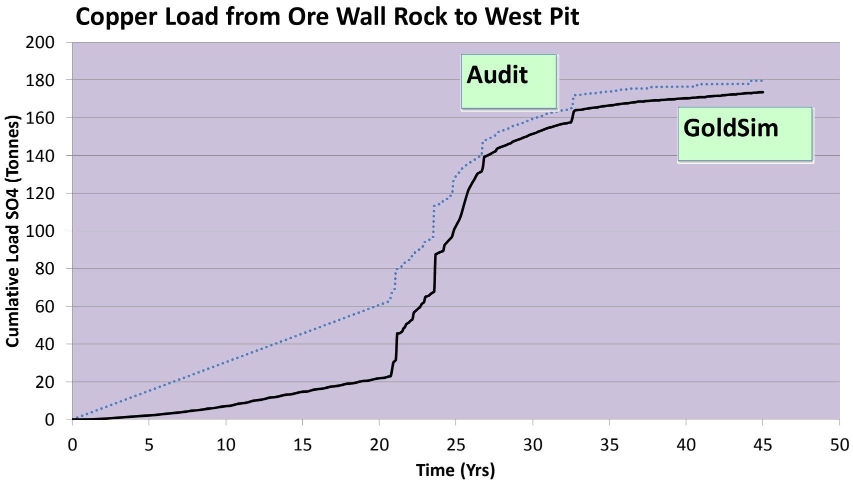
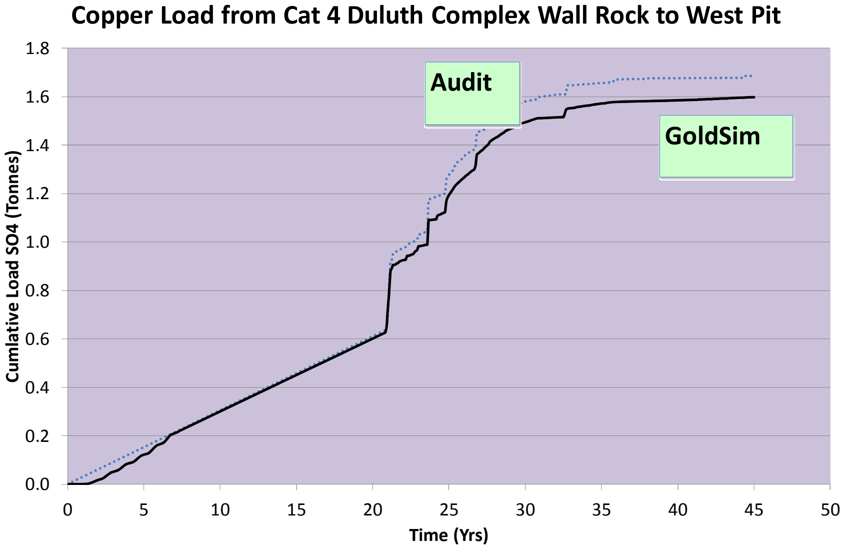
Figure 4 Comparison of Copper Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation





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Comparison of Copper Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation

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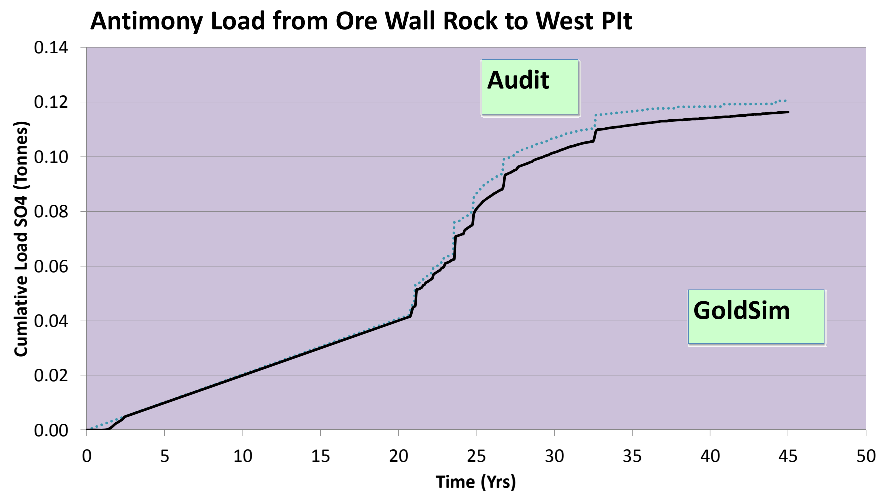
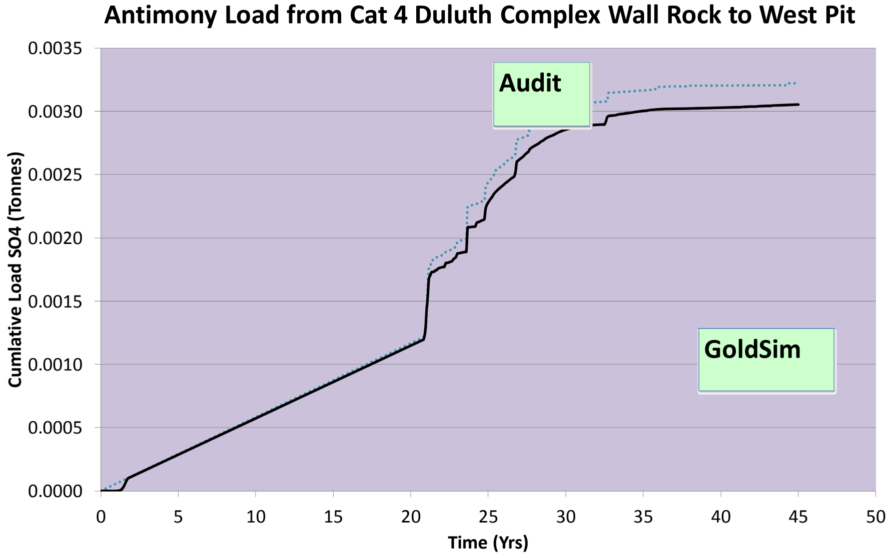
Figure 5 *Comparison of Antimony Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation*





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Comparison of Antimony Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation

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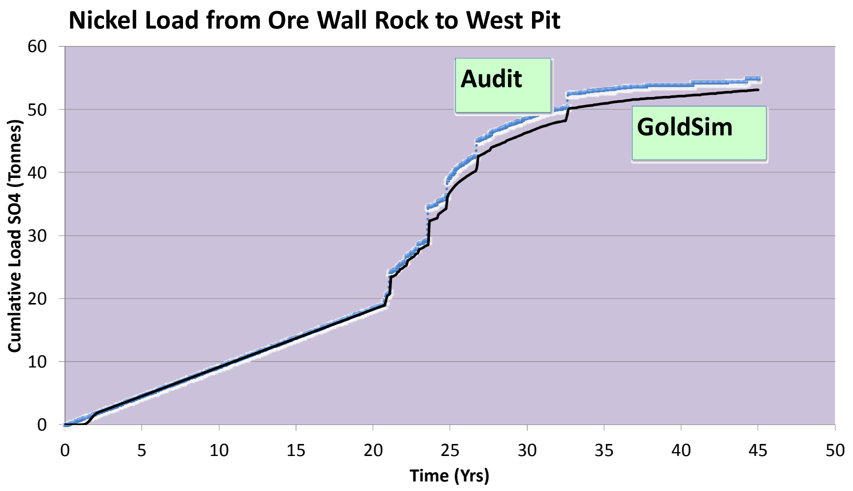
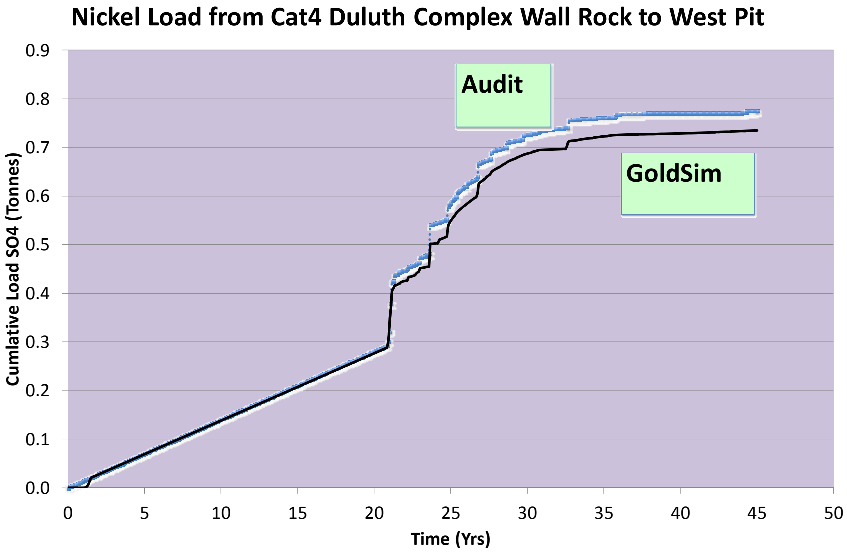
Figure 6 *Comparison of Nickel Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation*





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Comparison of Nickel Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation

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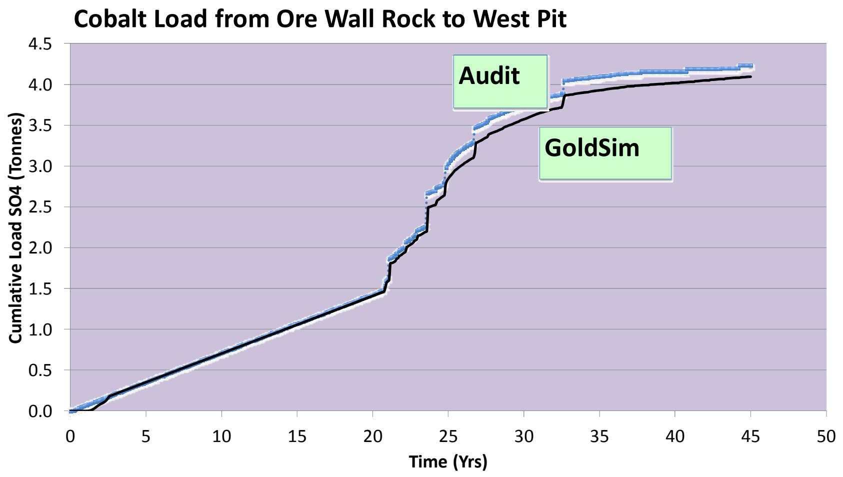
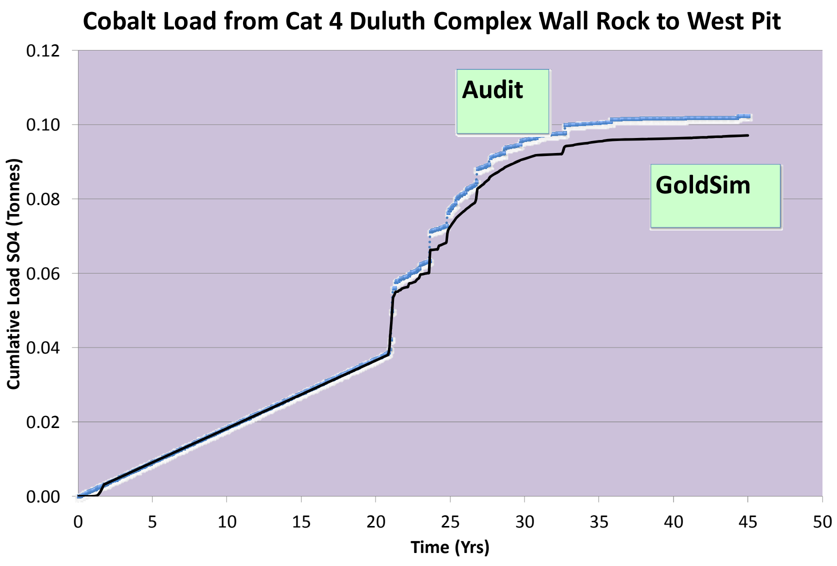
Figure 7 Comparison of Cobalt Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation





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Comparison of Cobalt Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation

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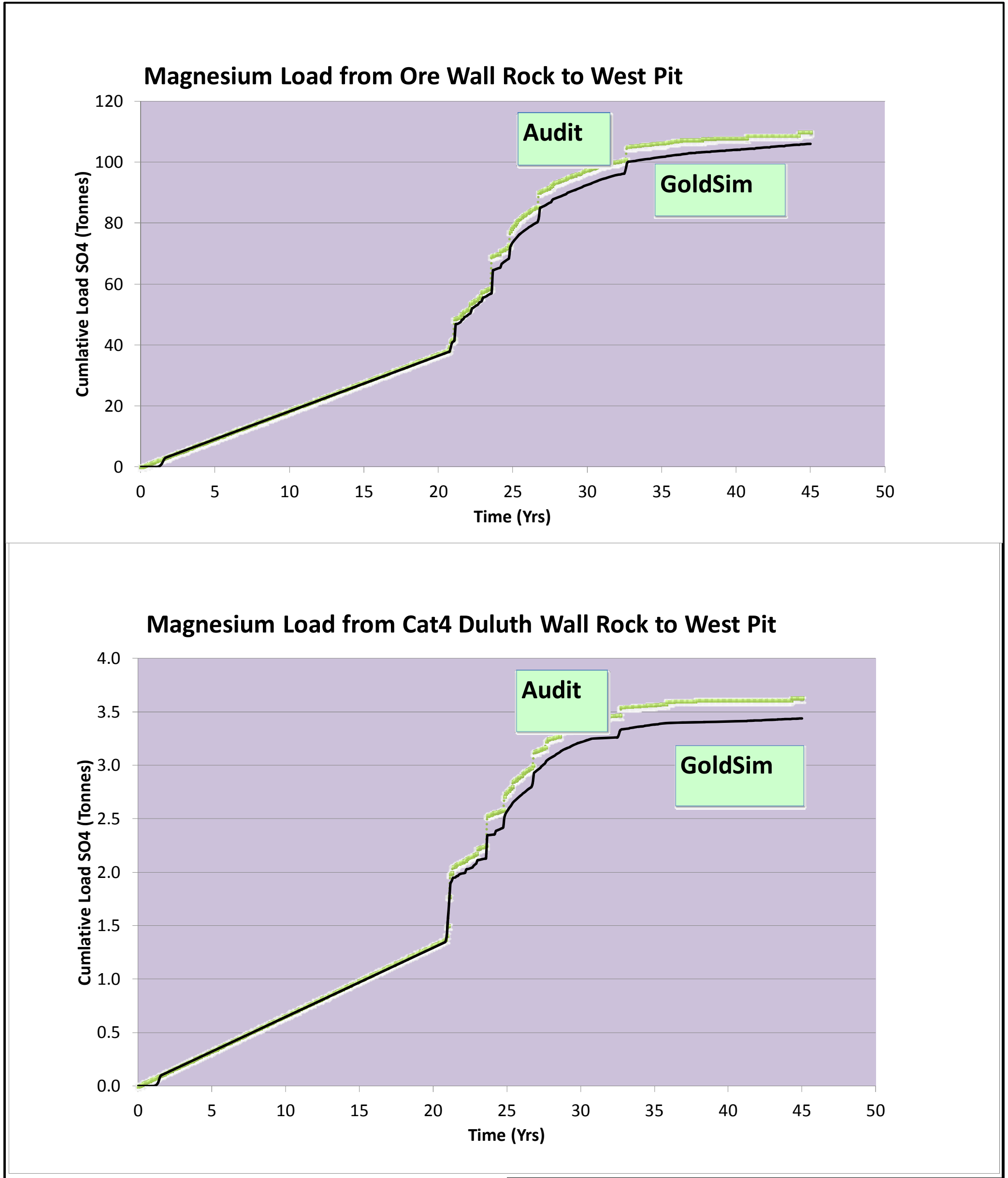
Figure 8 *Comparison of Magnesium Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation*



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Comparison of Magnesium Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation

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Discrepancies in Model Audit Results:

The “Culpability” files produced by GoldSim to indicate solute loading from West Pit wall rock may not contain all sources of loading.

The independent-audit estimates of wall-rock solute loading to the West Pit suggested that the GoldSim results provided in the “Culpability” files (i.e., indicating loads of specific constituents to specific facilities) did not include the loading of solutes leached to the lake when the wall rock is inundated by the lake. Although the mass balance results from GoldSim produced in the “Control Volume” files do contain a complete account of solute release from wall rock, and the culpability files should be modified so that they also contain all sources of solutes released from mine rock.

GoldSim uses solute release parameters for Ca2/3 rock to estimate solute release of several constituents from ore in wall rock.

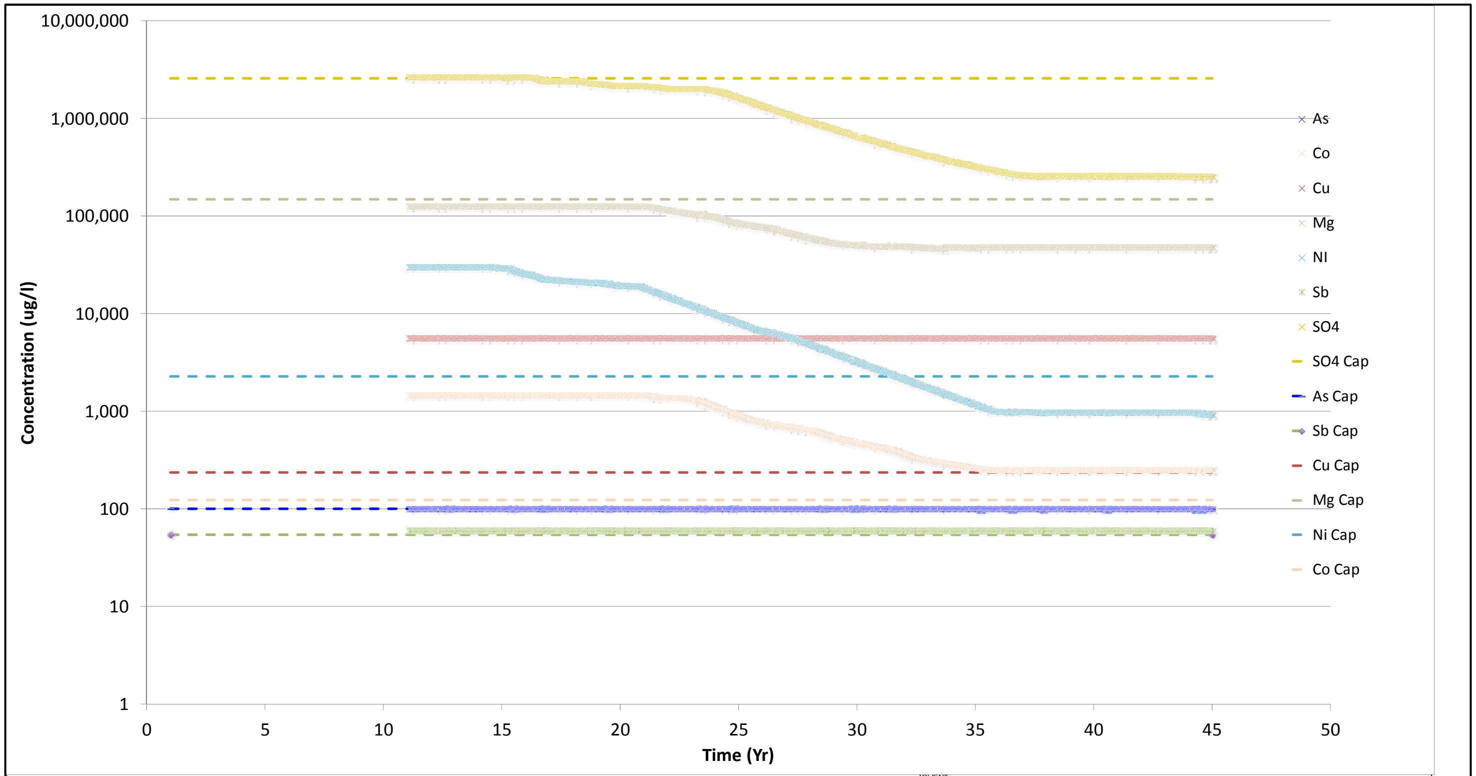
Parameters extracted from the GoldSim input files for ore wall rock indicate that the release of several solutes from ore wall rock were based on release rates for Cat 2/3 rock (i.e., in Barr 2012, Water Modeling Work Plan – Mine Site, ver. 7, July 2012, GoldSim applied values from Table 1-25 [Category 2/3 release distribution] instead of Table 1-27 [Ore Release Distributions]). This applies to ratios for Co/Ni, Mg/SO4, Co/SO4, Zn/SO4, Cd/SO4, Na/SO4, Zn/Ni, and Cd/Zn.

East Pit

The East Pit is critical to the overall NorthMet water management because it is the permanent repository for all of the high-sulfide, acid-generating waste rock (Category 2, 3, and 4). However, the backfilled East Pit is essentially an engineered system, and was thus not replicated in detail. Specifically, the rock backfilled to the East Pit will be flooded by natural inflow (groundwater and wall rock runoff), and inflow augmented with tailings pond water to inundate the reactive rock at the desired rate. Once flooded, the processes of oxidation, acid production, and solute-release essentially stop, and the water in the East Pit will be circulated and treated to achieve eventual restoration of the pore water composition to groundwater standards. Further, current mine plans retain an option to treat the rock backfilled to the East Pit to neutralize acidity, which will reduce initial pore-water concentrations to the concentration caps for Category 1 rock, thereby reducing further the need for water treatment.

In response, the audit of the East Pit was limited to confirming that pore-water concentrations in the backfilled were limited by solubility caps. Results from the NorthMet GoldSim Model ver. 3.0 (26 Sept 2012) were obtained from the file “EP_Pore_Cons_Output.txt.” These indicated that predicted pore water concentrations of all evaluated solutes are at capped values when the backfill is first flooded (year 11; Figure 9). Sulfate, magnesium, arsenic, and antimony are essentially at the concentrations caps for neutral Cat 1 rock. But cobalt, copper, and nickel exceed the neutral Cat 1 concentration caps, reflecting the use of intermediate caps for these metals. If mine plans indicate that water would benefit from lower concentrations of additional metals, then the discharge concentrations of all solutes could be reduced to the Cat 1 rock concentration caps by implementing the plan to amend the waste rock backfill to the East Pit as it is emplaced.

Figure 9 *Predicted concentrations of select solutes in East Pit backfill pore water, and the concentration caps for Cat 1 rock. GoldSim NorthMet simulation 3.0 (26 Sept 2012).*



CLIENT

PROJECT

TITLE

Predicted concentrations of select solutes in East Pit backfill pore water, and the concentration caps for Cat 1 rock. GoldSim NorthMet simulation 3.0 (26 Sept 2012).

Knight Piésold
CONSULTING

DESIGNED BY		LOCATION	PROJECT NUMBER	FIGURE NUMBER	REVISION
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C:\Users\karen.linck\Desktop\NoMet Memo 10-29-12\[Model_Audit_(Conc_Caps_E&W_Pits)_29Oct2012.xlsx]

ATTACHMENT 2: CALCULATION WORKSHEETS FOR INDEPENDENT VERIFICATION OF CHEMICAL MASS RELEASE FROM THE PLANT SITE TAILINGS BASIN

Interralogic, Inc.

This attachment contains a series of MathCad® calculation worksheets that estimate the release of sulfate and other constituents from different subareas of the FTB. The MathCad® calculations were developed independently of the GoldSim® model and therefore provide a check of the GoldSim® model results. In each worksheet blue entries represent values obtained from the GoldSim® model, and these are compared with the corresponding MathCad® value. In nearly all cases, there is relatively close agreement between the GoldSim® model values and the independently-computed values.

Cell 1E Coarse - Sulfate - Closure

LTVSMC coarse tailings

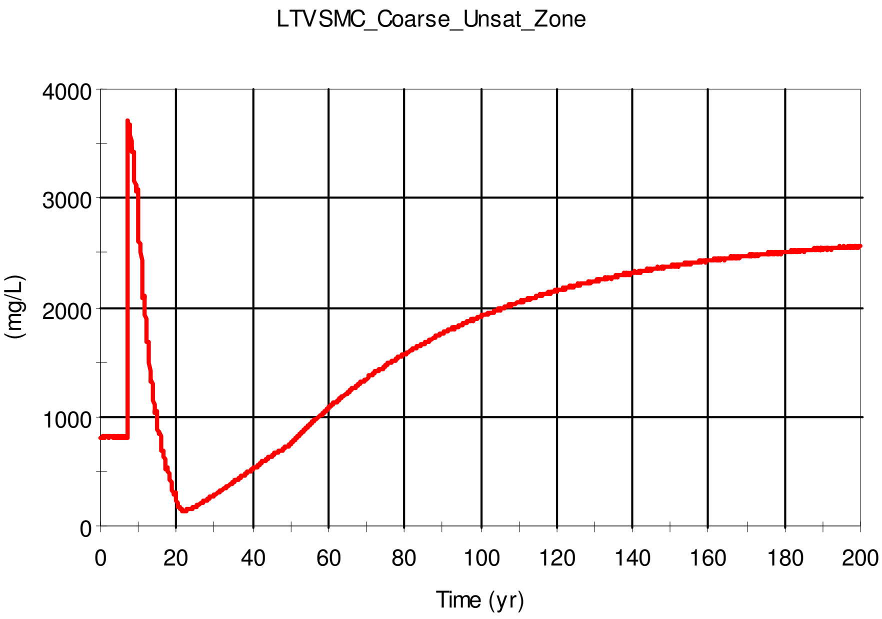
Blue values generated by GoldSim model

$K_s := 2.40 \cdot 10^{-3} \cdot \frac{cm}{sec}$	Saturated hydraulic conductivity (Table 1-12a)	
$\beta := 2$	vanGenuchten parameter (Table 1-12a)	
$\theta_r := 0.041$	Residual volumetric water content (Table 1-12a)	
$\phi := 0.412$	Porosity (Table 1-12a)	
$G := 2.80$	Specfic gravity (Table 1-12a)	$\mu g := 10^{-6} \cdot gm$
$\rho_w := 1 \cdot \frac{gm}{cm^3}$	Water density (standard value)	
$A := 3.3784 acre$	Map area (Table 1-33)	
$q := 2.6812 \cdot \frac{in}{yr}$	Percolation flux (from seepage spreadsheet with Barr edits)	
$\tau := 0.273$	Tortuosity (Table 1-1, sheet 5)	
$D_a := 1.8 \cdot 10^{-5} \cdot \frac{m^2}{sec}$	Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)	
$c := 3.28$	Empirical constant (Table 1-1, sheet 5)	
$D_w := 2.2 \cdot 10^{-9} \cdot \frac{m^2}{sec}$	Free difussion coeff of oxygen in water (Table 1-1, sheet 5)	
$K_H := 33.9$	Henry's constant for oxygen (Table 1-1, sheet 5)	
$C_o := 8.89 \cdot \frac{mol}{m^3}$	O2 concentration in air (Table 1-1, sheet 5)	
$W_{SO4} := 96.07 \cdot \frac{gm}{mole}$	Molecular weight of sulfate (standard value)	
$W_S := 32.066 \cdot \frac{gm}{mole}$	Molecular weight of sulfur (standard value)	
$R_{SO4} := 1.95186 \cdot \frac{mg}{kg \cdot 7 \cdot day}$	P50 SO4 distribution paramater for tailings (Table 1-19)	
$CF := 0.185$	Calibration factor for tailings (Table 1-1, sheet 5)	
$TF := 0.228589$	Temperature factor (computed in GS using numerous inputs)	
$FF := \frac{3.4}{12}$	Freeze factor (from Table 1-1, sheet 3)	$FF = 0.28333$
$moleratio := \frac{4}{9}$	mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6)	$moleratio = 0.444$
$DTW := 117.8 \cdot ft$	Depth to water table in cell 2E during closure (value in Table 1-34 is 51.0 ft; GS value used in calcs is 52.3 ft)	
$Cont_S := 329 \cdot \frac{mg}{kg}$	Sulfur content. Mass of S per unit mass of tailings. (Table 1-22)	
$\rho_b := G \cdot \rho_w \cdot (1 - \phi)$	Tailings dry bulk density. Mass of solids per unit bulk volume.	$\rho_b = 1.646 \cdot \frac{gm}{cm^3}$

$\gamma := 1 - \frac{1}{\beta}$	Computed vanGenuchten parameter		$\gamma = 0.5$
$K(ss) := K_s\cdot\left(\frac{ss\cdot\phi - \theta_r}{\phi - \theta_r}\right)^{0.5}\cdot\left[1 - \left[1 - \left(\frac{ss\cdot\phi - \theta_r}{\phi - \theta_r}\right)^{\frac{1}{\gamma}}\right]^{\gamma}\right]^2$	Unsaturated hydraulic conductivity as a function of saturation (ss) based on vanGenuchten relationship		
$f(ss) := q - K(ss) \qquad ss := 0.4$	Root equation and saturation guess		
$SAT := \mathrm{root}(f(ss), ss)$	Computed saturation associated with flux (q)	0.2816	$SAT = 0.2536$
$q - K(SAT) = -9.282\times 10^{-10}\cdot\frac{in}{yr}$	Confirm root calculation (result should be approx zero)		
$D := \tau\cdot D_a\cdot(1 - SAT)^c + \tau\cdot SAT\cdot\frac{D_w}{K_H}$	Effective O2 diffusion coeff referenced to void volume	1.661×10^{-6}	$D = 1.883\times 10^{-6}\,\frac{m^2}{s}$
$MRM_{SO4} := R_{SO4}\cdot CF\cdot TF\cdot(1 - FF)$	Mass rate of released SO4 per unit mass of tailings solids		$MRM_{SO4} = 0.0592\cdot\frac{mg}{kg\cdot 7\cdot day}$
	Effect of three factors $CF\cdot TF\cdot(1 - FF) = 0.030$		
$R_{O2} := \frac{MRM_{SO4}}{W_{SO4}\cdot moleratio}\cdot\frac{\rho_b}{\phi}$	Molar consumption rate of O2 per unit void volume.	0.005542	$R_{O2} = 0.005536\cdot\frac{mol}{m^3\cdot 7\cdot day}$
$d := \sqrt{\frac{2\cdot D\cdot C_o}{R_{O2}}}$	Thickness of sulfate reaction zone if controlled by diffusion	56.77	$d = 60.475\,m$
$b := \min(d, DTW)$	Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water.		$b = 35.905\,m$
$MR_{SO4} := MRM_{SO4}\cdot b\cdot A\cdot\rho_b$	Mass rate of released sulfate		$MR_{SO4} = 6.83\cdot\frac{kg}{day}$
$MRV_S := R_{O2}\cdot W_S\cdot moleratio\cdot\phi$	Mass rate of released S per unit bulk volume		$MRV_S = 4.644\cdot\frac{mg}{m^3\cdot day}$
$MRA_S := MRV_S\cdot b$	Mass rate of released S per unit map area (m^2)	1167.3	$MRA_S = 1167.2\cdot\frac{mg}{m^2\cdot 7\cdot day}$
$MR_S := MRA_S\cdot A$	Mass rate of released S		$MR_S = 2.28\cdot\frac{kg}{day}$
$Q := q\cdot A$	Seepage flow rate		$Q = 0.468\cdot gpm$
$C_{SO4} := \frac{MR_{SO4}}{Q}$	Sulfate concentration in seepage	2559 at t= 200 yrs	$C_{SO4} = 2679.2\cdot\frac{mg}{liter}$
$t_{end} := \frac{Cont_S\cdot\rho_b\cdot A\cdot DTW}{MR_S}$	Time to deplete all sulfur in the reaction zone.		$t_{end} = 319\cdot yr$

GoldSim Output

MR_{SO4} at 100 years is 4.882 kg/day



Other Chemicals

Arsenic

$RR_{As} := 0.09995$	Release ratio of As to S		
$CF_{As} := 0.0001$	As calibration factor		
$MR_{As} := MR_S \cdot RR_{As} \cdot CF_{As}$	Mass rate of released As	8.322×10^{-6}	$MR_{As} = 8.322 \times 10^{-6} \cdot \frac{tonne}{yr}$
$C_{As} := \frac{MR_{As}}{Q}$	As concentration in seepage		$C_{As} = 8.938 \cdot \frac{\mu g}{L}$

Cobalt

$RR_{Co} := 0.03076$	Release ratio of Co to S		
$CF_{Co} := 0.0006$	Co calibration factor		
$MR_{Co} := MR_S \cdot RR_{Co} \cdot CF_{Co}$	Mass rate of released Co	1.536×10^{-5}	$MR_{Co} = 1.537 \times 10^{-5} \cdot \frac{tonne}{yr}$
$C_{Co} := \frac{MR_{Co}}{Q}$	Co concentration in seepage		$C_{Co} = 16.505 \cdot \frac{\mu g}{L}$

Copper

$RR_{Cu} := 0.030598$	Release ratio of Cu to S		
$CF_{Cu} := 0.0005$	Cu calibration factor		
$MR_{Cu} := MR_S \cdot RR_{Cu} \cdot CF_{Cu}$	Mass rate of released Cu	1.274×10^{-5}	$MR_{Cu} = 1.274 \times 10^{-5} \cdot \frac{tonne}{yr}$
$C_{Cu} := \frac{MR_{Cu}}{Q}$	Cu concentration in seepage		$C_{Cu} = 13.681 \cdot \frac{\mu g}{L}$

Nickel

$RR_{Ni} := 0.014307$	Release ratio of Ni to S		
$CF_{Ni} := 0.0027$	Ni calibration factor		
$MR_{Ni} := MR_S \cdot RR_{Ni} \cdot CF_{Ni}$	Mass rate of released Ni	$3.216 \text{ x } 10^{-5}$	$MR_{Ni} = 3.216 \times 10^{-5} \cdot \frac{\text{tonne}}{\text{yr}}$
$C_{Ni} := \frac{MR_{Ni}}{Q}$	Ni concentration in seepage		$C_{Ni} = 34.544 \cdot \frac{\mu g}{L}$

Zinc

$RR_{Zn} := 5.0629 \cdot 10^{-5}$	Release ratio of Zn to SO4		
$CF_{Zn} := 0.2596$	Zn calibration factor		
$MR_{Zn} := MR_{SO4} \cdot RR_{Zn} \cdot CF_{Zn}$	Mass rate of released Zn	$3.278 \text{ x } 10^{-5}$	$MR_{Zn} = 3.279 \times 10^{-5} \cdot \frac{\text{tonne}}{\text{yr}}$
$C_{Zn} := \frac{MR_{Zn}}{Q}$	Zn concentration in seepage		$C_{Zn} = 35.214 \cdot \frac{\mu g}{L}$

Cell 2E Other - Sulfate - Closure

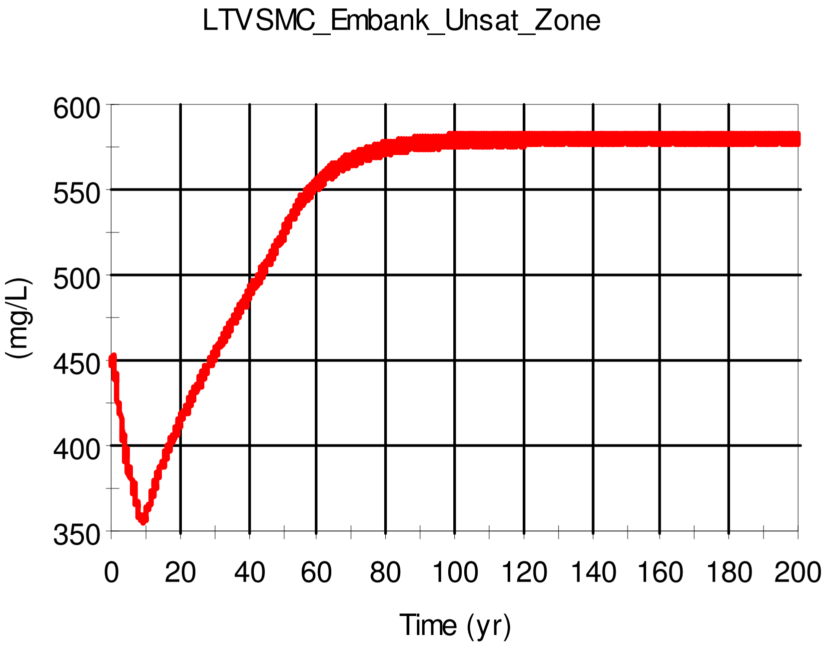
LTVSMC coarse tailings

Blue values generated by GoldSim model

$K_s := 2.24 \cdot 10^{-3} \cdot \frac{cm}{sec}$	Saturated hydraulic conductivity (Table 1-12a)	
$\beta := 2$	vanGenuchten parameter (Table 1-12a)	
$\theta_r := 0.041$	Residual volumetric water content (Table 1-12a)	
$\phi := 0.412$	Porosity (Table 1-12a)	
$G := 2.80$	Specfic gravity (Table 1-12a)	$\mu g := 10^{-6} \cdot gm$
$\rho_w := 1 \cdot \frac{gm}{cm^3}$	Water density (standard value)	
$A := 304688 \cdot m^2$	Map area (Table 1-33)	$A = 75.29 \cdot acre$
$q := 5.50 \cdot \frac{in}{yr}$	Percolation flux (from seepage spreadsheet with Barr edits)	
$\tau := 0.273$	Tortuosity (Table 1-1, sheet 5)	
$D_a := 1.8 \cdot 10^{-5} \cdot \frac{m^2}{sec}$	Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)	
$c := 3.28$	Empirical constant (Table 1-1, sheet 5)	
$D_w := 2.2 \cdot 10^{-9} \cdot \frac{m^2}{sec}$	Free difussion coeff of oxygen in water (Table 1-1, sheet 5)	
$K_H := 33.9$	Henry's constant for oxygen (Table 1-1, sheet 5)	
$C_o := 8.89 \cdot \frac{mol}{m^3}$	O2 concentration in air (Table 1-1, sheet 5)	
$W_{SO4} := 96.07 \cdot \frac{gm}{mole}$	Molecular weight of sulfate (standard value)	
$W_S := 32.066 \cdot \frac{gm}{mole}$	Molecular weight of sulfur (standard value)	
$R_{SO4} := 1.95186 \cdot \frac{mg}{kg \cdot 7 \cdot day}$	P50 SO4 distribution paramater for tailings (Table 1-19)	
$CF := 0.185$	Calibration factor for tailings (Table 1-1, sheet 5)	
$TF := 0.228589$	Temperature factor (computed in GS using numerous inputs)	
$FF := \frac{3.4}{12}$	Freeze factor (from Table 1-1, sheet 3)	$FF = 0.28333$
$moleratio := \frac{4}{9}$	mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6)	$moleratio = 0.444$
$DTW := 52.3 \cdot ft$	Depth to water table in cell 2E during closure (value in Table 1-34 is 51.0 ft; GS value used in calcs is 52.3 ft)	
$Cont_S := 329 \cdot \frac{mg}{kg}$	Sulfur content. Mass of S per unit mass of tailings. (Table 1-22)	
$\rho_b := G \cdot \rho_w \cdot (1 - \phi)$	Tailings dry bulk density. Mass of solids per unit bulk volume.	$\rho_b = 1.646 \cdot \frac{gm}{cm^3}$

$\gamma := 1 - \frac{1}{\beta}$	Computed vanGenuchten parameter		$\gamma = 0.5$
$K(ss) := K_s \left(\frac{ss \cdot \phi - \theta_r}{\phi - \theta_r}\right)^{0.5} \cdot \left[1 - \left[1 - \left(\frac{ss \cdot \phi - \theta_r}{\phi - \theta_r}\right)^{\frac{1}{\gamma}}\right]^{\gamma}\right]^2$	Unsaturated hydraulic conductivity as a function of saturation (ss) based on vanGenuchten relationship		
$f(ss) := q - K(ss) \qquad ss := 0.6$	Root equation and saturation guess		
$SAT := root(f(ss), ss)$	Computed saturation associated with flux (q)	0.2816	$SAT = 0.2828$
$q - K(SAT) = -1.216 \times 10^{-8} \cdot \frac{in}{yr}$	Confirm root calculation (result should be approx zero)	1.661×10^{-6}	
$D := \tau \cdot D_a \cdot (1 - SAT)^c + \tau \cdot SAT \cdot \frac{D_w}{K_H}$	Effective O2 diffusion coeff referenced to void volume		$D = 1.652 \times 10^{-6} \frac{m^2}{s}$
$MRM_{SO4} := R_{SO4} \cdot CF \cdot TF \cdot (1 - FF)$	Mass rate of released SO4 per unit mass of tailings solids		$MRM_{SO4} = 0.0592 \cdot \frac{mg}{kg \cdot 7 \cdot day}$
	Effect of three factors $CF \cdot TF \cdot (1 - FF) = 0.030$		
$R_{O2} := \frac{MRM_{SO4}}{W_{SO4} \cdot moleratio} \cdot \frac{\rho_b}{\phi}$	Molar consumption rate of O2 per unit void volume.	0.005542	$R_{O2} = 0.005536 \cdot \frac{mol}{m^3 \cdot 7 \cdot day}$
$d := \sqrt{\frac{2 \cdot D \cdot C_o}{R_{O2}}}$	Thickness of sulfate reaction zone if controlled by diffusion	56.77	$d = 56.642\,m$
$b := min(d, DTW)$	Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water.		$b = 15.941\,m$
$MR_{SO4} := MRM_{SO4} \cdot b \cdot A \cdot \rho_b$	Mass rate of released sulfate		$MR_{SO4} = 67.578 \cdot \frac{kg}{day}$
$MRV_S := R_{O2} \cdot W_S \cdot moleratio \cdot \phi$	Mass rate of released S per unit bulk volume		$MRV_S = 4.644 \cdot \frac{mg}{m^3 \cdot day}$
$MRA_S := MRV_S \cdot b$	Mass rate of released S per unit map area (m^2)	518.245	$MRA_S = 518.205 \cdot \frac{mg}{m^2 \cdot 7 \cdot day}$
$MR_S := MRA_S \cdot A$	Mass rate of released S		$MR_S = 22.556 \cdot \frac{kg}{day}$
$Q := q \cdot A$	Seepage flow rate		$Q = 21.379 \cdot gpm$
$C_{SO4} := \frac{MR_{SO4}}{Q}$	Sulfate concentration in seepage	579.9	$C_{SO4} = 579.9 \cdot \frac{mg}{liter}$
$t_{end} := \frac{Cont_S \cdot \rho_b \cdot A \cdot DTW}{MR_S}$	Time to deplete all sulfur in the reaction zone.		$t_{end} = 319 \cdot yr$

GoldSim Output



Other Chemicals

Arsenic

$RR_{As} := 0.09995$ Release ratio of As to S

$CF_{As} := 0.0001$ As calibration factor

$MR_{As} := MR_S \cdot RR_{As} \cdot CF_{As}$ Mass rate of released As 8.234 x 10^{-5} $MR_{As} = 8.234 \times 10^{-5} \cdot \frac{tonne}{yr}$

$C_{As} := \frac{MR_{As}}{Q}$ As concentration in seepage $C_{As} = 1.935 \cdot \frac{\mu g}{L}$

Cobalt

$RR_{Co} := 0.03076$ Release ratio of Co to S

$CF_{Co} := 0.0006$ Co calibration factor

$MR_{Co} := MR_S \cdot RR_{Co} \cdot CF_{Co}$ Mass rate of released Co 1.521 x 10^{-4} $MR_{Co} = 1.52 \times 10^{-4} \cdot \frac{tonne}{yr}$

$C_{Co} := \frac{MR_{Co}}{Q}$ Co concentration in seepage $C_{Co} = 3.572 \cdot \frac{\mu g}{L}$

Copper

$RR_{Cu} := 0.030598$ Release ratio of Cu to S

$CF_{Cu} := 0.0005$ Cu calibration factor

$MR_{Cu} := MR_S \cdot RR_{Cu} \cdot CF_{Cu}$ Mass rate of released Cu 1.261 x 10^{-4} $MR_{Cu} = 1.260 \times 10^{-4} \cdot \frac{tonne}{yr}$

$C_{Cu} := \frac{MR_{Cu}}{Q}$ Cu concentration in seepage $C_{Cu} = 2.961 \cdot \frac{\mu g}{L}$

Nickel

$RR_{Ni} := 0.014307$	Release ratio of Ni to S		
$CF_{Ni} := 0.0027$	Ni calibration factor		
$MR_{Ni} := MR_S \cdot RR_{Ni} \cdot CF_{Ni}$	Mass rate of released Ni	3.183 x 10^{-4}	$MR_{Ni} = 3.182 \times 10^{-4} \cdot \frac{tonne}{yr}$
$C_{Ni} := \frac{MR_{Ni}}{Q}$	Ni concentration in seepage		$C_{Ni} = 7.477 \cdot \frac{\mu g}{L}$

Zinc

$RR_{Zn} := 5.0629 \cdot 10^{-5}$	Release ratio of Zn to SO4		
$CF_{Zn} := 0.2596$	Zn calibration factor		
$MR_{Zn} := MR_{SO4} \cdot RR_{Zn} \cdot CF_{Zn}$	Mass rate of released Zn	3.244 x 10^{-4}	$MR_{Zn} = 3.244 \times 10^{-4} \cdot \frac{tonne}{yr}$
$C_{Zn} := \frac{MR_{Zn}}{Q}$	Zn concentration in seepage		$C_{Zn} = 7.621 \cdot \frac{\mu g}{L}$

Cell 2W Banks - Sulfur - Transient

LTVSMC coarse tailings

$A := 1372626\cdot m^2$ Map area (Table 1-33) $A = 339.183\cdot acre$

$q := 7.82\cdot\frac{in}{yr}$ Percolation flux (from seepage spreadsheet with Barr edits)

$K_s := 1.17\cdot 10^{-3}\cdot\frac{cm}{sec}$ Saturated hydraulic conductivity of tailings (Table 1-12a)

$\beta := 2$ vanGenuchten parameter of tailings (Table 1-12a)

$\theta_r := 0.041$ Residual volumetric water content of tailings (Table 1-12a)

$\phi := 0.412$ Porosity of tailings (Table 1-12a)

$G := 2.8$ Specfic gravity of tailings solids (Table 1-12a)

$\rho_w := 1\cdot\frac{gm}{cm^3}$ Water density (standard value)

$\tau := 0.273$ Tortuosity (Table 1-1, sheet 5)

$D_a := 1.8\cdot 10^{-5}\cdot\frac{m^2}{sec}$ Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)

$c := 3.28$ Empirical constant (Table 1-1, sheet 5)

$D_w := 2.2\cdot 10^{-9}\cdot\frac{m^2}{sec}$ Free difussion coeff of oxygen in water (Table 1-1, sheet 5)

$K_H := 33.9$ Henry's constant for oxygen (Table 1-1, sheet 5)

$C_o := 8.89\cdot\frac{mol}{m^3}$ O2 concentration in air. Moles of O2 per unit volume of air (Table 1-1, sheet 5)

$W_{SO4} := 96.07\cdot\frac{gm}{mole}$ Molecular weight of sulfate (standard value)

$W_S := 32.066\cdot\frac{gm}{mole}$ Molecular weight of sulfur (standard value)

$R_{SO4} := 1.95186\cdot\frac{mg}{kg\cdot 7\cdot day}$ 1.95186 P50 SO4 distribution parameter for tailings (Table 1-19; P50 from GoldSim)

$CF := 0.185$ Calibration factor for tailings (Table 1-1, sheet 5)

$TF := 0.228589$ Temperature factor (computed in GS using numerous inputs)

$FF := \frac{3.4}{12}$ Freeze factor (from Table 1-1, sheet 3) $FF = 0.28333$

$moleratio := \frac{4}{9}$ mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6) $moleratio = 0.444$

$Cont_S := 329\cdot\frac{mg}{kg}$ 329 Sulfur content. Mass of S per unit mass of tailings. (Table 1-22)

$Co_{SO4} := 728\cdot\frac{mg}{L}$ Initial concentration in tailings pore water

$t_1 := 0\cdot yr$ $D_1 := 96.4\cdot ft$ Piecewise linear function to approximate DTW vs time

$t_2 := 2\cdot yr$ $D_2 := 89.0\cdot ft$

$t_3 := 7\cdot yr$ $D_3 := 91.4\cdot ft$

$t_4 := 10 \cdot yr \qquad D_4 := 90.6 \cdot ft$

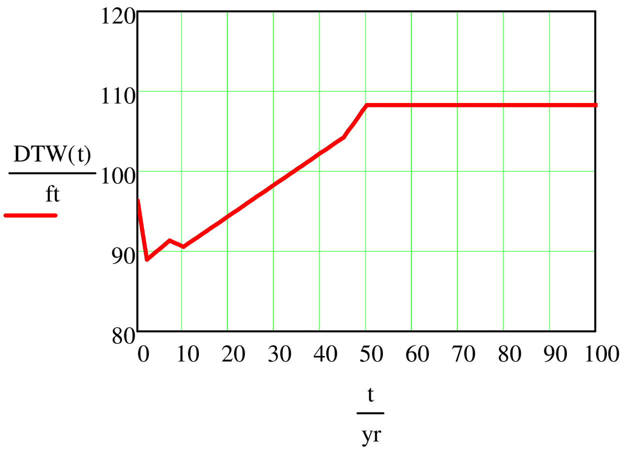
$t_5 := 45 \cdot yr \qquad D_5 := 104.3 \cdot ft$

$t_6 := 50 \cdot yr \qquad D_6 := 108.3 \cdot ft$

$t_7 := 200 \cdot yr \qquad D_7 := 108.3 \cdot ft$

$$DTW(t) := \left| \begin{array}{l} D_1 + \dfrac{D_2 - D_1}{t_2 - t_1} \cdot (t - t_1) \ \text{ if } \ t_1 \le t \le t_2 \\ D_2 + \dfrac{D_3 - D_2}{t_3 - t_2} \cdot (t - t_2) \ \text{ if } \ t_2 < t \le t_3 \\ D_3 + \dfrac{D_4 - D_3}{t_4 - t_3} \cdot (t - t_3) \ \text{ if } \ t_3 < t \le t_4 \\ D_4 + \dfrac{D_5 - D_4}{t_5 - t_4} \cdot (t - t_4) \ \text{ if } \ t_4 < t \le t_5 \\ D_5 + \dfrac{D_6 - D_5}{t_6 - t_5} \cdot (t - t_5) \ \text{ if } \ t_5 < t \le t_6 \\ D_6 + \dfrac{D_7 - D_6}{t_7 - t_6} \cdot (t - t_6) \ \text{ if } \ t_6 < t \le t_7 \end{array} \right.$$

$t := 0 \cdot yr, 1 \cdot yr .. 200 \cdot yr$



$\rho_b := G \cdot \rho_w \cdot (1 - \phi)$ — Tailings dry bulk density. Mass of solids per unit bulk volume. — $\rho_b = 1.646 \cdot \dfrac{gm}{cm^3}$

$\gamma := 1 - \dfrac{1}{\beta}$ — Computed vanGenuchten parameter — $\gamma = 0.5$

$$K(ss) := K_s \left(\frac{ss \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \cdot \left[1 - \left[1 - \left(\frac{ss \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{\frac{1}{\gamma}} \right]^{\gamma} \right]^2$$

Unsaturated hydraulic conductivity as a function of saturation (ss) based on vanGenuchten relationship

$f(ss) := q - K(ss) \qquad ss := .4$ — Root equation and saturation guess

$SAT := \mathrm{root}(f(ss), ss)$ — Computed saturation associated with flux (q) 0.32784 — $SAT = 0.32786$

$q - K(SAT) = -3.452 \times 10^{-7} \cdot \dfrac{in}{yr}$ — Confirm root calculation (result should be approx zero)

$D := \tau \cdot D_a \cdot (1 - SAT)^c + \tau \cdot SAT \cdot \dfrac{D_w}{K_H}$ — Effective O2 diffusion coeff used in GS. This diffusion coeff is referenced to void volume. — 1.335×10^{-6} — $D = 1.335 \times 10^{-6} \dfrac{m^2}{s}$

$MRM_{SO4} := R_{SO4} \cdot CF \cdot TF \cdot (1 - FF)$ — Mass rate of released SO4 per unit mass of tailings solids — $R_{SO4} = 1.952 \cdot \dfrac{mg}{kg \cdot 7 \cdot day}$

Effect of three factors $CF \cdot TF \cdot (1 - FF) = 0.030$

$R_{O2} := \dfrac{MRM_{SO4}}{W_{SO4} \cdot moleratio} \cdot \dfrac{\rho_b}{\phi}$ — Molar consumption rate of O2 per unit void volume — 0.00554 — $R_{O2} = 0.00554 \cdot \dfrac{mol}{m^3 \cdot 7 \cdot day}$

$d := \sqrt{\dfrac{2 \cdot D \cdot C_o}{R_{O2}}}$ Thickness of sulfate reaction zone if controlled by diffusion. Note: both D and R_{O2} are referenced to void volume. 50.90 $d = 50.923\,m$

$d = 167.07 \cdot ft$

$b(t) := \min(d, DTW(t))$ Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water.

$MR_{SO4}(t) := MRM_{SO4} \cdot b(t) \cdot A \cdot \rho_b$ Mass rate of released sulfate

$MRV_S := R_{O2} \cdot W_S \cdot moleratio \cdot \phi$ Mass rate of released S per unit bulk volume $MRV_S = 5.375 \times 10^{-11} \dfrac{kg}{m^3 \cdot s}$

$MRA_S(t) := MRV_S \cdot b(t)$ Mass rate of released S per unit map area (m^2)

$MR_S(t) := MRA_S(t) \cdot A$ Mass rate of released S

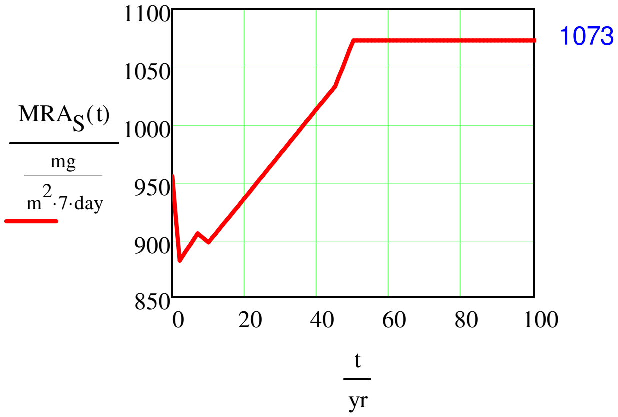
$M_S(t) := \int_0^t MR_S(t)\,dt$

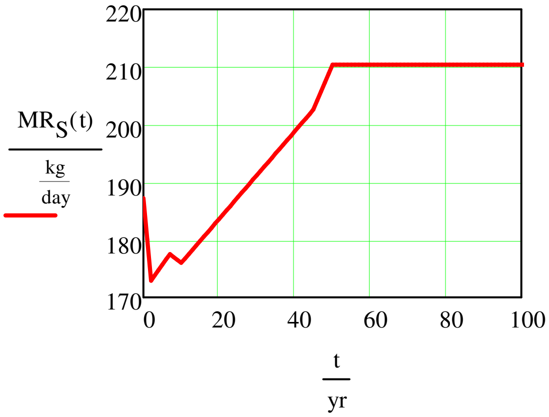
$MT_S := Cont_S \cdot \rho_b \cdot A \cdot DTW(200 \cdot yr)$ Total mass of available sulfur $MT_S = 2.454 \times 10^4 \cdot tonne$

$ff(tt) := M_S(tt) - MT_S$ $tt := 100 \cdot yr$ Root equation and time guess

$t_{end} := root(ff(tt), tt)$ Sulfate depletion time > 200 yr Set --> $t_{end} := 201 \cdot yr$

$MRA_S(t) := \begin{cases} MRV_S \cdot b(t) & \text{if } 0 \le t < t_{end} \\ 0 & \text{if } t \ge t_{end} \end{cases}$ $MR_S(t) := \begin{cases} MRA_S(t) \cdot A & \text{if } 0 \le t < t_{end} \\ 0 & \text{if } t \ge t_{end} \end{cases}$





$Q_{seep} := q \cdot A$ Seepage flow rate $Q_{seep} = 136.942 \cdot gpm$

$V_w := SAT \cdot \phi \cdot A \cdot DTW(200 \cdot yr)$ Water volume in unsat zone $V_w = 6.12 \times 10^6 \cdot m^3$

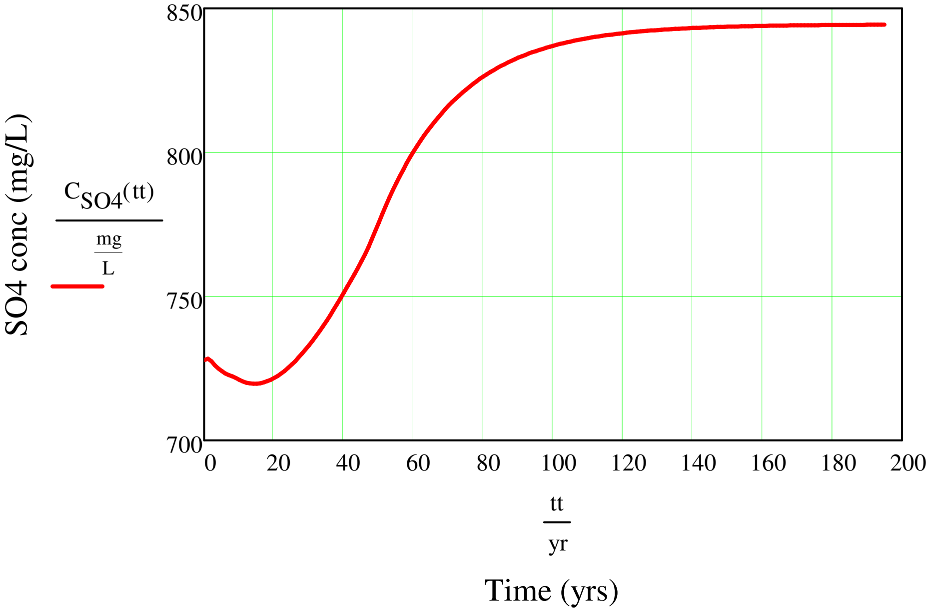
Set up dimensionless equations using m-kg-day units

$tt_{end} := \frac{t_{end}}{day}$	End of sulfate generation in days	$tt_{end} = 7.341 \times 10^{4}$
$MR(tt) := \frac{MR_{SO4}(tt \cdot day)}{kg \cdot day^{-1}}$	Mass rate of sulfate generation in kg/day	
$M(tt) := \left\| \begin{array}{l} MR(tt) \quad \text{if } tt < tt_{end} \\ 0 \quad \text{otherwise} \end{array} \right.$	Sultate mass generation function	
$V := \frac{V_w}{m^3}$	Water volume in m^3	$V = 6.12 \times 10^{6}$
$Q := \frac{Q_{seep}}{m^3 \cdot day^{-1}}$	Seepage flow rate in m^3/day	$Q = 746.469$
$Co := \frac{Co_{SO4}}{kg \cdot m^{-3}}$	Initial sulfate conc in kg/m^3	$Co = 0.728$

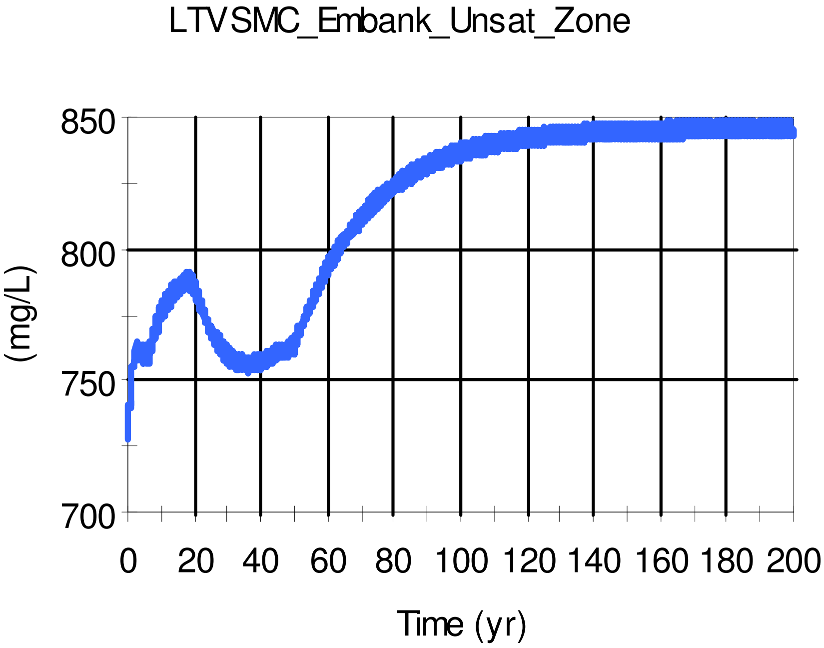
Given $\quad \frac{d}{dt}C(t) = \frac{M(t) - Q \cdot C(t)}{V} \qquad C(0) = Co \qquad C := \text{Odesolve}(t, 196 \cdot 365)$ Governing ODE and IC

$C_{SO4}(tt) := C\left(\frac{tt}{day}\right) \cdot kg \cdot m^{-3}$	Seepage sulfate conc as a function of time	$tt := 0, 1 \cdot yr .. 200 \cdot yr$

MathCad Output



GoldSim Output



Sulfate Generation - Cell 2W Coarse

LTVSMC coarse tailings

$A := 890625 \cdot m^2$	Map area (Table 1-33)	$A = 220.078 \cdot acre$
$q := 13.27 \cdot \frac{in}{yr}$	Percolation flux (from seepage spreadsheet with Barr edits)	
$K_s := 1.17 \cdot 10^{-3} \cdot \frac{cm}{sec}$	Saturated hydraulic conductivity of tailings (Table 1-12b)	
$\beta := 2$	vanGenuchten parameter of tailings (Table 1-12a)	
$\theta_r := 0.041$	Residual volumetric water content of tailings (Table 1-12a)	
$\phi := 0.412$	Porosity of tailings (Table 1-12a)	
$G := 2.8$	Specfic gravity of tailings (Table 1-12a)	
$\rho_w := 1 \cdot \frac{gm}{cm^3}$	Water density (standard value)	
$\tau := 0.273$	Tortuosity (Table 1-1, sheet 5)	
$D_a := 1.8 \cdot 10^{-5} \cdot \frac{m^2}{sec}$	Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)	
$c := 3.28$	Empirical constant (Table 1-1, sheet 5)	
$D_w := 2.2 \cdot 10^{-9} \cdot \frac{m^2}{sec}$	Free difussion coeff of oxygen in water (Table 1-1, sheet 5)	
$K_H := 33.9$	Henry's constant for oxygen (Table 1-1, sheet 5)	
$C_o := 8.89 \cdot \frac{mol}{m^3}$	O2 concentration in air. Moles of O2 per unit volume of air (Table 1-1, sheet 5)	
$W_{SO4} := 96.07 \cdot \frac{gm}{mole}$	Molecular weight of sulfate (standard value)	
$W_S := 32.066 \cdot \frac{gm}{mole}$	Molecular weight of sulfur (standard value)	
$R_{SO4} := 1.95186 \cdot \frac{mg}{kg \cdot 7 \cdot day}$ 1.95186	P50 SO4 distribution parameter of tailings (Table 1-19; P50 from GoldSim)	
$CF := 0.185$	Calibration factor for tailings (Table 1-1, sheet 5)	
$TF := 0.228589$	Temperature factor (computed in GS using numerous inputs)	
$FF := \frac{3.4}{12}$	Freeze factor (from Table 1-1, sheet 3)	$FF = 0.28333$
$moleratio := \frac{4}{9}$	mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6)	$moleratio = 0.444$
$Cont_S := 329 \cdot \frac{mg}{kg}$ 329	Sulfur content. Mass of S per unit mass of tailings. (Table 1-22)	
$Co_{SO4} := 560 \cdot \frac{mg}{L}$	Initial concentration in tailings pore water	

$t_1 := 0 \cdot yr$ $D_1 := 125.4 \cdot ft$ Piecewise linear function to approximate DTW vs time

$t_2 := 18 \cdot yr$ $D_2 := 114.8 \cdot ft$

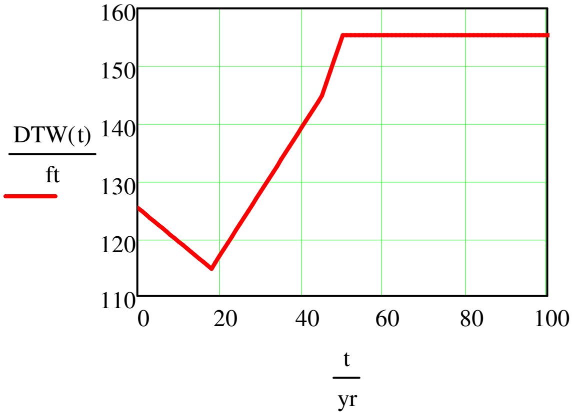
$t_3 := 45 \cdot yr$ $D_3 := 144.9 \cdot ft$

$t_4 := 50 \cdot yr \qquad D_4 := 155.4 \cdot ft$

$t_5 := 200 \cdot yr \qquad D_5 := 155.4 \cdot ft$

$$DTW(t) := \left| \begin{array}{l} D_1 + \dfrac{D_2 - D_1}{t_2 - t_1} \cdot (t - t_1) \ \text{ if } \ t_1 \le t \le t_2 \\ D_2 + \dfrac{D_3 - D_2}{t_3 - t_2} \cdot (t - t_2) \ \text{ if } \ t_2 < t \le t_3 \\ D_3 + \dfrac{D_4 - D_3}{t_4 - t_3} \cdot (t - t_3) \ \text{ if } \ t_3 < t \le t_4 \\ D_4 + \dfrac{D_5 - D_4}{t_5 - t_4} \cdot (t - t_4) \ \text{ if } \ t_4 < t \le t_5 \end{array} \right.$$

$t := 0 \cdot yr, 1 \cdot yr .. 200 \cdot yr$



$\rho_b := G \cdot \rho_w \cdot (1 - \phi)$

Tailings dry bulk density. Mass of solids per unit bulk volume.

$\rho_b = 1.646 \cdot \dfrac{gm}{cm^3}$

$\gamma := 1 - \dfrac{1}{\beta}$

Computed vanGenuchten parameter

$\gamma = 0.5$

$$K(ss) := K_s \left(\frac{ss \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \cdot \left[1 - \left[1 - \left(\frac{ss \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{\frac{1}{\gamma}} \right]^{\gamma} \right]^2$$

Unsaturated hydraulic conductivity as a function of saturation (ss) based on vanGenuchten relationship

$f(ss) := q - K(ss) \qquad ss := 0.5$

Root equation and saturation guess

$SAT := root(f(ss), ss)$

Computed saturation associated with flux (q) 0.35582 $SAT = 0.35583$

$q - K(SAT) = -3.36 \times 10^{-6} \cdot \dfrac{in}{yr}$

Confirm root calculation
(result should be approx zero)

$D := \tau \cdot D_a \cdot (1 - SAT)^c + \tau \cdot SAT \cdot \dfrac{D_w}{K_H}$

Effective O2 diffusion coeff used in GS. This diffusion coeff is referenced to void volume. 1.161×10^{-6} $D = 1.161 \times 10^{-6} \dfrac{m^2}{s}$

$MRM_{SO4} := R_{SO4} \cdot CF \cdot TF \cdot (1 - FF)$

Mass rate of released SO4 per unit mass of tailings solids

$R_{SO4} = 1.952 \cdot \dfrac{mg}{kg \cdot 7 \cdot day}$

Effect of three factors $CF \cdot TF \cdot (1 - FF) = 0.030$

$R_{O2} := \dfrac{MRM_{SO4}}{W_{SO4} \cdot moleratio} \cdot \dfrac{\rho_b}{\phi}$

Molar consumption rate of O2 per unit void volume 0.00554 $R_{O2} = 0.00554 \cdot \dfrac{mol}{m^3 \cdot 7 \cdot day}$

$d := \sqrt{\dfrac{2 \cdot D \cdot C_o}{R_{O2}}}$

Thickness of sulfate reaction zone if controlled by diffusion. Note: both D and R_{O2} are referenced to void volume. 47.47 $d = 47.494\,m$

$b(t) := \min(d, DTW(t))$

Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water.

$MR_{SO4}(t) := MRM_{SO4} \cdot b(t) \cdot A \cdot \rho_b$ Mass rate of released sulfate

$MRV_S := R_{O2} \cdot W_S \cdot moleratio \cdot \phi$ Mass rate of released S per unit bulk volume $MRV_S = 5.375 \times 10^{-11} \frac{kg}{m^3 \cdot s}$

$MRA_S(t) := MRV_S \cdot b(t)$ Mass rate of released S per unit map area (m²)

$MR_S(t) := MRA_S(t) \cdot A$ Mass rate of released S

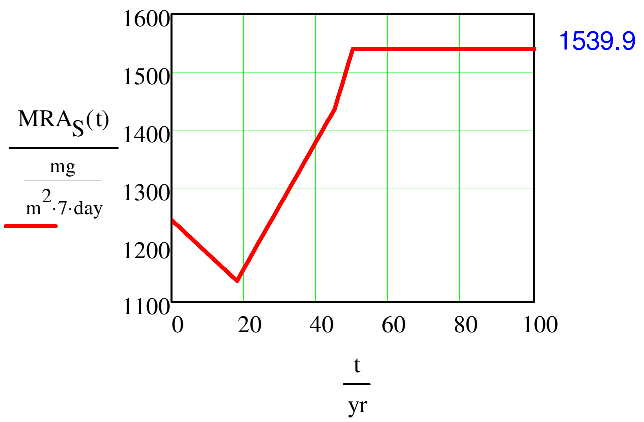
$$M_S(t) := \int_0^t MR_S(t)\, dt$$

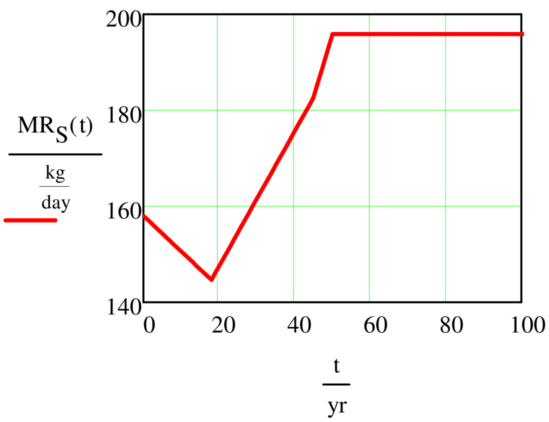
$MT_S := Cont_S \cdot \rho_b \cdot A \cdot DTW(200 \cdot yr)$ Total mass of available sulfur $MT_S = 2.285 \times 10^4 \cdot tonne$

$ff(tt) := M_S(tt) - MT_S \quad tt := 100 \cdot yr$ Root equation and time guess

$t_{end} := root(ff(tt), tt)$ Sulfate depletion time > 200 yr Set --> $t_{end} := 201 \cdot yr$

$$MRA_S(t) := \begin{vmatrix} MRV_S \cdot b(t) & \text{if } 0 \le t < t_{end} \\ 0 & \text{if } t \ge t_{end} \end{vmatrix} \qquad MR_S(t) := \begin{vmatrix} MRA_S(t) \cdot A & \text{if } 0 \le t < t_{end} \\ 0 & \text{if } t \ge t_{end} \end{vmatrix}$$





$Q_{seep} := q \cdot A$ Seepage flow rate $Q_{seep} = 150.78 \cdot gpm$

$V_w := SAT \cdot \phi \cdot A \cdot DTW(200 \cdot yr)$ Water volume in unsat zone $V_w = 6.184 \times 10^6 \cdot m^3$

Set up dimensionless equations using m-kg-day units

$tt_{end} := \frac{t_{end}}{day}$ End of sulfate generation in days $tt_{end} = 7.341 \times 10^{4}$

$MR(tt) := \frac{MR_{SO4}(tt \cdot day)}{kg \cdot day^{-1}}$ Mass rate of sulfate generation in kg/day

$M(tt) := \left| \begin{array}{l} MR(tt) \quad \text{if } tt < tt_{end} \\ 0 \quad \text{otherwise} \end{array} \right.$ Sultate mass generation function

$V := \frac{V_w}{m^3}$ Water volume in m^3 $V = 6.184 \times 10^{6}$

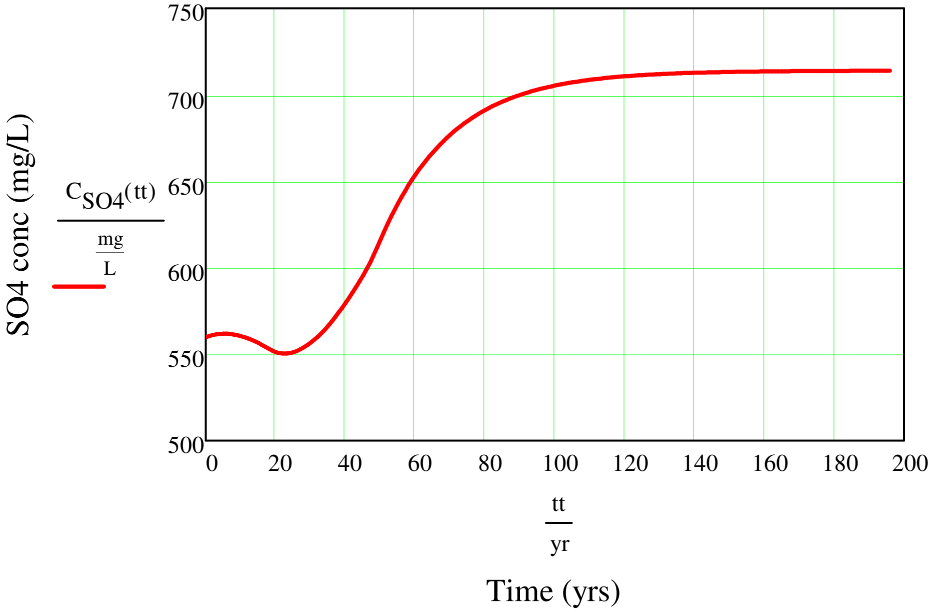
$Q := \frac{Q_{seep}}{m^3 \cdot day^{-1}}$ Seepage flow rate in m^3/day $Q = 821.899$

$Co := \frac{Co_{SO4}}{kg \cdot m^{-3}}$ Initial sulfate conc in kg/m^3 $Co = 0.56$

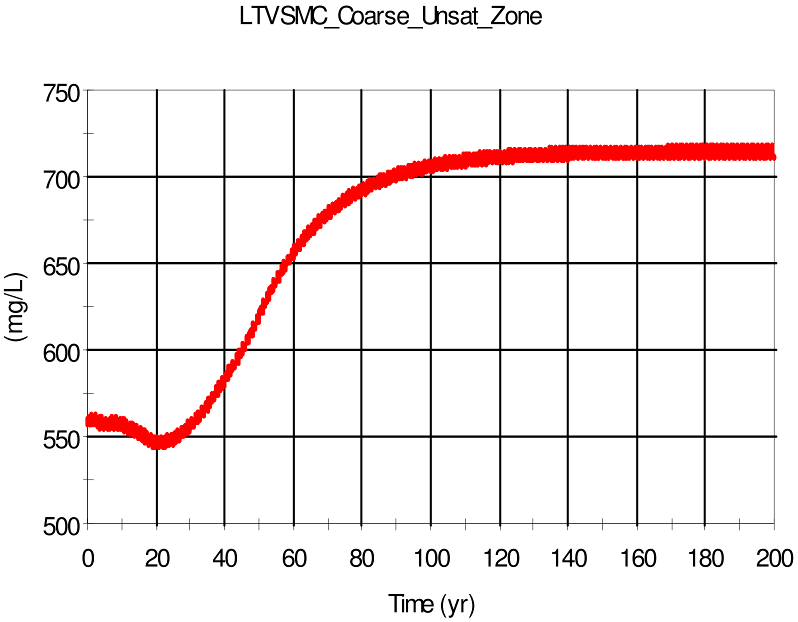
Given $\frac{d}{dt}C(t) = \frac{M(t) - Q \cdot C(t)}{V}$ $C(0) = Co$ $C := \text{Odesolve}(t, 197 \cdot 365)$ Governing ODE and IC

$C_{SO4}(tt) := C\left(\frac{tt}{day}\right) \cdot kg \cdot m^{-3}$ Seepage sulfate conc as a function of time $tt := 0, 1 \cdot yr .. 200 \cdot yr$

MathCad Output



GoldSim Output



Sulfate Generation - Cell 2W Fine

LTVSMC fine tailings

$A := 3027344 \cdot m^2$		Map area (Table 1-33)	$A = 748.073 \cdot acre$
$q := 15.93 \cdot \frac{in}{yr}$		Percolation flux (from seepage spreadsheet with Barr edits)	
$K_s := 1.1 \cdot 10^{-4} \cdot \frac{cm}{sec}$		Saturated hydraulic conductivity of tailings (Table 1-12b)	
$\beta := 1.6$		vanGenuchten parameter of tailings (Table 1-12a)	
$\theta_r := 0.059$		Residual volumetric water content of tailings (Table 1-12a)	
$\phi := 0.493$		Porosity of tailings (Table 1-12a)	
$G := 2.9$		Specfic gravity of tailings solids (Table 1-12a)	
$\rho_w := 1 \cdot \frac{gm}{cm^3}$		Water density (standard value)	
$\tau := 0.273$		Tortuosity (Table 1-1, sheet 5)	
$D_a := 1.8 \cdot 10^{-5} \cdot \frac{m^2}{sec}$		Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)	
$c := 3.28$		Empirical constant (Table 1-1, sheet 5)	
$D_w := 2.2 \cdot 10^{-9} \cdot \frac{m^2}{sec}$		Free difussion coeff of oxygen in water (Table 1-1, sheet 5)	
$K_H := 33.9$		Henry's constant for oxygen (Table 1-1, sheet 5)	
$C_o := 8.89 \cdot \frac{mol}{m^3}$		O2 concentration in air. Moles of O2 per unit volume of air (Table 1-1, sheet 5)	
$W_{SO4} := 96.07 \cdot \frac{gm}{mole}$		Molecular weight of sulfate (standard value)	
$W_S := 32.066 \cdot \frac{gm}{mole}$		Molecular weight of sulfur (standard value)	
$R_{SO4} := 1.95186 \cdot \frac{mg}{kg \cdot 7 \cdot day}$	1.95186	P50 SO4 distribution parameter for tailings (Table 1-19; P50 from GoldSim)	
$CF := 0.36$		Calibration factor for tailings (Table 1-1, sheet 5)	
$TF := 0.228589$		Temperature factor (computed in GS using numerous inputs)	
$FF := \frac{3.4}{12}$		Freeze factor (from Table 1-1, sheet 3)	$FF = 0.28333$
$moleratio := \frac{4}{9}$		mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6)	$moleratio = 0.444$
$Cont_S := 329 \cdot \frac{mg}{kg}$	329	Sulfur content. Mass of S per unit mass of tailings. (Table 1-22)	
$Co_{SO4} := 272.4 \cdot \frac{mg}{L}$		Initial concentration in tailings pore water	

$t_1 := 0 \cdot yr$ $D_1 := 114.9 \cdot ft$ Piecewise linear function to approximate DTW vs time

$t_2 := 7 \cdot yr$ $D_2 := 70.9 \cdot ft$

$t_3 := 10 \cdot yr$ $D_3 := 70.6 \cdot ft$

$t_4 := 18 \cdot yr$ $\qquad D_4 := 59.8 \cdot ft$

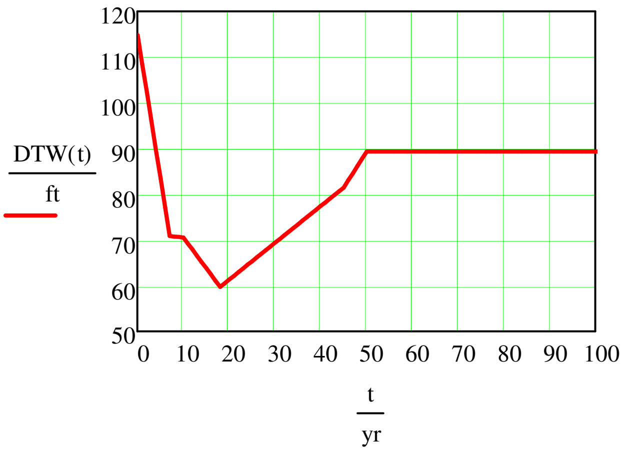
$t_5 := 45 \cdot yr$ $\qquad D_5 := 81.5 \cdot ft$

$t_6 := 50 \cdot yr$ $\qquad D_6 := 89.4 \cdot ft$

$t_7 := 200 \cdot yr$ $\qquad D_7 := 89.4 \cdot ft$

$$DTW(t) := \left| \begin{array}{ll} D_1 + \dfrac{D_2 - D_1}{t_2 - t_1} \cdot (t - t_1) & \text{if } t_1 \le t \le t_2 \\ D_2 + \dfrac{D_3 - D_2}{t_3 - t_2} \cdot (t - t_2) & \text{if } t_2 < t \le t_3 \\ D_3 + \dfrac{D_4 - D_3}{t_4 - t_3} \cdot (t - t_3) & \text{if } t_3 < t \le t_4 \\ D_4 + \dfrac{D_5 - D_4}{t_5 - t_4} \cdot (t - t_4) & \text{if } t_4 < t \le t_5 \\ D_5 + \dfrac{D_6 - D_5}{t_6 - t_5} \cdot (t - t_5) & \text{if } t_5 < t \le t_6 \\ D_6 + \dfrac{D_7 - D_6}{t_7 - t_6} \cdot (t - t_6) & \text{if } t_6 < t \le t_7 \end{array} \right.$$

$t := 0 \cdot yr, 1 \cdot yr .. 200 \cdot yr$



$\rho_b := G \cdot \rho_w \cdot (1 - \phi)$ Tailings dry bulk density. Mass of solids per unit bulk volume. $\rho_b = 1.47 \cdot \dfrac{gm}{cm^3}$

$\gamma := 1 - \dfrac{1}{\beta}$ Computed vanGenuchten parameter $\gamma = 0.375$

$$K(ss) := K_s \left(\frac{ss \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \cdot \left[1 - \left[1 - \left(\frac{ss \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{\frac{1}{\gamma}} \right]^{\gamma} \right]^2$$

Unsaturated hydraulic conductivity as a function of saturation (ss) based on vanGenuchten relationship

$f(ss) := q - K(ss)$ $\qquad ss := 0.8$ Root equation and saturation guess

$SAT := root(f(ss), ss)$ Computed saturation associated with flux (q) 0.6741 $SAT = 0.6741$

$q - K(SAT) = -4.179 \times 10^{-9} \cdot \dfrac{in}{yr}$ Confirm root calculation (result should be approx zero)

$D := \tau \cdot D_a \cdot (1 - SAT)^c + \tau \cdot SAT \cdot \dfrac{D_w}{K_H}$ Effective O2 diffusion coeff used in GS. This diffusion coeff is referenced to void volume. 1.243×10^{-7} $D = 1.243 \times 10^{-7} \dfrac{m^2}{s}$

$MRM_{SO4} := R_{SO4} \cdot CF \cdot TF \cdot (1 - FF)$ Mass rate of released SO4 per unit mass of tailings solids $R_{SO4} = 1.952 \cdot \dfrac{mg}{kg \cdot 7 \cdot day}$

Effect of three factors $CF \cdot TF \cdot (1 - FF) = 0.059$

$R_{O2} := \dfrac{MRM_{SO4}}{W_{SO4} \cdot moleratio} \cdot \dfrac{\rho_b}{\phi}$ Molar consumption rate of O2 per unit void space 0.00805 $R_{O2} = 0.00804 \cdot \dfrac{mol}{m^3 \cdot 7 \cdot day}$

$$d := \sqrt{\frac{2 \cdot D \cdot C_o}{R_{O2}}}$$

Thickness of sulfate reaction zone if controlled by diffusion. Note: both D and R_{O2} are referenced to void volume.

12.88

$d = 12.892\,m$

$d = 42.297 \cdot ft$

$b(t) := \min(d, DTW(t))$

Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water.

$MR_{SO4}(t) := MRM_{SO4} \cdot b(t) \cdot A \cdot \rho_b$

Mass rate of released sulfate

$MRV_S := R_{O2} \cdot W_S \cdot moleratio \cdot \phi$

Mass rate of released S per unit bulk volume

$MRV_S = 9.341 \times 10^{-11} \frac{kg}{m^3 \cdot s}$

$MRA_S(t) := MRV_S \cdot b(t)$

Mass rate of released S per unit map area (m^2)

$MR_S(t) := MRA_S(t) \cdot A$

Mass rate of released S

$$M_S(t) := \int_0^t MR_S(t)\,dt$$

$MT_S := Cont_S \cdot \rho_b \cdot A \cdot DTW(200 \cdot yr)$

Total mass of available sulfur

$MT_S = 3.99 \times 10^4 \cdot tonne$

$ff(tt) := M_S(tt) - MT_S \qquad tt := 100 \cdot yr$

Root equation and time guess

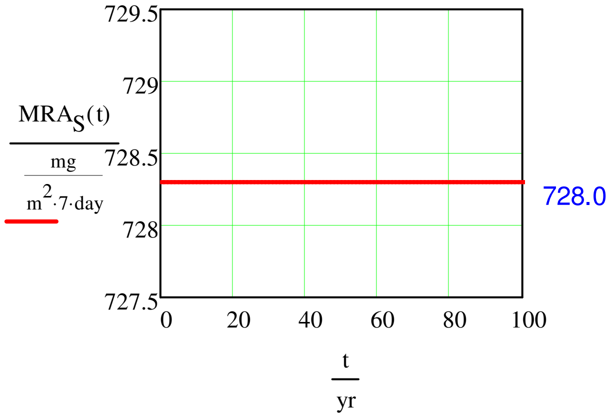
$t_{end} := root(ff(tt), tt)$

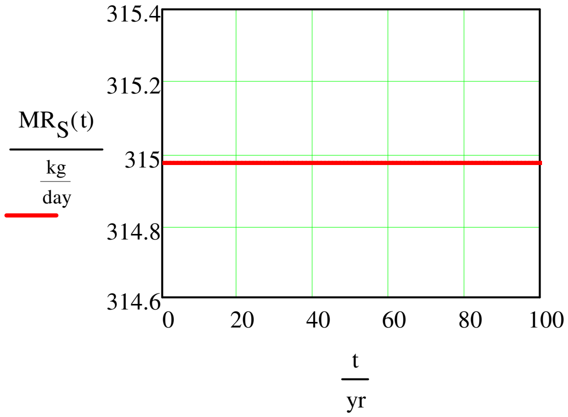
Sulfate depletion time > 200 yr

Set --> $t_{end} := 201 \cdot yr$

$$MRA_S(t) := \begin{cases} MRV_S \cdot b(t) & \text{if } 0 \le t < t_{end} \\ 0 & \text{if } t \ge t_{end} \end{cases}$$

$$MR_S(t) := \begin{cases} MRA_S(t) \cdot A & \text{if } 0 \le t < t_{end} \\ 0 & \text{if } t \ge t_{end} \end{cases}$$





$Q_{seep} := q \cdot A$

Seepage flow rate

$Q_{seep} = 615.254 \cdot gpm$

$V_w := SAT \cdot \phi \cdot A \cdot DTW(200 \cdot yr)$

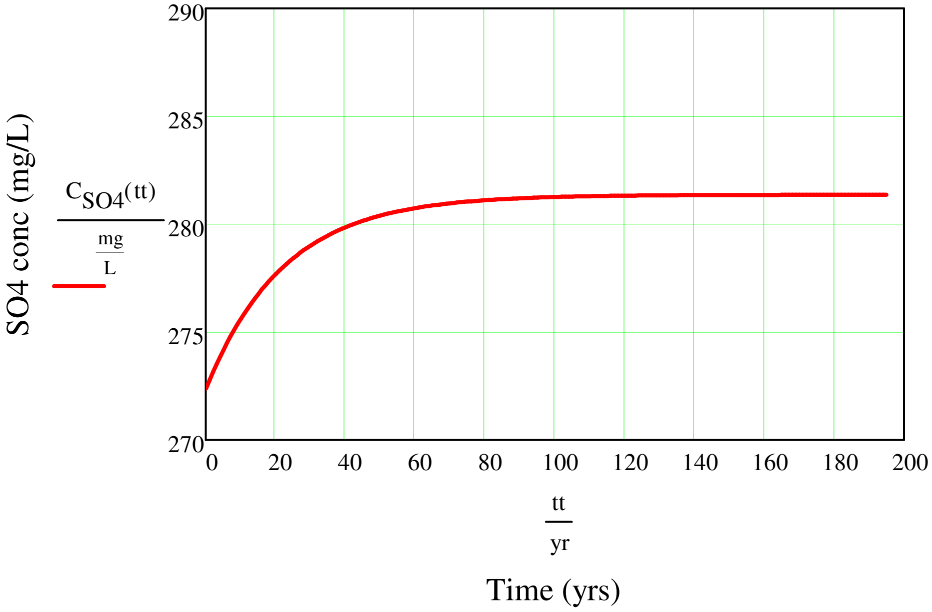
Water volume in unsat zone

$V_w = 2.741 \times 10^7 \cdot m^3$

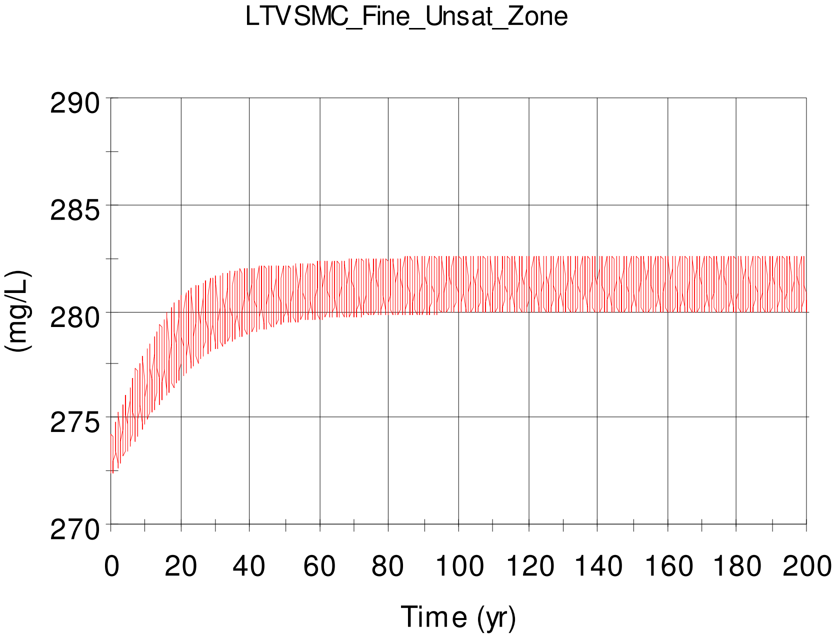
Set up dimensionless equations using m-kg-day units

$tt_{end} := \frac{t_{end}}{day}$	End of sulfate generation in days	$tt_{end} = 7.341 \times 10^{4}$
$MR(tt) := \frac{MR_{SO4}(tt \cdot day)}{kg \cdot day^{-1}}$	Mass rate of sulfate generation in kg/day	
$M(tt) := \left\vert \begin{array}{l} MR(tt) \quad \text{if } \ tt < tt_{end} \\ 0 \quad \text{otherwise} \end{array} \right.$	Sultate mass generation function	
$V := \frac{V_w}{m^3}$	Water volume in m^3	$V = 2.741 \times 10^{7}$
$Q := \frac{Q_{seep}}{m^3 \cdot day^{-1}}$	Seepage flow rate in m^3/day	$Q = 3.354 \times 10^{3}$
$Co := \frac{Co_{SO4}}{kg \cdot m^{-3}}$	Initial sulfate conc in kg/m^3	$Co = 0.272$
Given $\quad \frac{d}{dt}C(t) = \frac{M(t) - Q \cdot C(t)}{V} \quad C(0) = Co \quad C := \text{Odesolve}(t, 196 \cdot 365)$	Governing ODE and IC	
$C_{SO4}(tt) := C\left(\frac{tt}{day}\right) \cdot kg \cdot m^{-3}$	Seepage sulfate conc as a function of time	$tt := 0, 1 \cdot yr .. 200 \cdot yr$

MathCad Output



GoldSim Output



North Beach - Misc Chemicals - Closure

Mixture of fine and coarse NM tailings with bentonite amendment

$\mu g := 10^{-6} \cdot gm$

Blue values are generated by GoldSim model

$q := 6.07 \cdot \frac{in}{yr}$ Percolation flux

$A := 75.67 \cdot acre$ Map area

Tailings

$F := 0.35$ Fraction of fine tailings

$R_{SO4coarse} := 11.83451 \cdot \frac{mg}{kg \cdot 7 \cdot day}$ P50 SO4 distribution parameter for coarse tailings (GS for P50 value)

$R_{SO4fine} := 19.32669 \cdot \frac{mg}{kg \cdot 7 \cdot day}$ P50 SO4 distribution parameter for fine tailings (GS for P50 value)

$CF := 1$ Calibration factor

$DTW := 137.3 \cdot ft$ Depth to water table during closure (Table 1-29)

$G := 3.0$ Specfic gravity (Table 1-12a)

$\phi := 0.41$ Porosity (Table 1-12a)

$K_s := 1.04961 \cdot 10^{-3} \cdot \frac{cm}{sec}$ Saturated hydraulic conductivity (Table 1-12a)

$\theta_r := 0.0113$ Residual water content (Table 1-12a)

$\alpha := 0.008775 \cdot cm^{-1}$ vanGenuchten parameter (Table 1-12a)

$\beta := 2.6944$ vanGenuchten parameter (Table 1-12a)

Bentonite-Amended Layer

$\phi_{bn} := 0.36$ Porosity of bentonite amended tailings (Table 1-1, sheet 4)

$K_{sbn} := 5.56 \cdot 10^{-6} \cdot \frac{cm}{sec}$ Saturated hydraulic conductivity of bentonite amended tailings (Table 1-1; sheet 4)

$\theta_{rbn} := 0.07$ Residual volumetric water content for bentonite amended tailings (Table 1-1, sheet 4)

$\beta_{bn} := 1.09$ vanGenuchten parameter for bentonite amended tailings (Table 1-1, sheet 4

$\alpha_{bn} := 0.005 \cdot cm^{-1}$ vanGenuchten parameter for bentonite amended tailings (Table 1-1,sheet4)

General Inputs

$\tau := 0.273$ Tortuosity (Table 1-1, sheet 5)

$D_a := 1.8 \cdot 10^{-5} \cdot \frac{m^2}{sec}$ Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)

$c := 3.28$ Empirical constant (Table 1-1, sheet 5)

$D_w := 2.2 \cdot 10^{-9} \cdot \frac{m^2}{sec}$ Free difussion coeff of oxygen in water (Table 1-1, sheet 5)

$K_H := 33.9$ Henry's constant for oxygen (Table 1-1, sheet 5)

$C_o := 8.89 \cdot \frac{mol}{m^3}$ O2 concentration in air (Table 1-1, sheet 5)

$W_{SO4} := 96.07 \cdot \frac{gm}{mole}$ Molecular weight of sulfate (standard value)

$W_S := 32.066 \cdot \frac{gm}{mole}$ Molecular weight of sulfur (standard value)

$TF := 0.228589$ Temperature factor (computed in GS using numerous inputs)

$FF := \frac{3.4}{12}$ Freeze factor (from Table 1-1, sheet 3) $FF = 0.28333$

$moleratio := \frac{4}{9}$ mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6) $moleratio = 0.444$

$W_{O2} := 32 \cdot \frac{gm}{mole}$ Molecular weight of O2

$\rho_w := 1 \cdot \frac{gm}{cm^3}$ Water density (standard value)

Calcs for LTV Bulk Tailings

$\rho := G \cdot \rho_w \cdot (1 - \phi)$ Bulk density $\rho = 1.77 \times 10^3 \frac{kg}{m^3}$

$\gamma := 1 - \frac{1}{\beta}$ Computed vanGenuchten parameter $\gamma = 0.629$

$Sat := 0.18228476$ 0.18450 Saturation

$$K := K_s \left(\frac{Sat \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \cdot \left[1 - \left[1 - \left(\frac{Sat \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{\frac{1}{\gamma}} \right]^{\gamma} \right]^2$$

Unsaturated hydraulic conductivity as a function of saturation (Sat) based on vanGenuchten relationship and unit hydraulic gradient

For unit gradient conditions $q = 6.07000 \cdot \frac{in}{yr}$ $K = 6.070000 \cdot \frac{in}{yr}$

$$h := \frac{1}{\alpha} \cdot \left[\left(\frac{\phi - \theta_r}{Sat \cdot \phi - \theta_r} \right)^{\frac{1}{\gamma}} - 1 \right]^{\frac{1}{\beta}}$$

Suction head in tailings for unit gradient conditions 332.426 $h = 330.36 \cdot cm$

Calcs for Bentonite-Amended Tailings

$\gamma_{bn} := 1 - \frac{1}{\beta_{bn}}$ Computed vanGenuchten parameter

$$Sat_{bn} := \frac{1}{\phi_{bn}} \cdot \left[\theta_{rbn} + \frac{\phi_{bn} - \theta_{rbn}}{\left[1 + (\alpha_{bn} \cdot h)^{\beta_{bn}} \right]^{\gamma_{bn}}} \right]$$

Saturation at bottom of the bentonite layer. Assumed to apply to entire layer. $Sat_{bn} = 0.9359$ 0.93567

$$D_{bn} := \tau \cdot D_a \cdot (1 - Sat_{bn})^c + \tau \cdot Sat_{bn} \cdot \frac{D_w}{K_H}$$

Effective O2 diffusion coeff used in GS. This parameter is referenced to the void volume. $D_{bn} = 6.151 \times 10^{-10} \frac{m^2}{s}$

6.2326×10^{-10}

Diffusion Related Calcs

$R_{SO4} := F \cdot R_{SO4fine} + (1 - F) \cdot R_{SO4coarse}$ $R_{SO4} = 14.457 \cdot \frac{mg}{kg \cdot 7 \cdot day}$

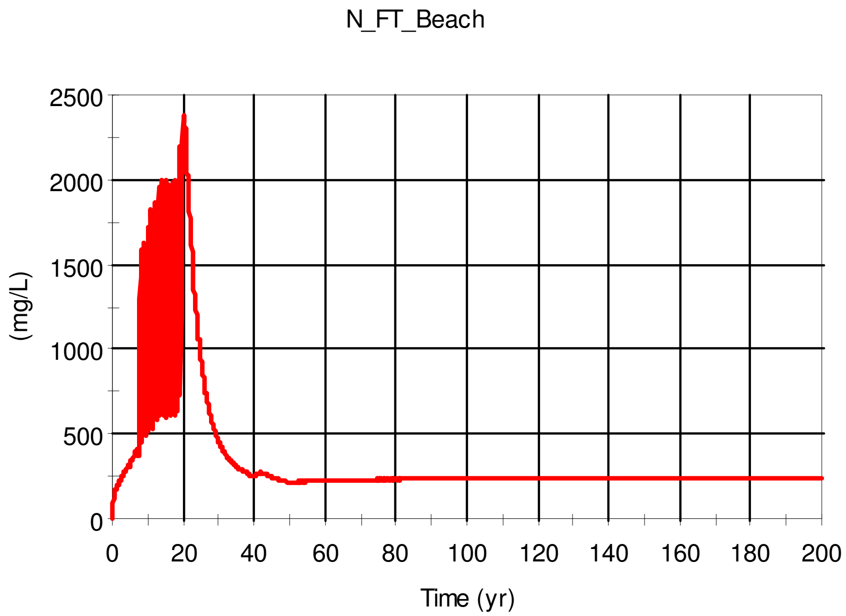
$MRM_{SO4} := R_{SO4} \cdot CF \cdot TF \cdot (1 - FF)$ Mass rate of released SO4 per unit mass of tailings solids $MRM_{SO4} = 2.368 \cdot \frac{mg}{kg \cdot 7 \cdot day}$

	Effect of three factors		$\mathrm{CF}\cdot\mathrm{TF}\cdot(1-\mathrm{FF}) = 0.164$
$r_{nm} := \frac{MRM_{SO4}}{W_{SO4}\cdot moleratio}\cdot\frac{\rho}{\phi}$	Molar consumption rate of O2 per unit volume of voids	0.23968	$r_{nm} = 0.23946\cdot\frac{mol}{m^3\cdot 7\cdot day}$
$d := \sqrt{\frac{2\cdot D_{bn}\cdot C_o}{r_{nm}}}$	Thickness of sulfate reaction zone if controlled by diffusion		$d = 0.166\,m$
$b := \min(d, DTW)$	Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water.	0.1672	$b = 0.166\,m$

Sulfate Calcs

$MRV_{SO4} := MRM_{SO4}\cdot\rho$	Mass rate of released sulfate per unit bulk volume		$MRV_{SO4} = 6.931\times 10^{-9}\,\frac{kg}{m^3\cdot s}$
$MR_{SO4} := MRV_{SO4}\cdot A\cdot b$	Mass rate of released SO4		$MR_{SO4} = 30.479\cdot\frac{kg}{day}$
$Q := q\cdot A$	Seepage flow rate		$Q = 23.714\cdot gpm$
$C_{SO4} := \frac{MR_{SO4}}{Q}$	Sulfate concentration in seepage	237.5	$C_{SO4} = 235.79\cdot\frac{mg}{liter}$

GoldSim Output



Sulfur Calcs

$MRV_S := MRV_{SO4}\cdot\frac{W_S}{W_{SO4}}$	Mass rate per unit bulk volume of released sulfur		$MRV_S = 2.313\times 10^{-9}\,\frac{kg}{m^3\cdot s}$
$MRA_S := MRV_S\cdot b$	Mass rate per unit area of released sulfur	233.99	$MRA_S = 232.552\cdot\frac{mg}{m^2\cdot 7\cdot day}$
$MR_S := MRA_S\cdot A$	Mass rate of sulfur generation		$MR_S = 10.173\cdot\frac{kg}{day}$

Other Chemicals

Arsenic

$RR_{As} := F \cdot 0.00189041 + (1 - F) \cdot 0.00178929$ Release ratio of As to S

$CF_{As} := 1$ As calibration factor

$MR_{As} := MR_S \cdot RR_{As} \cdot CF_{As}$ Mass rate of released As 6.822 x 10^{-3} $MR_{As} = 6.780 \times 10^{-3} \cdot \frac{tonne}{yr}$

$C_{As} := \frac{MR_{As}}{Q}$ As concentration in seepage $C_{As} = 143.604 \cdot \frac{\mu g}{L}$

Copper

$RR_{Cu} := F \cdot 00.09250 + (1 - F) \cdot 0.208367$ Release ratio of Cu to S

$CF_{Cu} := 1$ Cu calibration factor

$MR_{Cu} := MR_S \cdot RR_{Cu} \cdot CF_{Cu}$ Mass rate of released Cu 6.274 x 10^{-1} $MR_{Cu} = 6.235 \times 10^{-1} \cdot \frac{tonne}{yr}$

$C_{Cu} := \frac{MR_{Cu}}{Q}$ Cu concentration in seepage $C_{Cu} = 13207.082 \cdot \frac{\mu g}{L}$

Nickel

$RR_{Ni} := 0.00272356$ Release ratio of Ni to S

$CF_{Ni} := 1$ Ni calibration factor

$MR_{Ni} := MR_S \cdot RR_{Ni} \cdot CF_{Ni}$ Mass rate of released Ni 1.018 x 10^{-2} $MR_{Ni} = 1.012 \times 10^{-2} \cdot \frac{tonne}{yr}$

$C_{Ni} := \frac{MR_{Ni}}{Q}$ Ni concentration in seepage $C_{Ni} = 214.347 \cdot \frac{\mu g}{L}$

Cobalt

$RR_{Co} := 0.0770998$ Release ratio of Co to Ni

$CF_{Co} := 1$ Co calibration factor

$MR_{Co} := MR_{Ni} \cdot RR_{Co} \cdot CF_{Co}$ Mass rate of released Co 7.851 x 10^{-4} $MR_{Co} = 7.803 \times 10^{-4} \cdot \frac{tonne}{yr}$

$C_{Co} := \frac{MR_{Co}}{Q}$ Co concentration in seepage $C_{Co} = 16.526 \cdot \frac{\mu g}{L}$

Zinc

$RR_{Zn} := 0.168192$ Release ratio of Zn to Ni

$CF_{Zn} := 1$ Zn calibration factor

$MR_{Zn} := MR_{Ni} \cdot RR_{Zn} \cdot CF_{Zn}$ Mass rate of released Zn 1.713 x 10^{-3} $MR_{Zn} = 1.702 \times 10^{-3} \cdot \frac{tonne}{yr}$

$C_{Zn} := \frac{MR_{Zn}}{Q}$ Zn concentration in seepage $C_{Zn} = 36.051 \cdot \frac{\mu g}{L}$

North Dam - Misc Chemicals - Closure

LTVSMC bulk tailings with bentonite amendment

$q := 6.07 \cdot \frac{in}{yr}$ Percolation flux

$\mu g := 10^{-6} \cdot gm$

$A := 249 \cdot acre$ Map area of North Dam

Blue values are generated by GoldSim model

LTV bulk tailings

$R_{SO4} := 1.95186 \cdot \frac{mg}{kg \cdot 7 \cdot day}$ P50 SO4 distribution parameter (GS for P50 value)

$CF_{coarse} := 0.185$ SO4 calibration factor for coarse tailings (Table 1-1, sheet 5)

$CF_{fine} := 0.360$ SO4 calibration factor for fine tailings (Table 1-1, sheet 5)

$DTW := 152 \cdot ft$ Depth to water table during closure (Table 1-29)

$G := 2.85$ Specfic gravity (Table 1-12a)

$\phi := 0.440$ Porosity (Table 1-12a)

$K_s := 8.02 \cdot 10^{-5} \cdot \frac{cm}{sec}$ Saturated hydraulic conductivity (Table 1-12a)

$\theta_r := 0.048$ Residual water content (Table 1-12a)

$\alpha := 0.011 \cdot cm^{-1}$ vanGenuchten parameter (Table 1-12a)

$\beta := 2.0$ vanGenuchten parameter (Table 1-12a)

Bentonite-Amended Layer

$\phi_{bn} := 0.36$ Porosity of bentonite amended tailings (Table 1-1, sheet 4)

$K_{sbn} := 5.56 \cdot 10^{-6} \cdot \frac{cm}{sec}$ Saturated hydraulic conductivity of bentonite amended tailings (Table 1-1; sheet 4)

$\theta_{rbn} := 0.07$ Residual volumetric water content for bentonite amended tailings (Table 1-1, sheet 4)

$\beta_{bn} := 1.09$ vanGenuchten parameter for bentonite amended tailings (Table 1-1, sheet 4

$\alpha_{bn} := 0.005 \cdot cm^{-1}$ vanGenuchten parameter for bentonite amended tailings (Table 1-1,sheet4)

General Inputs

$\tau := 0.273$ Tortuosity (Table 1-1, sheet 5)

$D_a := 1.8 \cdot 10^{-5} \cdot \frac{m^2}{sec}$ Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)

$c := 3.28$ Empirical constant (Table 1-1, sheet 5)

$D_w := 2.2 \cdot 10^{-9} \cdot \frac{m^2}{sec}$ Free difussion coeff of oxygen in water (Table 1-1, sheet 5)

$K_H := 33.9$ Henry's constant for oxygen (Table 1-1, sheet 5)

$C_o := 8.89 \cdot \frac{mol}{m^3}$ O2 concentration in air (Table 1-1, sheet 5)

$W_{SO4} := 96.07 \cdot \frac{gm}{mole}$ Molecular weight of sulfate (standard value)

$W_S := 32.066 \cdot \frac{gm}{mole}$ Molecular weight of sulfur (standard value)

$TF := 0.228589$ Temperature factor (computed in GS using numerous inputs)

$FF := \frac{3.4}{12}$ Freeze factor (from Table 1-1, sheet 3) $FF = 0.28333$

$moleratio := \frac{4}{9}$ mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6) $moleratio = 0.444$

$W_{O2} := 32 \cdot \frac{gm}{mole}$ Molecular weight of O2

$\rho_w := 1 \cdot \frac{gm}{cm^3}$ Water density (standard value)

Calcs for LTV Bulk Tailings

$\rho := G \cdot \rho_w \cdot (1 - \phi)$ Bulk density $\rho = 1.596 \times 10^3 \frac{kg}{m^3}$

$\gamma := 1 - \frac{1}{\beta}$ Computed vanGenuchten parameter $\gamma = 0.5$

$Sat := 0.490864$ Saturation

0.48785

$$K := K_s \left(\frac{Sat \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \cdot \left[1 - \left[1 - \left(\frac{Sat \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{\frac{1}{\gamma}} \right]^{\gamma} \right]^2$$

Unsaturated hydraulic conductivity as a function of saturation (Sat) based on vanGenuchten relationship and unit hydraulic gradient

For unit gradient conditions $q = 6.07000 \cdot \frac{in}{yr}$ $K = 6.07000 \cdot \frac{in}{yr}$

$$h := \frac{1}{\alpha} \cdot \left[\left(\frac{\phi - \theta_r}{Sat \cdot \phi - \theta_r} \right)^{\frac{1}{\gamma}} - 1 \right]^{\frac{1}{\beta}}$$

Suction head in tailings for unit gradient conditions $h = 191.681 \cdot cm$

193.549

Calcs for Bentonite-Amended Tailings

$\gamma_{bn} := 1 - \frac{1}{\beta_{bn}}$ Computed vanGenuchten parameter

$$Sat_{bn} := \frac{1}{\phi_{bn}} \cdot \left[\theta_{rbn} + \frac{\phi_{bn} - \theta_{rbn}}{\left[1 + (\alpha_{bn} \cdot h)^{\beta_{bn}} \right]^{\gamma_{bn}}} \right]$$

Saturation at bottom of the bentonite layer. Assumed to apply to entire layer. $Sat_{bn} = 0.9566$

0.9563

$$D_{bn} := \tau \cdot D_a \cdot (1 - Sat_{bn})^c + \tau \cdot Sat_{bn} \cdot \frac{D_w}{K_H}$$

Effective O2 diffusion coeff used in GS. This parameter is referenced to the void volume. $D_{bn} = 1.835 \times 10^{-10} \frac{m^2}{s}$

1.876×10^{-10}

Diffusion Related Calcs

$CF := \frac{CF_{fine} + CF_{coarse}}{2}$ Sulfate calibration factor

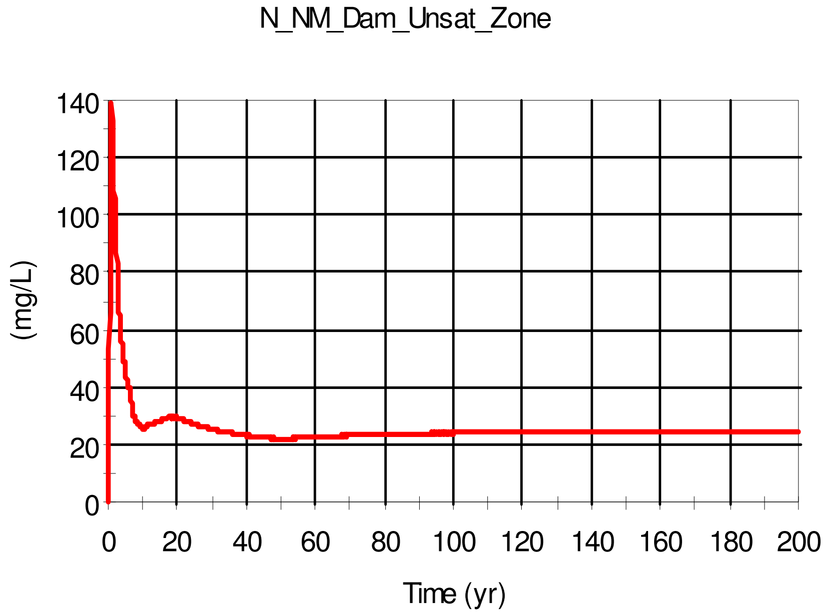
$MRM_{SO4} := R_{SO4} \cdot CF \cdot TF \cdot (1 - FF)$ Mass rate of released SO4 per unit mass of tailings solids $MRM_{SO4} = 0.087 \cdot \frac{mg}{kg \cdot 7 \cdot day}$

	Effect of three factors	$CF\cdot TF\cdot(1-FF) = 0.045$
$r_{nm} := \frac{MRM_{SO4}}{W_{SO4}\cdot moleratio}\cdot\frac{\rho}{\phi}$	Molar consumption rate of O2 per unit volume of voids	$r_{nm} = 0.00740\cdot\frac{mol}{m^3\cdot 7\cdot day}$ 0.00741
$d := \sqrt{\frac{2\cdot D_{bn}\cdot C_o}{r_{nm}}}$	Thickness of sulfate reaction zone if controlled by diffusion	$d = 0.516\,m$
$b := \min(d, DTW)$	Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water.	$b = 0.516\,m$ 0.522

Sulfate Calcs

$MRV_{SO4} := MRM_{SO4}\cdot\rho$	Mass rate of released sulfate per unit bulk volume	$MRV_{SO4} = 2.299\times 10^{-10}\,\frac{kg}{m^3\cdot s}$
$MR_{SO4} := MRV_{SO4}\cdot A\cdot b$	Mass rate of released SO4	$MR_{SO4} = 10.335\cdot\frac{kg}{day}$
$Q := q\cdot A$	Seepage flow rate	$Q = 78.034\cdot gpm$
$C_{SO4} := \frac{MR_{SO4}}{Q}$	Sulfate concentration in seepage 24.5	$C_{SO4} = 24.3\cdot\frac{mg}{liter}$

GoldSim Output



Sulfur Calcs

$MRV_S := MRV_{SO4}\cdot\frac{W_S}{W_{SO4}}$	Mass rate per unit bulk volume of released sulfur	$MRV_S = 7.675\times 10^{-11}\,\frac{kg}{m^3\cdot s}$
$MRA_S := MRV_S\cdot b$	Mass rate per unit area of released sulfur	$MRA_S = 23.962\cdot\frac{mg}{m^2\cdot 7\cdot day}$ 24.22
$MR_S := MRA_S\cdot A$	Mass rate of sulfur generation	$MR_S = 3.449\cdot\frac{kg}{day}$

Other Chemicals

$RR_{As} := 0.09995$	Release ratio of As to S		
$CF_{As} := 0.0001$	As calibration factor		
$MR_{As} := MR_S \cdot RR_{As} \cdot CF_{As}$	Mass rate of released As	1.273×10^{-5}	$MR_{As} = 1.259 \times 10^{-5} \cdot \frac{tonne}{yr}$
$C_{As} := \frac{MR_{As}}{Q}$	As concentration in seeapge		$C_{As} = 0.081 \cdot \frac{\mu g}{L}$
$RR_{Co} := 0.03076$	Release ratio of Co to S		
$CF_{Co} := 0.0006$	Co calibration factor		
$MR_{Co} := MR_S \cdot RR_{Co} \cdot CF_{Co}$	Mass rate of released Co	2.350×10^{-5}	$MR_{Co} = 2.325 \times 10^{-5} \cdot \frac{tonne}{yr}$
$C_{Co} := \frac{MR_{Co}}{Q}$	Co concentration in seeapge		$C_{Co} = 0.150 \cdot \frac{\mu g}{L}$
$RR_{Cu} := 0.030598$	Release ratio of Cu to S		
$CF_{Cu} := 0.0005$	Cu calibration factor		
$MR_{Cu} := MR_S \cdot RR_{Cu} \cdot CF_{Cu}$	Mass rate of released Cu	1.948×10^{-5}	$MR_{Cu} = 1.928 \times 10^{-5} \cdot \frac{tonne}{yr}$
$C_{Cu} := \frac{MR_{Cu}}{Q}$	Cu concentration in seeapge		$C_{Cu} = 0.124 \cdot \frac{\mu g}{L}$
$RR_{Ni} := 0.014307$	Release ratio of Ni to S		
$CF_{Ni} := 0.0027$	Ni calibration factor		
$MR_{Ni} := MR_S \cdot RR_{Ni} \cdot CF_{Ni}$	Mass rate of released Ni	4.920×10^{-5}	$MR_{Ni} = 4.867 \times 10^{-5} \cdot \frac{tonne}{yr}$
$C_{Ni} := \frac{MR_{Ni}}{Q}$	Ni concentration in seeapge		$C_{Ni} = 0.313 \cdot \frac{\mu g}{L}$
$RR_{Zn} := 5.0629 \cdot 10^{-5}$	Release ratio of Zn to SO4		
$CF_{Zn} := 0.2596$	Zn calibration factor		
$MR_{Zn} := MR_{SO4} \cdot RR_{Zn} \cdot CF_{Zn}$	Mass rate of released Zn	5.014×10^{-5}	$MR_{Zn} = 4.961 \times 10^{-5} \cdot \frac{tonne}{yr}$
$C_{Zn} := \frac{MR_{Zn}}{Q}$	Zn concentration in seeapge		$C_{Zn} = 0.319 \cdot \frac{\mu g}{L}$

Pond Area - Sulfate - Bentonite Amended - Closure at t = 100 yrs

$A := 972.6 \cdot \mathrm{acre}$ Pond area (GS output)

$q := 6.5 \cdot \frac{\mathrm{in}}{\mathrm{yr}}$ Seepage flux for bentonite amended pond bottom (Table 1-31)

$C_o := 12.48 \cdot \frac{\mathrm{mg}}{\mathrm{L}}$ Average annual pond DO concentration (Table 1-18)

$W_{O2} := 32 \cdot \frac{\mathrm{gm}}{\mathrm{mole}}$ O2 molecular weight

$W_{SO4} := 96.07 \cdot \frac{\mathrm{gm}}{\mathrm{mole}}$ SO4 molecular weight

$W_S := 32.07 \cdot \frac{\mathrm{gm}}{\mathrm{mole}}$ S molecular weight

$C_{SO4p} := 16.19 \cdot \frac{\mathrm{mg}}{\mathrm{L}}$ 16.19 Sulfate concentration in pond water (GS output table)

$\mathrm{moleratio} := \frac{4}{9}$ moles of SO4 generated per mole of O2 consumed $\mathrm{moleratio} = 0.444$

$Q := q \cdot A$ Seepage flow rate 326.4 $Q = 326.394 \cdot \mathrm{gpm}$

$MR_{O2} := C_o \cdot Q$ Mass rate of O2 brought in with pond seeapge water 1.555 x 10^8 $MR_{O2} = 1.554 \times 10^8 \cdot \frac{\mathrm{mg}}{7 \cdot \mathrm{day}}$

$MR_S := MR_{O2} \cdot \left(\frac{W_S}{W_{O2}}\right) \cdot \mathrm{moleratio}$ Mass rate of S produced by tailings oxidation 6.917 x 10^7 $MR_S = 6.923 \times 10^7 \cdot \frac{\mathrm{mg}}{7 \cdot \mathrm{day}}$

$MR_{SO4o} := MR_{O2} \cdot \left(\frac{W_{SO4}}{W_{O2}}\right) \cdot \mathrm{moleratio}$ Mass rate of SO4 produced by tailings oxidation 29.622 $MR_{SO4o} = 29.627 \cdot \frac{\mathrm{kg}}{\mathrm{day}}$

$MR_{SO4o} = 29.627 \cdot \frac{\mathrm{kg}}{\mathrm{day}}$

$MR_{SO4p} := C_{SO4p} \cdot Q$ Mass rate of SO4 brought in with pond seepage $MR_{SO4p} = 28.805 \cdot \frac{\mathrm{kg}}{\mathrm{day}}$

$MR_{SO4} := MR_{SO4o} + MR_{SO4p}$ Mass rate of SO4 in pond area seepage. This value is transferred to Table 2. $\boxed{MR_{SO4} = 58.432 \cdot \frac{\mathrm{kg}}{\mathrm{day}}}$

$C_{SO4} := \frac{MR_{SO4}}{Q}$ Sulfate concentration in seepage water to toes $C_{SO4} = 32.842 \cdot \frac{\mathrm{mg}}{\mathrm{L}}$

Buttress North - Sulfate - Closure

Assume Cat 1 Waste Rock

$A := 45\cdot \text{acre}$	Map area (Table 1-23)		
$q := 13.241\cdot\frac{\text{in}}{\text{yr}}$	Percolation rate		
$V_{tail} := 1145900\cdot \text{yd}^3$	Volume of tailings (Table 1-23)		
$Cont_S := 0.063\cdot\%$	Sulfur content (Table 1-1, sheet 7)		
$\rho_b := 140\cdot\frac{\text{lbm}}{\text{ft}^3}$	Dry bulk density (Table 1-1, sheet 7)		
$MRMP_{SO4} := 13.92\cdot\frac{\text{mg}}{\text{kg}\cdot 7\cdot \text{day}\cdot\%}$	Cat 1 sulfate release rate as function of % sulfur. Mass rate per unit mass of tailings per % sulfur. (Table 1-1, sheet 10; also see Mine Site Worklan Table 1-27)		
$SF := 0.107685$	P50 LAM scale factor (Table 1-1, sheet 6, P50 from GS)		
$MRM_{SO4} := MRMP_{SO4}\cdot Cont_S\cdot SF$	Mass rate of produced sulfate per unit mass of tailings	0.094435	$MRM_{SO4} = 0.094435\cdot\frac{\text{mg}}{\text{kg}\cdot 7\cdot \text{day}}$
$M_{tail} := \rho_b\cdot V_{tail}$	Mass tailings	1.965×10^6	$M_{tail} = 1.965\times 10^6\cdot \text{tonne}$
$Q := A\cdot q$	Percolation rate	30.76	$Q = 30.763\cdot \text{gpm}$
$MR_{SO4} := MRM_{SO4}\cdot M_{tail}$	Mass rate of sulfate generated by buttress	26.501	$MR_{SO4} = 26.506\cdot\frac{\text{kg}}{\text{day}}$
$C_{SO4} := \frac{MR_{SO4}}{Q}$	Sulfate concentration in bottom drainage		$C_{SO4} = 158.066\cdot\frac{\text{mg}}{\text{L}}$

Buttress South - Sulfate - Closure

Assume Cat 1 Waste Rock

$A := 15 \cdot \text{acre}$ Map area (Table 1-23)

$q := 13.241 \cdot \frac{\text{in}}{\text{yr}}$ Percolation rate

$V_{tail} := 325500 \cdot \text{yd}^3$ Volume of tailings (Table 1-23)

$Cont_S := 0.063 \cdot \%$ Sulfur content (Table 1-1, sheet 7)

$\rho_b := 140 \cdot \frac{\text{lbm}}{\text{ft}^3}$ Dry bulk density (Table 1-1, sheet 7)

$MRMP_{SO4} := 13.92 \cdot \frac{\text{mg}}{\text{kg} \cdot 7 \cdot \text{day} \cdot \%}$ Cat 1 sulfate release rate as function of % sulfur. Mass rate per unit mass of tailings per % sulfur. (Table 1-1, sheet 10; also see Mine Site Worklan Table 1-27)

$SF := 0.107685$ P50 LAM scale factor (Table 1-1, sheet 6, P50 from GS)

$MRM_{SO4} := MRMP_{SO4} \cdot Cont_S \cdot SF$ Mass rate of produced sulfate per unit mass of tailings $MRM_{SO4} = 0.094435 \cdot \frac{\text{mg}}{\text{kg} \cdot 7 \cdot \text{day}}$

$M_{tail} := \rho_b \cdot V_{tail}$ Mass tailings $M_{tail} = 5.581 \times 10^5 \cdot \text{tonne}$

$Q := A \cdot q$ Percolation rate $Q = 10.254 \cdot \text{gpm}$

$MR_{SO4} := MRM_{SO4} \cdot M_{tail}$ Mass rate of sulfate generated by buttress $MR_{SO4} = 7.529 \cdot \frac{\text{kg}}{\text{day}}$

$C_{SO4} := \frac{MR_{SO4}}{Q}$ Sulfate concentration in bottom drainage $C_{SO4} = 134.699 \cdot \frac{\text{mg}}{\text{L}}$

ATTACHMENT 3: QA/QC TRACKING LOG FOR PLANT AND MINE SITE MODELS

Barr Engineering Company

This attachment contains the ongoing model QA/QC tracking log maintained by Barr Engineering Company. The tracking log documents all model-related issues identified by either model developers or model reviewers and details how each issues was resolved. The Review Team verifies that the log is accurate with regard to communications that have taken place between the Review Team and Barr.

Mine and Plant Site Model QA/QC Tracking Log (Maintained by Barr)

Item	Date	Model / AWMP Version	Problem / Issue	Change (changes affecting input tables in BOLD)	Updated Model Version	Previous change, status in AWMP V3.0 Model
1	8/2/2012	MS V1.0 / AWMPV2.0	ERM found that the pH used in the model did not match that proposed in Version 2 of the AWMP	The Mine Site model was updated (email from Peter Hinck to Fred Marinelli on 7/19/12) to match AWMP V2. However, subsequent discussion of the AWMP modeling parameters has led to this change being dropped from the proposed model. **Cat1SP_pH_Geomem no longer used in modeling**	MS AWMPV2.1	Unchanged from V2.1
2	8/2/2012	MS V1.0 / AWMPV2.0	ERM identified a greater-than-expected mass removal in the Cat 1 PRB	This issue is associated with the percolation through the Category 1 geomembrane, which was updated in the 7/19/12 email submittal to match the distribution proposed in the AWMP V2. The design flow of the PRB was not updated at the same time, resulting in longer-than-intended retention times in the PRB, and therefore greater-than-intended mass removal. **Cat1SP_PRB_Design_Flow value changed to 2.5 gpm**	MS AWMPV2.1	Cat 1 PRB no longer modeled
3	8/2/2012	MS V1.0 / AWMPV2.0	Additional model outputs are necessary to facilitate the impacts analysis	Barr added additional results reporting and standards checking functionality in the surface water portion of the model.	MS AWMPV2.1	Additional outputs added
4	8/2/2012	MS V1.0 / AWMPV2.0	Barr found during internal QA/QC that the flow lines carrying wall rock mass to the West Pit in the flow chart were combined into one defined function in the model. Task 2 QA/QC needed those flow lines separated into water flows and direct mass transfers.	The functions, which were the addition of all wall rock flow lines for a rock category, were changed into 2 functions which separated mass flux in flowing water and direct transfers via wall rock inundation. These are now two distinct elements to facilitate the Task 2 QA/QC.	MS AWMPV2.1	Unchanged from V2.1
5	8/2/2012	MS V1.0 / AWMPV2.0	Barr found during internal QA/QC that the groundwater inflow to the West Pit was not properly accounted for in the water balance, although the mass balance was correct.	Barr corrected the West Pit water balance equations.	MS AWMPV2.1	Unchanged from V2.1
6	8/2/2012	MS V1.0 / AWMPV2.0	Barr found during internal QA/QC that the calculation of added alkalinity and calcium to the pit outflow as a result of pH adjustment in the limestone channel was not correct.	Barr updated the calculations relating to limestone dissolution.	MS AWMPV2.1	West Pit limestone / wetland treatment no longer modeled
7	8/2/2012	MS V1.0 / PS V1.0 / AWMPV2.0	Internal QA/QC has identified several small inconsistencies in the model flowcharts (not the models themselves).	Barr marked up the flowcharts used for the Task 2 QA/QC control volume identification.	MS AWMPV2.1 / PS AWMPV2.1	Updated for V3.0
8	8/2/2012	PS V1.0 / AWMPV2.0	Plant Site mass balance: first Plant Site control volume mass balance did not appear to close when using the initially provided flows and concentrations to calculate mass loading rates	Barr has shown (and discussed with Fred Marinelli on 8/1/12) that the model output flows and concentrations cannot be used to replicate GoldSim's mass loading results due to the complex differential equation solutions performed in GoldSim. An alternative means of performing the control volume calculations is to use GoldSim-reported water flow rates and GoldSim-reported constituent mass flux rates along with stored water volumes and constituent masses.	PS AWMPV2.1	
9	8/2/2012	PS V1.0 / AWMPV2.0	Barr could not do a direct comparison of Existing Conditions and Project Conditions without the two models being in one model. Critical for the impact analysis.	Barr incorporated the Existing Conditions Model INTO the Project (Base) model so that there is only 1 model to transfer now rather than 2 separate models.	PS AWMPV2.1	

Mine and Plant Site Model QA/QC Tracking Log (Maintained by Barr)

Item	Date	Model / AWMP Version	Problem / Issue	Change (changes affecting input tables in BOLD)	Updated Model Version	Previous change, status in AWMP V3.0 Model
10	8/2/2012	PS V1.0 / AWMPV2.0	Barr found during internal QA/QC that the defined volume in river nodes MLC-3 and MLC-2 were incorrect (MLC-3 referenced the MLC-2 volume and vice-versa).	Barr changed the volume definition of river nodes MLC-3 and MLC-2 in both the Project portion of the model and the Existing portion of the model.	PS AWMPV2.1	
11	8/2/2012	PS V1.0 / AWMPV2.0	Barr found during internal QA/QC that 2 of the flow lines in the flow chart (surface runoff and tailings basin runoff to MLC-3) were combined into one defined function in the model. Task 2 QA/QC needed those two flow lines separate.	The function, which was the addition of two separate flow lines, was changed into 2 functions which separated runoff from natural areas and the tailings basin. These are now two distinct flow lines to facilitate the Task 2 QA/QC.	PS AWMPV2.1	
12	8/2/2012	PS V1.0 / AWMPV2.0	Barr found that the MODFLOW model of the FTB in closure did not match the AWMPV2.0 (reduced infiltration from the pond in Cell 1E/2E).	Barr updated the predictive MODFLOW simulation of the closure period and updated several tables of the work plan related to directions of flow and depths to the water table. **Updated Plant Site tables 1-25, 1-27, 1-29, 1-31, 1-34, 1-35, 1-37, and 1-39.**	PS AWMPV2.1	
13	8/8/2012	MS AWMPV2.1	Barr found during internal QA/QC that the West Pit outflow mass balance model combines the controlled outflow and any pit overtopping.	Barr changed the mass balance of the West Pit so that overtopping flows (unlikely) bypass the passive treatment and contribute directly to SW-004a.	MS AWMPV2.2	Unchanged from V2.2
14	8/8/2012	MS AWMPV2.1	Barr found during internal QA/QC that the West Pit surficial aquifer flow calculations contained an error in the flows for Section 2 (between Dunka Road and the Property Boundary).	Barr edited the cell flows vector calculation in the West Pit surficial aquifer (\Flowpath_Models\WP_Surf\Cell_Flows\Flows)	MS AWMPV2.2	Unchanged from V2.2
15	8/9/2012	MS AWMPV2.1	Based on comments from reviewers and Barr staff, PRB modeling was determined to be overly complicated.	Barr edited the modeling of the Category 1 stockpile PRB to be a constant removal efficiency (ex. 50% removal for SO4) irrespective of flow rates or retention time.	MS AWMPV2.2	Cat 1 PRB no longer modeled
16	8/10/2012	MS AWMPV2.1	During detailed West Pit treatment wetland design it was determined that the West Pit water elevation needs to be increased slightly.	Barr added a new variable representing the elevation that the West Pit water returns to after annual discharge. **WP_Outlet_Elev_New value set to 1575'** Barr also edited the equation for WP_Seasonal_Discharge to account for the current timestep inflows in calculating the desired outflow	MS AWMPV2.2	West Pit limestone / wetland treatment no longer modeled; elevation returned to previous value
17	8/15/2012	MS AWMPV2.2	Barr found during internal QA/QC that the East Pit wetland outflow to the surficial aquifer was defined differently in the flowpath and pit water balances	Barr edited the water balance calculation (EPCP_GW_Outflow) and aquifer (EP_at_Aquifer) to both initiate seepage when water levels reach the aquifer, without respect to pit pump-and-treat.	MS AWMPV2.3	Unchanged from V2.3
18	8/15/2012	PS AWMPV2.1	Mitigation measure at Tailings Basin	Barr has made significant edits to the features at the toes of the Tailings Basin, namely converting from a PRB system to a Wetland treatment system	PS AWMPV2.2	Unchanged from V2.2

Mine and Plant Site Model QA/QC Tracking Log (Maintained by Barr)

Item	Date	Model / AWMP Version	Problem / Issue	Change (changes affecting input tables in BOLD)	Updated Model Version	Previous change, status in AWMP V3.0 Model
19	8/15/2012	PS AWMPV2.1	Barr found during internal QA/QC that the inputs of Table 1-49 did not differentiate runoff area of the embankments of the existing Tailings Basin between Cell 2W and Cell 2E.	The areas which were under Cell 2W were divided into Cell 2W and Cell 2E. **See Table 1-49.**	PS AWMPV2.2	Unchanged from V2.2
20	8/15/2012	PS AWMPV2.1	During review of the tailings humidity cells, it was determined that the rates currently being used were not appropriate.	SRK suggested a new method and new distributions were created. These have not yet been checked by the agencies so the distributions are in the "proposal" stage; current distributions are as discussed with LAM on 9/28/12. **See tables 1-13 and 1-14**	PS AWMPV2.2	Updated for V3.0
21	8/15/2012	PS AWMPV2.1	ERM found that the sulfate concentration cap for the tailings was not checking correctly. The calcium release rate was changed from a ratio to Na to a ratio to SO4 using CDF056. This change was captured in the release of Ca, but was not changed in the calculation of the sulfate cap.	The error in the model was fixed.	PS AWMPV2.2	Unchanged from V2.2
22	8/16/2012	MS AWMPV2.2	Barr found during internal QA/QC that the East Pit wetland overflow to the West Pit did not appropriately calculate flows during low-inflow periods.	Barr changed the calculation for EPCP_Wetland_Outflow so that outflow equals inflow if the starting water level for the month is equal to the outlet elevation.	MS AWMPV2.3	Unchanged from V2.3
23	8/16/2012	MS AWMPV2.2	Barr found during internal QA/QC that the flow lines carrying wall rock mass to the East Pit in the flow chart were combined into one defined function in the model. Task 2 QA/QC needed those flow lines separated into water flows and direct mass transfers.	The functions, which were the addition of all wall rock flow lines for a rock category, were changed into 5 functions which separated mass flux in flowing water and direct transfers via wall rock inundation to the 3 East Pit mass storage nodes. These are now 5 distinct elements to facilitate the Task 2 QA/QC.	MS AWMPV2.3	Unchanged from V2.3
24	8/16/2012	MS AWMPV2.2	Barr found during internal QA/QC that there was an inconsistency between the stockpile liner leakage flows used for the stockpile and GW flowpath water balances.	Barr changed the calculations for the source zone recharge ("S") terms for the following flowpaths: EPCat23_Surf, OSP_Surf, OSLA_Surf. Flow into the flowpath now equals the stockpile outflow rate.	MS AWMPV2.3	Unchanged from V2.3
25	8/21/2012	PS AWMPV2.3	Foth found an inconsistency between the plant site input tables and the model. The release rates for several constituents were defined using log-normal or discrete distributions rather than beta distributions as defined in the work plan (Tables 1-13 and 1-14).	The work plan tables are correct. The model was modified in anticipation of CDF056, which was later rejected. The values in the input tables were changed back, but the input distributions themselves were not changed back from log-normal and discrete distributions to beta distributions. The model has since been updated so that the release rates match the work plan input tables.	PS AWMPV3.0	
26	8/22/2012	MS AWMPV2.3	Based on recommendation from Agency staff it was determined that the sulfate wild rice standard has been applied at incorrect locations in the Partridge River.	Barr changed the locations where the wild rice standard applies in the model variable Wild_Rice_Locs to be only at SW-005. **Updated Mine Site Tables 2-2 and 1-17.**	MS AWMPV3.0	

	Mine and Plant Site Model QA/QC Tracking Log (Maintained by Barr)					
Item	**Date**	**Model / AWMP Version**	**Problem / Issue**	**Change (changes affecting input tables in BOLD)**	**Updated Model Version**	**Previous change, status in AWMP V3.0 Model**
27	8/31/2012	MS AWMPV2.3	Based on decision to switch to mechanical treatment and constant discharge in post-closure, the model needs to be updated to remove non-mechanical treatment systems and alter the treatment system modeling.	Barr made major changes to the modeling of the WWTF and previous passive treatment systems to reflect the shift to long-term active treatment, including: * Category 1 stockpile PRB deactivated, inputs removed * West Pit controlled (seasonal) discharge deactivated * West Pit limestone/wetland treatment deactivated, inputs removed * Category 1 stockpile containment water balance revised; water routed to WWTF in operations/reclamation/long-term closure * Added detail to the WWTF water balance calculations * Added new triggers to define "reclamation" and "long-term" conditions, updated pit and Category 1 stockpile water balances to use new triggers * Added new mixing cells to represent reclamation and long-term WWTFs, updated pit and stockpile contaminant transport elements to direct flow to new cells * Updated pit, Category 1 stockpile, and WWTF mass balance checks *** Updated Mine Site Tables 1-35, 1-36, and 1-37 (Plant Site flow and quality to West Pit).** *** Reclam_Pump_Total set at 2400 gpm** *** LongTerm_Pump_WP set at 600 gpm** *** EP_Return_Deficit set at 100 gpm** *** Retentate_Reclam set at 20%, Retentate_LongTerm set at 15%** *** Updated Mine Site Table 1-34 (WWTF targets)**	MS AWMPV3.0	
28	9/17/2012	MS AWMPV2.3	Based on MODFLOW modeling of the Category 1 stockpile, some uncaptured seepage is expected to enter the West Pit even under 100% containment.	Barr changed the Category 1 stockpile water balance modeling to direct seepage "leaking" past the containment system to the West Pit. **Cat1_Contain_Leak defined as 7% of total infiltration**	MS AWMPV3.0	
29	9/21/2012	MS AWMPV2.1	Barr identified in response to agency questions that not all WWTF interactions between the Mine Site and Plant Site were accounted for in the WWTF water and mass balance.	Barr added an inflow of Plant Site brine (flow and chemistry) to the West EQ Pond and reclamation WWTF. Barr added an outflow of sludge water (flow) from the operations WWTF and (chemistry) from the CPS pond; and an outflow of sludge water (flow and chemistry) from the reclamation WWTF. **New Mine Site Tables 1-38, 1-39, and 1-40 (Brine flow and quality).** **New input variable Sludge_Water_Out defined as 5 gpm.**	MS AWMPV3.0	
30	9/21/2012	MS AWMPV2.3	The time of the West Pit overflow has changed to approximately year 40.	Barr changed the overflow year from 65 to 40 in the Partridge River flow tables. **Updated Mine Site Tables 1-18, 1-20a through 1-20l and 1-21.**	MS AWMPV3.0	
31	9/24/2012	MS AWMPV2.3	Agency staff requested that the background groundwater distributions be updated	Barr updated the distributions for the surficial groundwater quality (data through June 2012); subsequently Barr updated the surface water quality calibration. **Updated Mine Site Tables 1-12 and 1-13**	MS AWMPV3.0	
32	9/24/2012	MS AWMPV2.3	Partridge River concentration outputs were overly complicated	Barr changed the concentration summary calculations for the NoAction and NorthMet models	MS AWMPV3.0	
33	9/24/2012	MS AWMPV2.3	Internal QA/QC identified an unnecessary timestep in one of the input tables	Barr edited the West Pit footprint input table to remove the unnecessary timestep. **Updated Mine Site Table 1-9b**	MS AWMPV3.0	

Mine and Plant Site Model QA/QC Tracking Log (Maintained by Barr)

Item	Date	Model / AWMP Version	Problem / Issue	Change (changes affecting input tables in BOLD)	Updated Model Version	Previous change, status in AWMP V3.0 Model
34	9/24/2012	MS AWMPV2.3	Updated Plant Site modeling has changed the water quality available to flood the West Pit	Barr edited the West Pit water balance to identify the desired flow quantity and duration **Updated Mine Site Tables 1-35, 1-36, and 1-37 (Plant Site flow and quality to West Pit)** **TB_Stop_Vol defined as 50,000 acre-ft**	MS AWMPV3.0	
35	9/24/2012	MS AWMPV2.3	Based on MODFLOW modeling of the Category 1 stockpile, reclamation needs to begin earlier to avoid water table mounding beneath the stockpile	Barr changed the beginning of the 8-year reclamation period to the start of mine year 14 (t = 13 years). **Updated Mine Site Table 1-5b**	MS AWMPV3.0	
36	9/28/2012	PS AWMPV2.3	No longer considering trees in Cell 2W to improve evaporation and reduce percolation	Changed the Current_2W_Evap element, moved the Use_Mitigation_Evap_in_2W element to the Inactive_Container, and modified the Precip_Budget elements of the coarse and fine tailings in Cell 2W of the project.	PS AWMPV3.0	
37	9/28/2012	PS AWMPV2.3		Changed the triggers of multiple switches in the Globals container to match the control of water flow.	PS AWMPV3.0	
38	9/28/2012	PS AWMPV2.3	No input that controls the drainage time of the Hydrometallurgical Residue Facility	**HRF_Drainage_Period** element added to control the draining and treating of the HRF. This input is added to the Work Plan Table 1-1. Also had to add functionality to the drainage from the HRF in closure to properly send the total volume to the WWTP over the drainage period.	PS AWMPV3.0	
39	9/28/2012	PS AWMPV2.3	Barr found that the magnesium concentration cap for the tailings was not checking correctly. The calcium release rate was changed from a ratio to Na to a ratio to SO4 using CDF056. This change was captured in the release of Ca, but was not changed in the calculation of the sulfate cap.	The Mg_Cap was corrected for both the Atmospheric and CO2 Enriched conditions. This is similar to the fix for the sulfate release cap error of Item 22.	PS AWMPV3.0	
40	9/28/2012	PS AWMPV2.3	Barr found errors in the constituent content of the LTVSMC tailings for multiple constituents.	The Work Plan table has been updated and highlighted. The element LTVSMC_Content was updated in the model.	PS AWMPV3.0	
41	9/28/2012	PS AWMPV2.3	Cleaning up the QA/QC folders	Multiple changes were made to the Inputs_Checking container to facilitate the Task 1 QA/QC that is coming up.	PS AWMPV3.0	
42	9/28/2012	PS AWMPV2.3	Missing a control for the total volume of water than can be sent to the Mine Site	Added element **Max_Vol_To_Mine** to the container \Project\MINE_SITE. Also added to the Work Plan Table 1-1 and highlighted.	PS AWMPV3.0	
43	9/28/2012	PS AWMPV2.3	Changes to the Project Description	Major changes were made to the containers Interception_System, FTB_WWTP, and Tailings_Basin_Toes to account for the updates to the collection plan, the treatment plan, and the distribution of treated/blended water.	PS AWMPV3.0	
44	9/28/2012	PS AWMPV2.0	Could not directly export flow and stored water values to spreadsheets during the Task 2 QA/QC review.	Added flow related elements to the unsaturated tailings portions of the model. Changed flow controls (outflow rates) of the mixing cells in the unsaturated tailings portions of the model. All of this was for the purpose of aiding the Task 2 QA/QC.	PS AWMPV3.0	
45	9/28/2012	PS AWMPV2.3	The model was applying inappropriate solubility limits to the unsaturated tailings portions of the Tailings Basin	Solubility controls were added to each of the unsaturated tailings portions of the models so that each mixing cell was referencing the correct solubility limit.	PS AWMPV3.0	
46	9/28/2012	PS AWMPV2.3	Elements that show up in the Existing and Project models that should be identical were both in the model independently as inputs.	Those few elements in \Project\Tailings_Basin\NorthMet_Basin\CELL_1E\Basin_Characteristics were cloned to prevent possible differences in the future.	PS AWMPV3.0	

	Mine and Plant Site Model QA/QC Tracking Log (Maintained by Barr)					
Item	Date	Model / AWMP Version	Problem / Issue	Change (changes affecting input tables in BOLD)	Updated Model Version	Previous change, status in AWMP V3.0 Model
47	9/28/2012	MS AWMPV2.3	Barr found during internal QA/QC that there was an over-release of consituents in the first timestep from all stockpiles, due to an attempt to prevent divide-by-zero errors.	Barr changed the calculations for the release rate terms throughout the model (stockpiles, pit walls, pit backfill) to release zero mass in the initial timestep when the previous "InRock" mass is zero. See model element \Stockpile_Models\Cat4SP_Model\Cat4SP_MassBal\Cat4SP_VFCat4SP_ReleaseVF_frac for an example.	MS AWMPV3.0 / PS AWMPV3.0	
48	9/28/2012	PS AWMPV2.3	During Task 2 QA/QC review, Barr found that the initial conditions of the existing basin did not seem correct.	Barr found that the initial conditions of the basin were not updated when CDF 055 was approved which changed the initial saturation conditions and necessarily changed the initial mass and loading rates. Initial values were modified.	PS AWMPV3.0	
49	9/28/2012	PS AWMPV2.3	Barr found during internal QA/QC that the pH-based concentration caps used in the Plant Site model were not the same as the Cat1 concentration caps in the Mine Site model.	Both the lookup tables in the model and in the work plan were updated so that the two models are using the same inputs as they should be.	PS AWMPV3.0	
50	9/28/2012	PS AWMPV2.3	The Plant Site model was not accounting for the watershed area between the toes of the tailings basin and the containment system in the project condition.	Barr modified Input Table 1-49 to show both the existing condition and the project condition, accounting for the watershed area to the containment system, which is taken out of the Embarrass River Tributary watershed areas.	PS AWMPV3.0	

Appendix B
NorthMet Quality Assurance Memo January 17, 2013

Memorandum

Environmental
Resources
Management

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To: Bill Johnson, MDNR

From: Fred Marinelli, InTerraLogic
Houston Kempton, Knights Piesold
John Adams, ERM
Dave Blaha, ERM

CC: Al Trippel, ERM
Melinda Todorov, ERM

Date: January 17, 2013

Subject: NorthMet Project Quality Assurance Update - Mine Site

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This technical memorandum describes a screening-level audit of the NorthMet Project Mine Site GoldSim water-quality model version 4.1 (simulation run on December 11, 2012). This model for the Mine Site was developed by Barr Engineering Company (Barr) to estimate potential environmental effects from the proposed mine on the quality and quantity of water resources. This audit has been conducted by members of the ERM Project Team to provide technical support to the State of Minnesota in preparation of the NorthMet Project Supplemental Draft Environmental Impact Statement (SDEIS). Previously, the ERM team conducted an audit of version 3 of the GoldSim model (run on September 26, 2012), which included project components of the Mine Site and Plant Site. Results of the version 3 audit were summarized in an October 2012 memorandum. The 2012 audit was not a 100-percent verification of model calculations, but instead focused on evaluating select model components that are critical in the estimates of solute release/transport and associated water management costs. This update provides a supplementary audit of certain additional model components at the Mine Site that were not evaluated previously. It was confirmed during this audit that the few input assumptions that have changed since the prior review were incorporated into the current GoldSim model (version 4.1) and the changes did not raise any Quality Assurance (QA) concerns.

For this QA update, the following evaluations were performed, with each presented as a separate attachment:

- Attachment 1: GoldSim Estimates of Water Quality in the West Pit and East Pit
- Attachment 2: GoldSim Estimates of Groundwater Transport
- Attachment 3: GoldSim Estimates of Partridge River Water Quality

The results of this audit provide good evidence that the Mine Site GoldSim model (version 4.1) has appropriate and mathematically correct algorithms for (1) estimating chemical concentrations in the East and West pits, (2) simulating chemical migration in the surficial groundwater flowpaths, and (3) estimating Partridge River chemical concentrations by the mixing of background and impacted water sources to the river.

ATTACHMENT 1: MINE SITE AUDIT – GOLDSIM ESTIMATES OF WATER QUALITY IN THE WEST PIT AND EAST PIT

INTRODUCTION

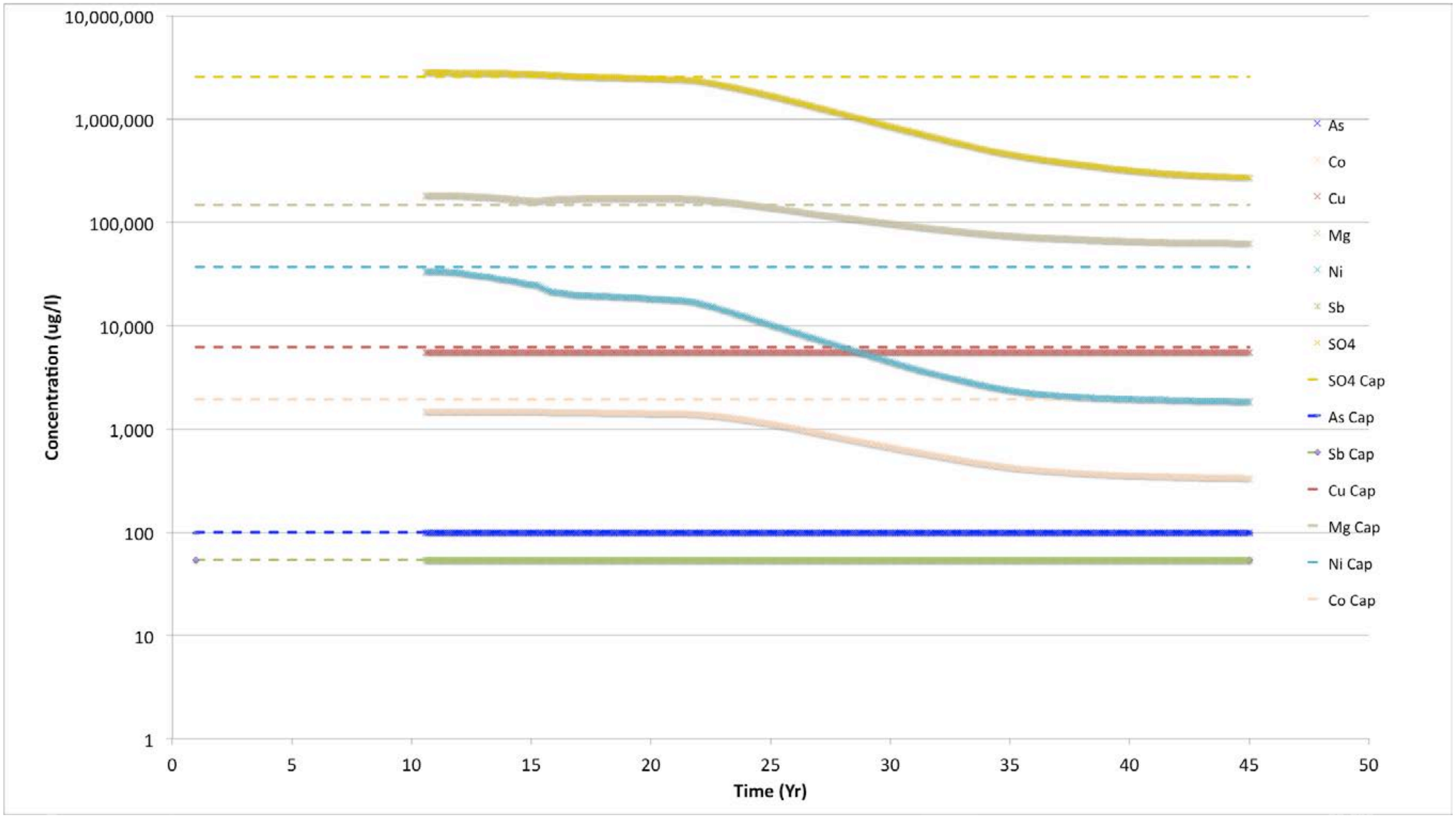
This audit of the GoldSim model version 4.1 re-visits the components in the audit of GoldSim model version 3 related to the East and West Pits, both of which are located in the Mine Site. As with the audit of model version 3, this audit checks the GoldSim estimates for pit water quality and load rates for the same 6 water-quality constituents included in the full GoldSim modeling (arsenic, antimony, copper, cobalt, nickel, and sulfate). A seventh constituent, manganese, was also included in the audit as it was tracked to determine nickel loads. The audit comparisons apply the 50th-percentile (P50) model input parameter values in deterministic calculations to provide an independent check on the GoldSim predictions. Specific components in this audit include solubility caps in the pit waters and the load of pollutants from the West Pit wall rock.

EAST PIT PORE WATER QUALITY - COMPARISON OF SOLUBILITY CAPS

The audit of the East Pit assessed whether the GoldSim model accurately limited pore-water concentrations to the concentration caps presented in NorthMet Project model work plans. The East Pit is a critical component in to the overall NorthMet water management because it is the permanent repository for all of the high-sulfide, acid-generating waste rock (Category 2, 3, and 4). However, the backfilled East Pit is essentially an engineered system and mine plans include an option to lime the pit backfill if necessary to maintain pore waters at near-neutral pH and thus ensure that dissolved pollutant concentrations remain at the concentration caps for neutral pH. This audit thus compared predicted pore water concentrations in the East Pit backfill to the applicable concentration caps (i.e., Category 2, 3, and 4 waste rock under non-acidic conditions) for the 7 evaluated solutes. The evaluation period was mine year 1 through 45, which covers the period when the East Pit is excavated, backfilled with reactive waste rock, and then completely flooded to stop oxidation. Simulated solute concentrations were obtained from the GoldSim model results provided by Barr.

As shown on Figure 1, GoldSim results indicate that the solute concentration caps simulated in the East Pit are consistent with the concentration-cap values specified in Waste Characterization Data Package, v9 (Large Table 13, PolyMet Mining, July 2012).

Figure 1 ***Predicted concentrations of selected solutes in East Pit backfill pore water, and the concentration caps for Cat 2,3,4 rock (non-acidic).***

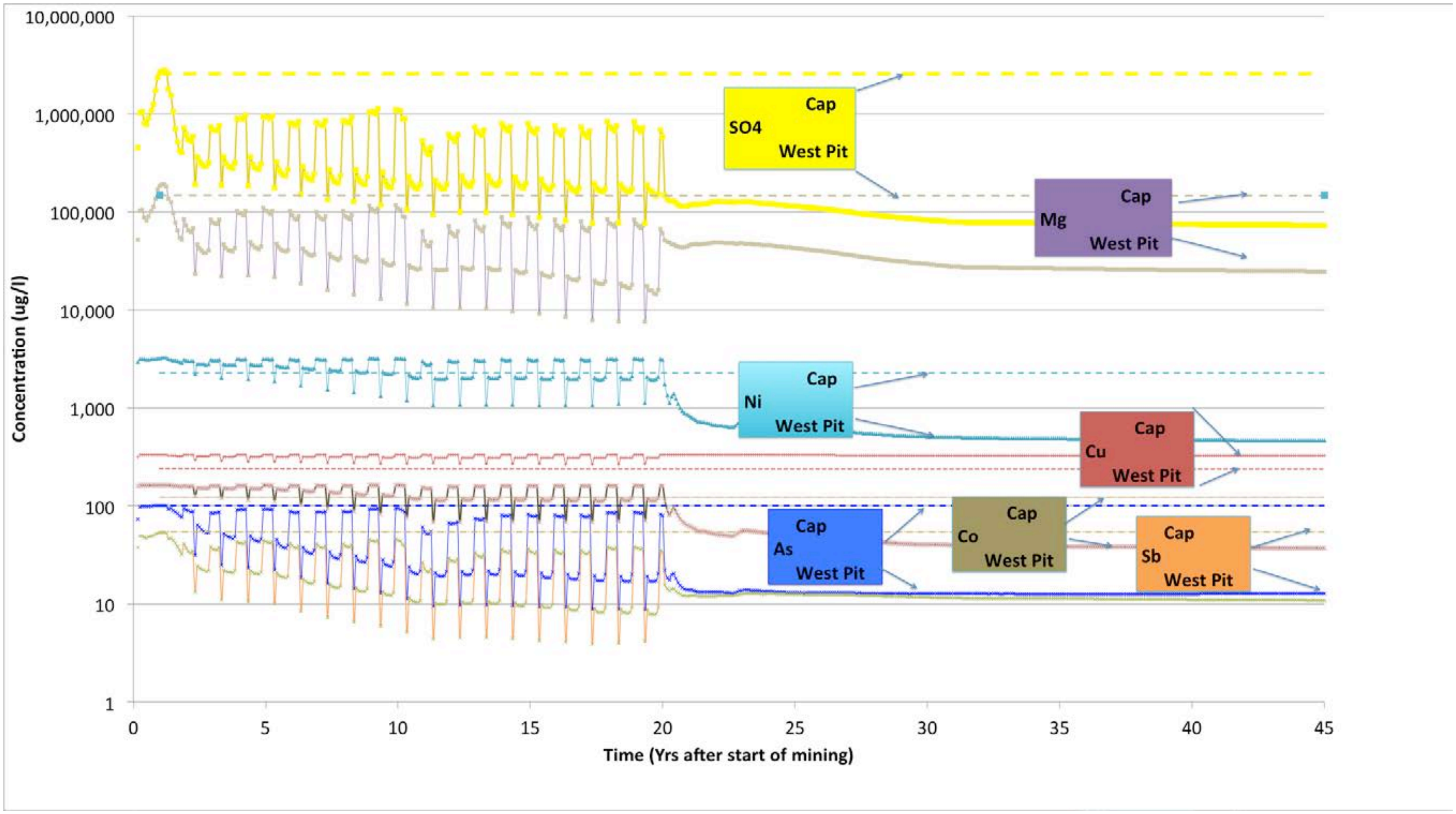


WEST PIT LAKE WATER QUALITY - COMPARISON TO SOLUBILITY CAPS

Water Management Plans for the NorthMet project include contingencies to maintain water in the West Pit at a near-neutral pH so that solute concentrations in the lake will be limited to concentration caps near the values applied for Category 1 rock. In response, this audit compared predicted water quality in the West Pit Lake water to determine whether the GoldSim model accurately limited solute concentrations to the Category 1 thresholds. Predicted solute concentrations in the West Pit (median values) were obtained from model outputs provided by Barr.

Results of this comparison (Figure 2) indicate that GoldSim does limit solute concentrations in the West Pit Lake to the concentration caps identified in Large Table 12 of the Waste Characterization Data Package version 9 (PolyMet, September 2012). The trend for all solutes (except copper) is that concentrations are initially limited by the concentration cap for some period, or at least for part of the year. The concentration cycles apparent between years 1 and 20 reflect seasonal changes in wall-rock runoff and pit volume over the period, when water is assumed to be sumped out to allow excavation. Beyond year 20, the lake begins to fill and concentrations stabilize as seasonal runoff becomes a smaller fraction relative to the increasing volume of the lake. In this period beyond year 20, the concentrations of all solutes tracked in this audit (except copper) drop below their concentration cap level.

Figure 2 Predicted concentrations of select solutes in the West Pit Lake, and their concentration caps.



WEST PIT LAKE - SOLUTE LOADING FROM WALL ROCK

The GoldSim model of the West Pit water quality predicts that the oxidation in the wall rock will be a major source of solutes to the West Pit Lake. In response, the 2012 audit of the GoldSim Mine Site Model version 3 included an independent calculation of loading to the lake from two wall-rock zones: (1) Cat 4 Duluth Complex Wall rock, which is predicted to be a minor source of metals (included in the audit to confirm that it was in fact a minor contributor of pollutants) and (2) the ore wall rock, which is predicted to be the dominant source of nickel, cobalt, and copper to the West Pit Lake. The audit of wall-rock loading incorporated 13 parameters, with the most important for chemical solute release being intrinsic oxidation rate in wall rock, the effects of temperature and fragment size on oxidation rate, and the change in oxidation rate that occurs when the pore waters shift from neutral to acidic conditions. The independent calculations used to audit the version 3 GoldSim model reproduced the loading of the 6 audit solutes from the two wall-rock units during both the excavation phase (mine year 1 to 20), when the pit is assumed to be open and solutes leached from wall rock are capture in a sump, and the filling phase (mine years 20 to 45), when loads to the lake also includes dissolution of solutes previously stored in the wall rock (Table 1). The only discrepancy larger than ~5% was in copper loading, a discrepancy caused by the omission of concentration-cap effects in the audit. Note that copper is predicted to be at its concentration cap in the West Pit Lake over the entire 45-year filling period, which limits the load of copper from wall rock runoff (Figure 2).

Table 1 Cumulative Loads to West Pit from Ore in Wall Rock at Year 20, GoldSim Model v 3 and 4.1

Constituent	Model v 3 GoldSim [tonne]	Model v 3 Audit [tonne]	Model v 3 Discrepancy Rel. % Diff. [%]	Model v 4.1 GoldSim [tonne]	Change in Model Result GoldSim v3 to v4.1 Rel. % Diff. [%]
Sulfate	355	361	1.69%	317	-11%
Cobalt	1.41	1.43	1.67%	1.02	-32%
Arsenic	0.109	0.111	1.67%	0.097	-12%
Magnesium	36.4	37.1	1.80%	31.6	-14%
Nickel	18.3	18.6	1.67%	14.3	-24%
Antimony	0.040	0.041	1.67%	0.034	-16%
Copper	21.8	60.7	94.30%	19.6	-11%

This review of the version 4.1 NorthMet model compared cumulative load from the ore wall rock (the main wall-rock source of metals and sulfate to the West Pit during excavation and filling) through year 20. The 1-20 year time interval was selected because it incorporates the important physical parameters: pit geometry and the areas of lithologic units in pit wall rock, plus the effects of temperature, fragment size, and pit-wall sulfide S concentration on chemical reaction rates. The loading during lake filling (years 20 to 45) was not considered in this screening audit to avoid the additional complexity that arises when the estimates of cumulative loads vary more in response to water balance changes that affect the fill rate of the West Pit.

The results of this comparison indicate that the estimates of cumulative wall-rock loading to the West Pit in GoldSim model version 4.1 is similar to the loads estimated in model version 3 (Table 1). The cumulative loads are systematically lower in version 4.1 than were predicted in version 3 (relative percent difference in cumulative loading from ore wall-rock between Mine Site model version 3 and version 4.1 ranged from -11 and -32 percent). The cause of this discrepancy is not clear, because the pit geometry should be unchanged and at the selected evaluation time (year 20), the effects of West Pit filling have not begun. However, these discrepancies are much lower than the uncertainty range indicated by the model (e.g., the cumulative loads at year 20 for the 7 solutes considered in this audit ranged by several hundred percent or more between the 10th and 90th percentile model result). Additional refinement of the audit of pollutant loads to the West Pit would involve updating the independent audit values will all GoldSim values for wall-rock geometry and chemistry, and extending the audit period through pit filling (year 45) under the revised water balance assumptions included in Model version 4.1.

ATTACHMENT 2: MINE SITE AUDIT – GOLDSIM ESTIMATES OF GROUNDWATER TRANSPORT

INTRODUCTION

This attachment documents a strategic audit of the Mine Site GoldSim model (version 4.1) with regard to chemical migration in groundwater flowpaths that transport solutes from project-related chemical sources to the Partridge River. Emphasis was placed on the West Pit Surficial Flowpath and the East Pit Cat 2/3 Surficial Flowpath, because these flowpaths within the surficial groundwater aquifer connect long-term chemical sources (West Pit and East Pit) to the Partridge River. Other surficial flowpaths (OSLA, WWTP, and OSP) were not analyzed because they are tied to temporary chemical sources and use the same model algorithms for chemical transport. Bedrock flowpaths were not considered because hand calculations show that chemical migration in these flowpaths has negligible impact on water quality in the Partridge River. GoldSim results were compared to independent calculations of chemical transport for sulfate, cobalt, and aluminum. These nonreactive solutes were chosen because their source concentrations are significantly different from background concentrations, their transport behavior should be similar to other nonreactive solutes in the model, and they serve as good tracers for evaluating chemical migration.

METHODS

The Mine Site GoldSim model has been programmed by Barr to generate extensive Excel spreadsheets of the model results on a time step by time step basis. Separate spreadsheets are generated for ten Control Volumes that divide the Mine Site into hydraulic subcomponents. Each time the model is run, the outputs are generated for one chemical solute specified by the user. For each Control Volume, a separate spreadsheet documents the water balance (inflows, outflows, and internal water storage) and chemical mass balance (inflow concentrations, outflow concentrations, and concentrations of stored water).

The GoldSim model has been programmed to develop a separate Control Volume (and output spreadsheet) for the West Pit Flowpath and East Pit Cat 2/3 Flowpath. To generate the output required for this evaluation, three deterministic (P50 input) model runs were performed by the ERM team, with outputs specified for sulfate, cobalt, and aluminum. This provided a total of six output spreadsheets; three spreadsheets (sulfate, cobalt, and aluminum) for the West Pit Flowpath and three similar spreadsheets for the East Pit Cat 2/3 Flowpath. With regard to flow, the general approach was to compile the GoldSim water balance for each flowpath and compare the numerical values with independent hand calculations. For chemical transport, the GoldSim estimates of chemical migration were compared to hand calculations of sharp-front chemical arrival times at the Partridge River and peak concentrations of groundwater discharge to the river.

RESULTS

Figures 1 and 2 show the GoldSim water balance for the West Pit Flowpath and East Pit Cat 2/3 Flowpath, respectively. There is no temporal change in the internal water storage of each flowpath, so the water balance simplifies to:

> Inflow entering flowpath at upgradient boundary + recharge along flowpath = groundwater discharge to Partridge River

Figure 1

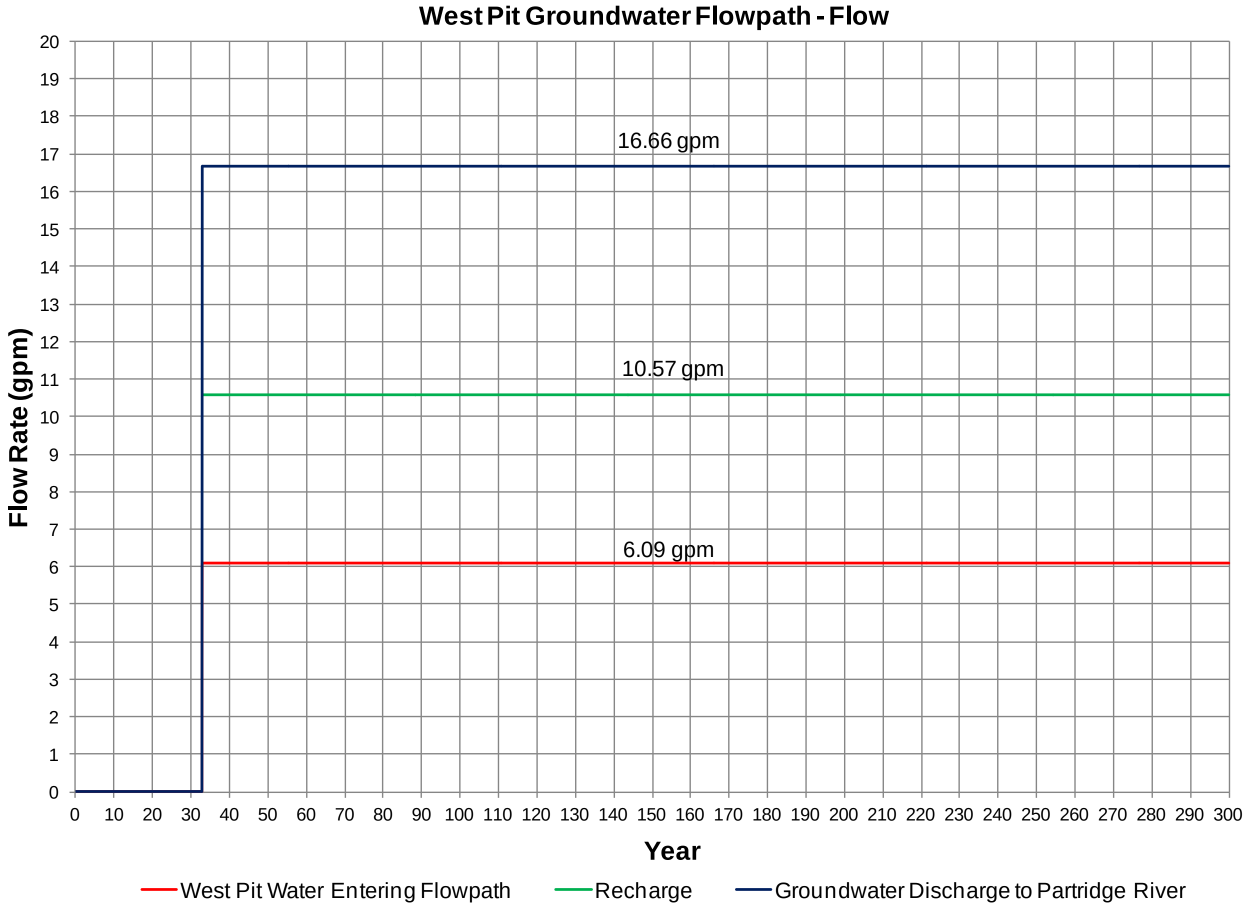
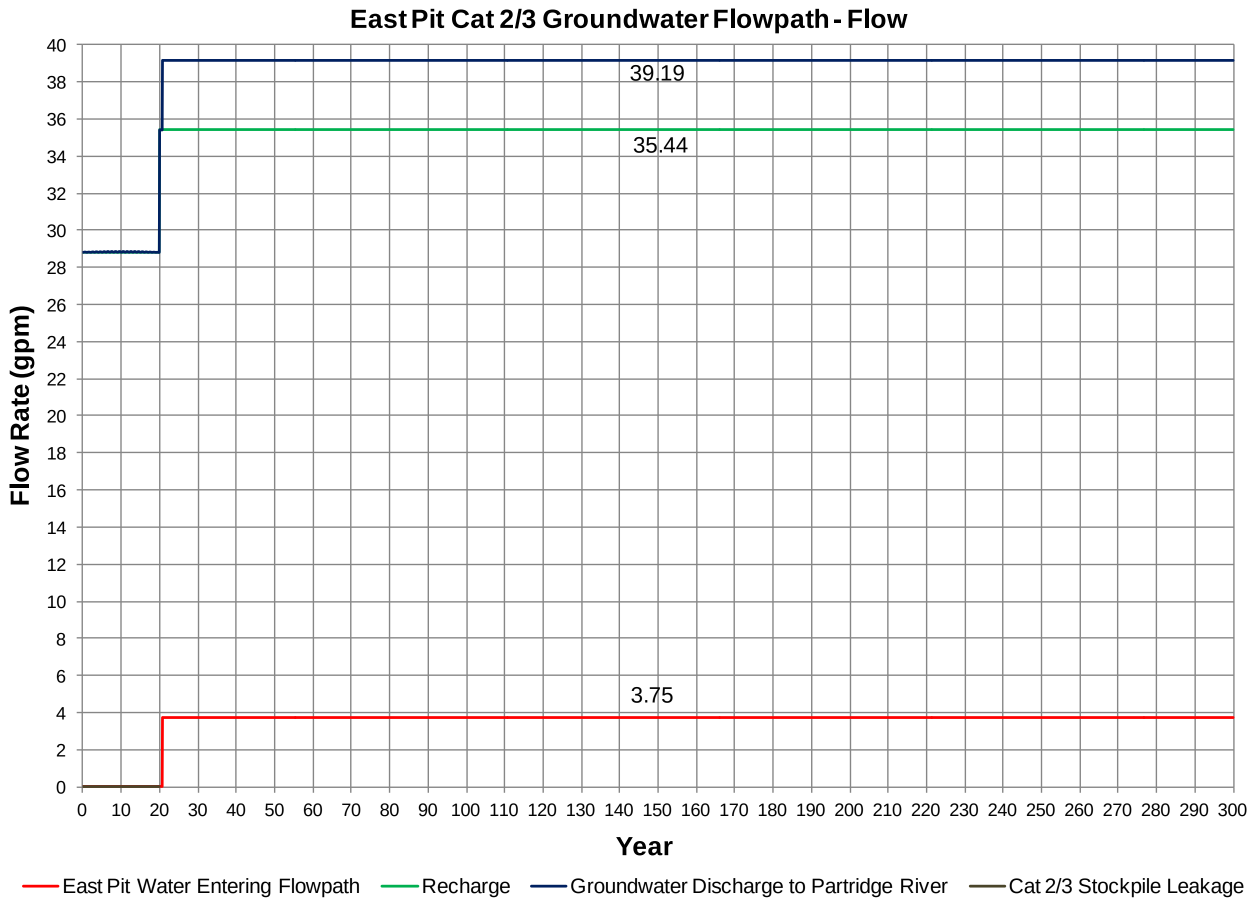


Figure 2



Figures 1 and 2 show that the GoldSim model conserves the flow balance for each flowpath. For the two selected flowpaths, Table 1 shows very good agreement between the GoldSim water balance results and independent hand calculations.

Table 1 Mine Site Flowpath Water Balance

		Flowpath				
Description	**Units**	**West Pit**	**OSLA**	**WWTP**	**OSP**	**East Pit - Cat 2/3**
Flow rate entering flowpath	gpm	6.09	2.62	0.83	1.14	3.75
Net meteoric recharge rate	in/yr	0.828	0.993	0.647	0.902	0.910
Flowpath width	m	665	550	240	430	1440
Flowpath total length	m	1505	1600	1730	1415	2120
Recharge	gpm	10.58	11.16	3.43	7.01	35.47
Computed groundwater discharge to surface water	gpm	16.67	13.78	4.26	8.15	39.22
GoldSim groundwater discharge to surface water	gpm	16.66				39.19

Figures 3, 4, and 5 pertain to the West Pit Flowpath and show GoldSim inflow (chemical source) concentrations and outflow (groundwater discharge) concentrations for sulfate, cobalt, and aluminum, respectively. On each plot, the groundwater discharge concentration shows the GoldSim-predicted arrival of a chemical plume at the Partridge River. For sulfate and cobalt, the plume arrival is shown as an increase in discharge concentration because the source (West Pit) concentration is higher than the background groundwater concentration. For aluminum, the plume arrival is indicated by a decrease in discharge concentration because the source concentration is lower than background. Due to longitudinal dispersion, the GoldSim plume arrival is gradual over a period of about thirty years and the effective arrival time of 105 years is taken as the midpoint of the initial change in discharge concentration. Table 2 shows a comparison between the GoldSim-predicted arrival time and an independent (sharp-front) hand calculation based on the following equation that accounts for the effect of recharge on groundwater seepage velocity:

$$\mathrm{t_a(x) = t_s + \frac{b\,n}{R} \ln\left(1 + \frac{R\,w\,x}{Q_o}\right)}$$

where:

t_a = chemical (sharp-front) arrival time
x = distance from chemical source to location of interest (Partridge River)
t_s = chemical source start-up time
b = flowpath saturated thickness
w = flowpath width
n = effective porosity
R = recharge flux
Q_o = groundwater flow rate at the chemical source

Figure 3

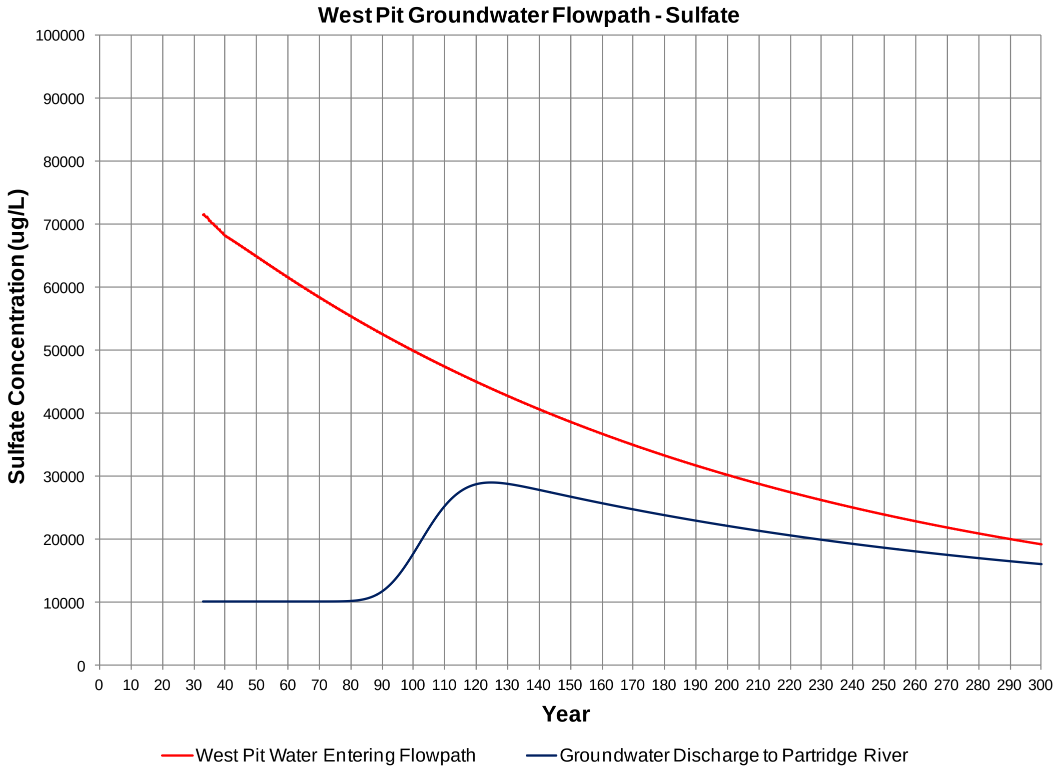


Figure 4

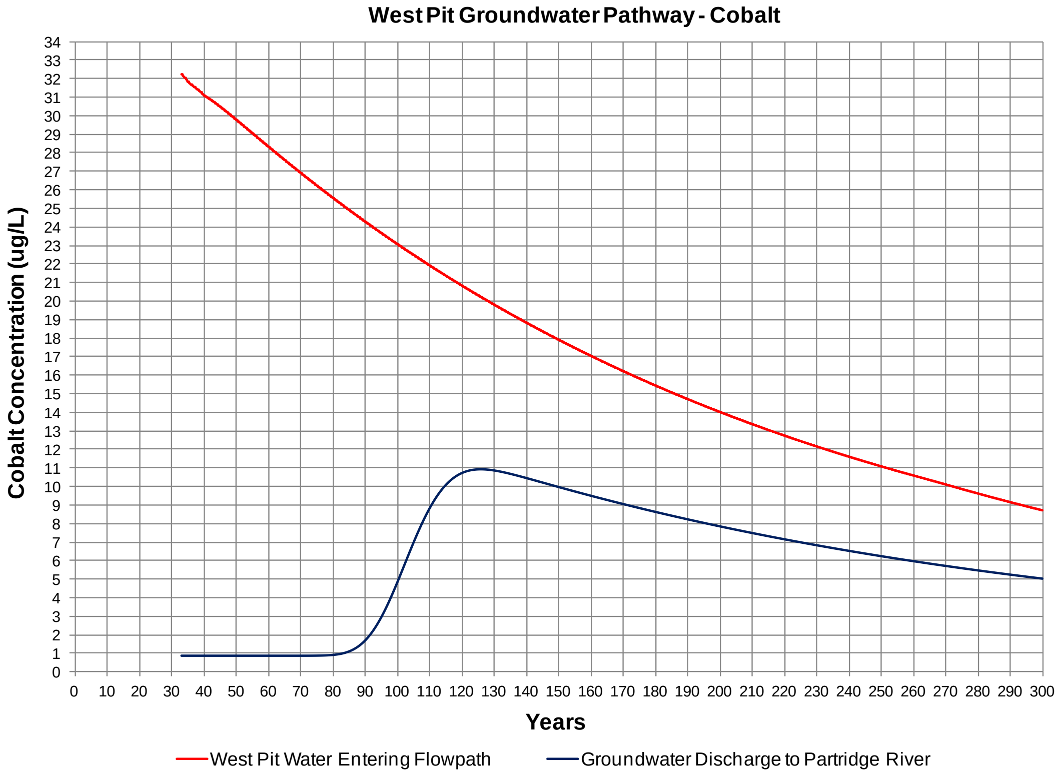
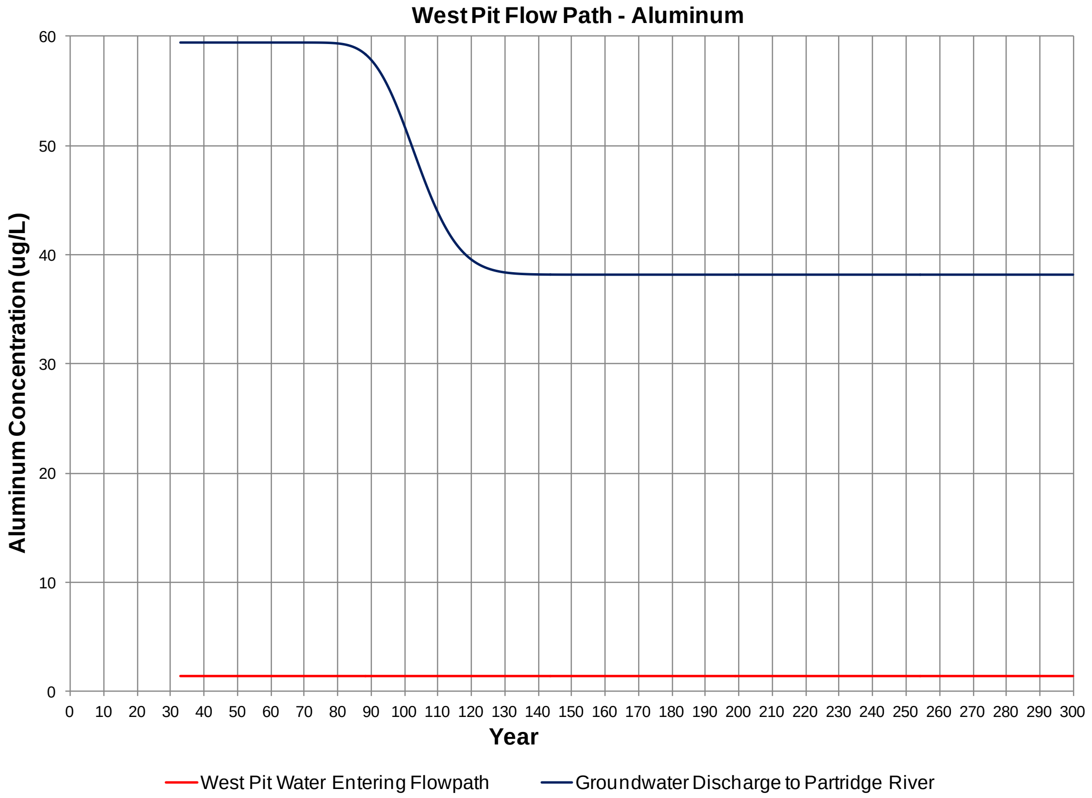


Figure 5



As shown in Table 2, there is very good agreement between the GoldSim arrival time and the independent calculation for the West Pit Flowpath (105 years).

Table 2 Chemical Arrival Time

Description	**Units**	**Flowpath**					
		West Pit	**OSLA**	**WWTP**	**OSP**	**Cat 2/3**	**East Pit**
Groundwater flow rate at chemical source	gpm	6.09	2.62	0.83	1.14	23.31	3.75
Net meteoric recharge rate	in/yr	0.828	0.993	0.647	0.902	0.910	0.910
Flowpath width	m	665	550	240	430	1440	1440
Flowpath thickness	m	5	5	5	5	5	5
Aquifer porosity	(--)	0.30	0.30	0.30	0.30	0.30	0.30
Distance from chemical source to mine property boundary (groundwater compliance point)	m	860	235	910	1085	140	1345
Distance from chemical source to Partridge River (surface water discharge)	m	1505	1225	1310	1185	955	2120
Groundwater travel time from chemical source to mine property boundary	yr	49	29	105	114	6	126
Groundwater travel time from chemical source to Partridge River	yr	72	86	129	119	34	152
Chemical source begin time	yr	33	0	0	0	0	21
Chemical source end time	yr	Contin-uous	20	35	21	20	Contin-uous
Sharp front chemical arrival time at property boundary (based on chemical source begin time)	yr	82	29	105	114	6	147
Computed sharp front chemical arrival time at the Partridge River (based on chemical source begin time)	yr	105	86	129	119	34	173
GoldSim sharp front chemical arrival time at the Partridge River (based on chemical source begin time)	yr	105				48	148

Figures 6 through 11 pertain to the East Pit Cat 2/3 Flowpath and show GoldSim inflow and discharge concentrations for the three solutes on interest. Due to concentration contrasts, separate plots are shown for source concentrations and discharge concentrations. Note that the flowpath is affected by two chemical sources that are at different locations and operate at different times; Cat 2/3 leakage from zero to 20 years followed by East Pit inflow after 20 years. As a consequence, GoldSim predicts the arrival of two chemical plumes at the Partridge River. The first arrival at 48 years results from Cat 2/3 stockpile leakage, and the second at 148 years is associated with East Pit inflow to the flowpath. Table 2 provides a comparison between these GoldSim arrival times and independent hand calculations based on the above equation. The values are similar, but in general the GoldSim arrival times are 16 to 34 percent longer than the hand-calculated arrival times. Given the excellent agreement for the West Pit Flowpath, it would be valuable to understand the discrepancy between the GoldSim and hand-calculated arrival times. However, the discrepancy for the East Pit Cat 2/3 Flowpath is not considered large enough to question the GoldSim results.

Figure 6

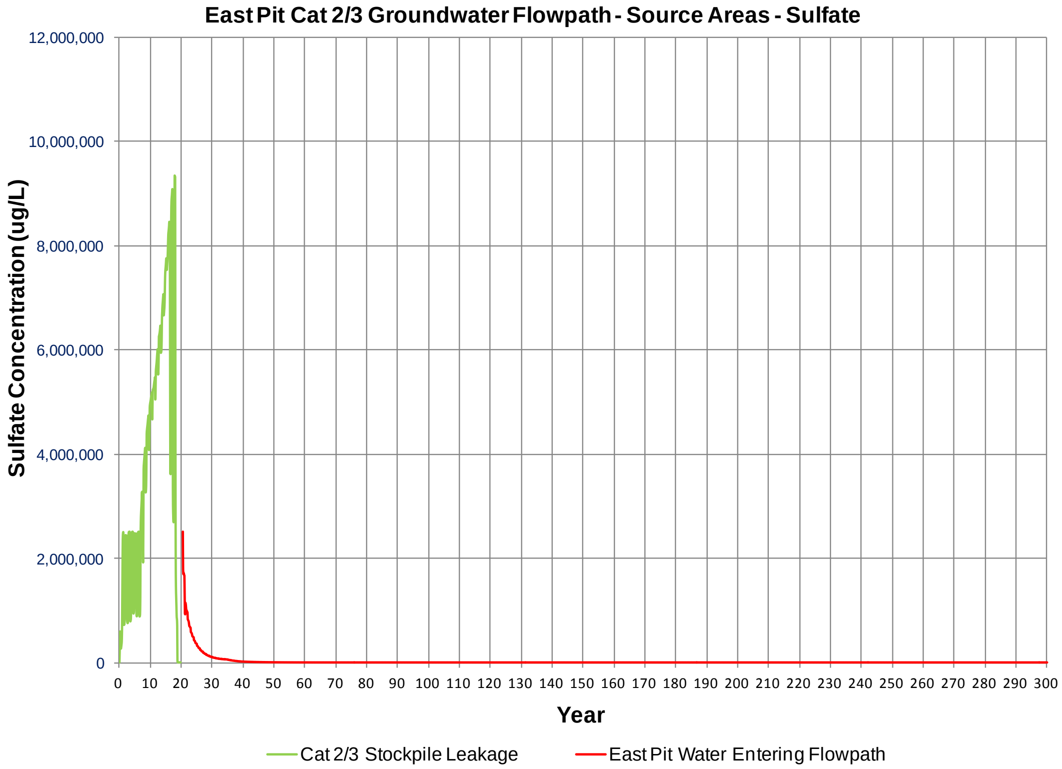


Figure 7

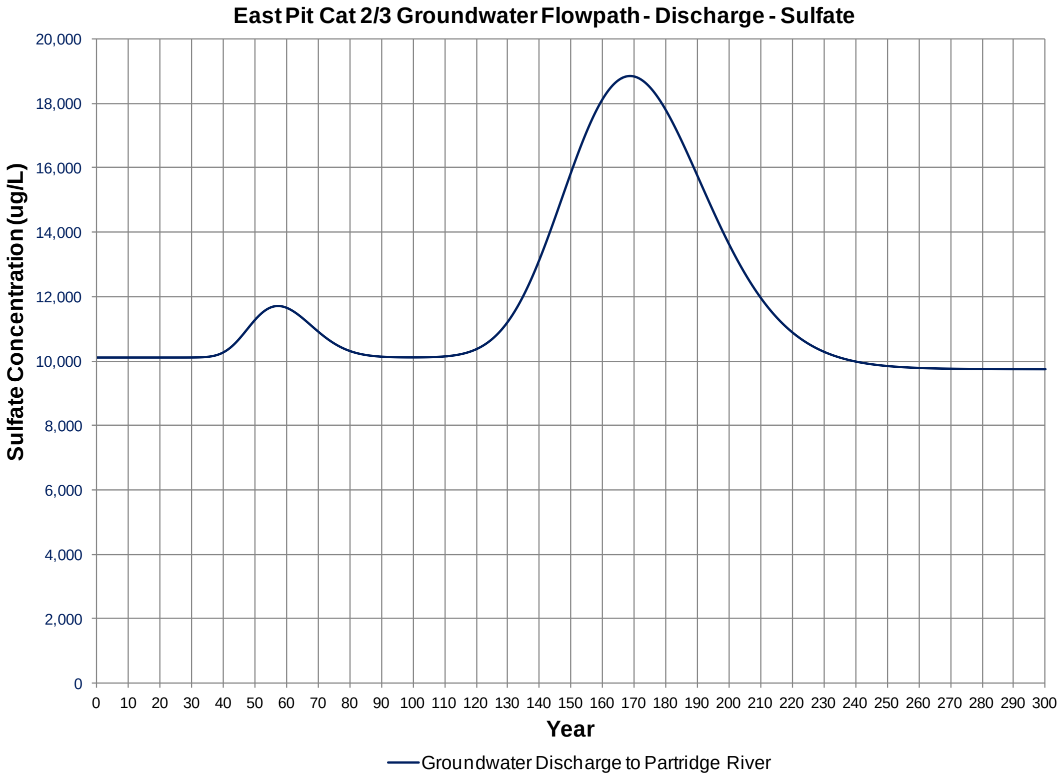


Figure 8

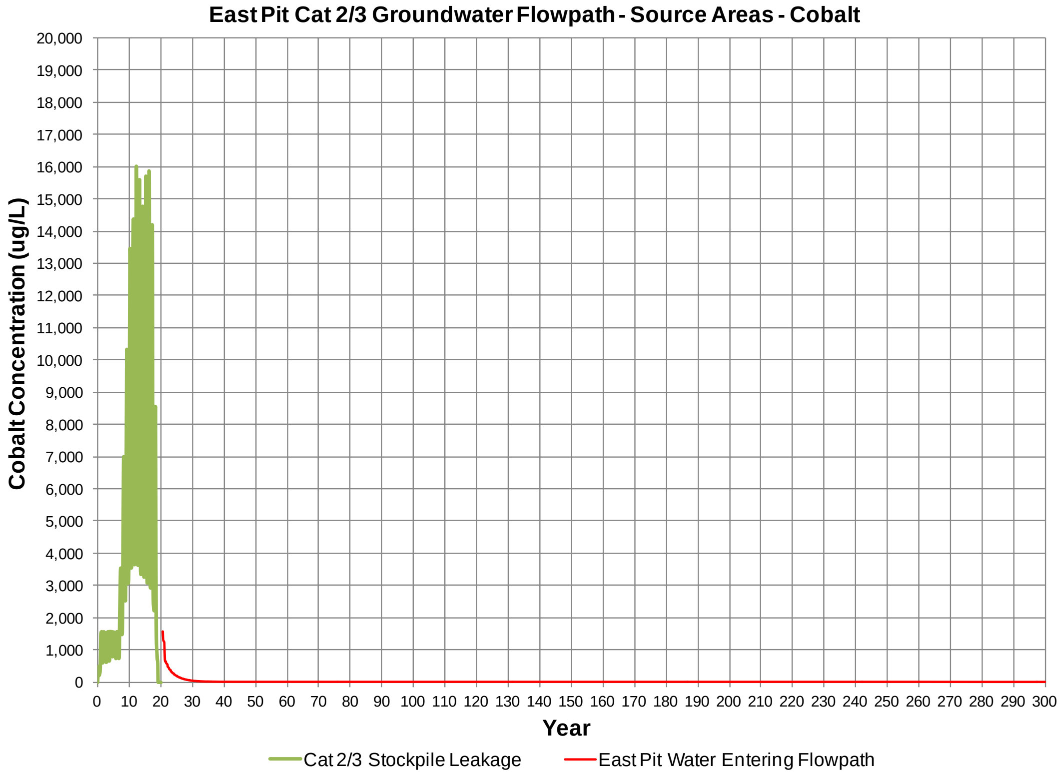


Figure 9

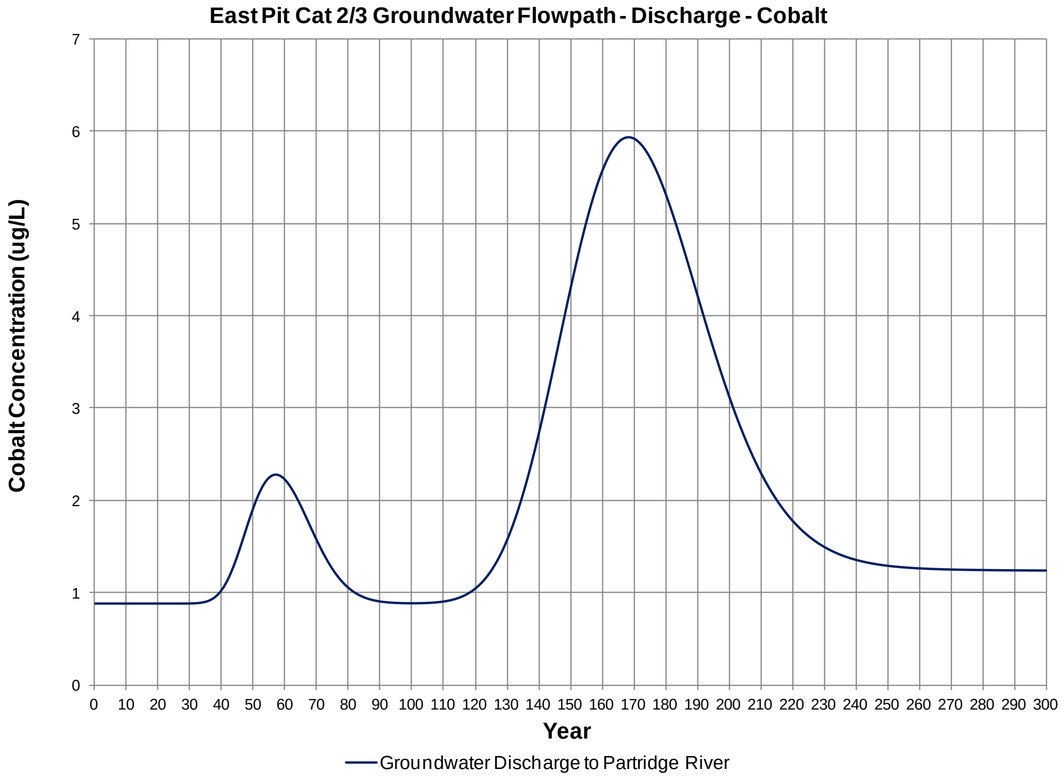


Figure 10

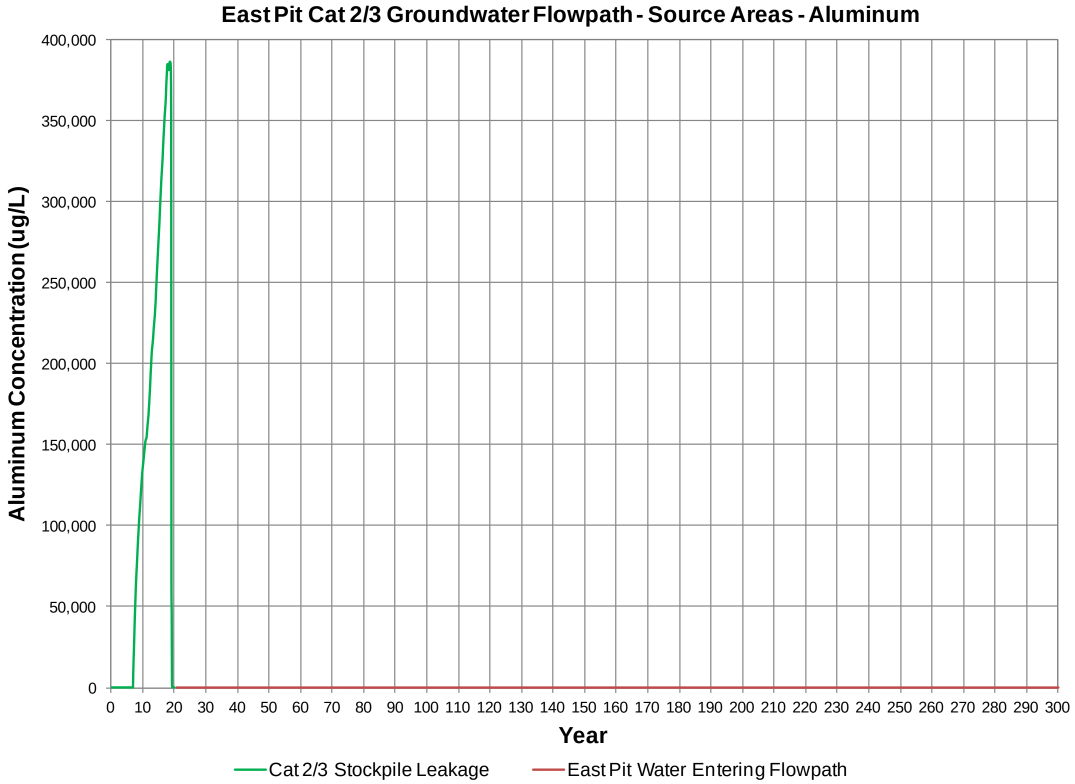
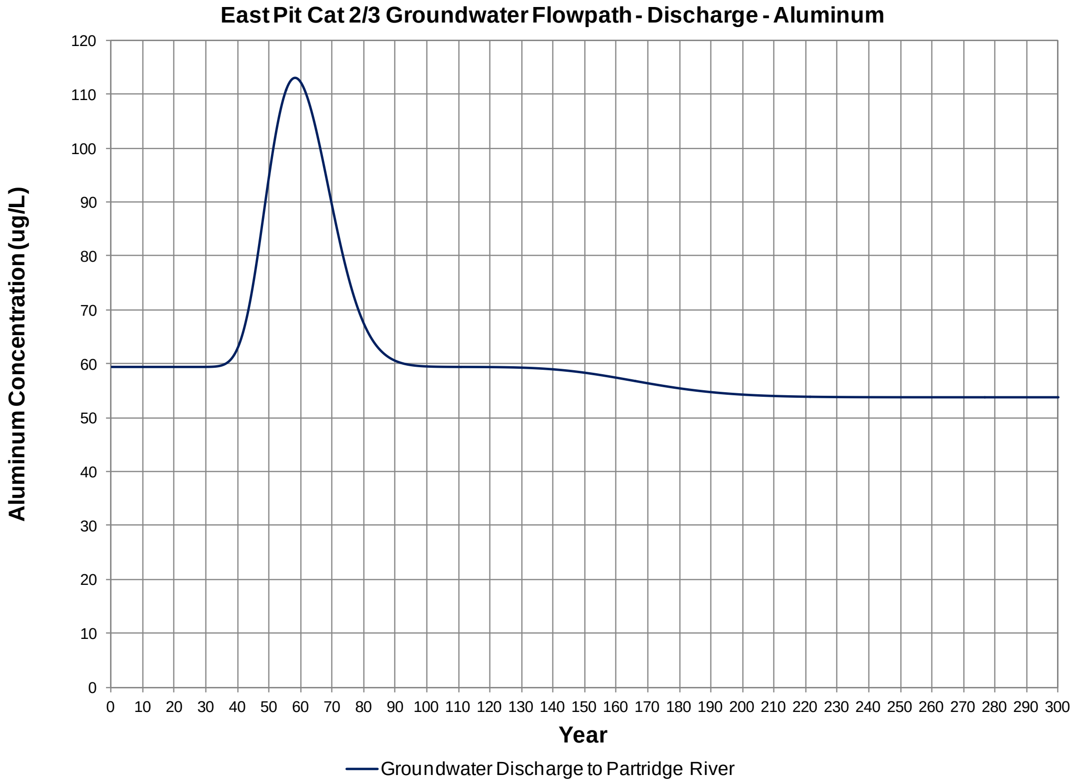


Figure 11



As shown in Table 3, an additional check was performed using independent mixing calculations to estimate the peak concentrations of groundwater discharging into the Partridge River. These calculations consider the arrival of plumes from three chemical sources; West Pit (via the West Pit Flowpath), and Cat 2/3 and East Pit (via the East Pit Cat 2/3 Flowpath). The calculated peak concentration is considered approximate because it assumes a constant source concentration that generally differs from the time-varying source concentrations simulated in the GoldSim model. To perform the hand calculations, it was generally assumed that the source concentration was equal to the average GoldSim source concentration over the first twenty years that the source is active. As shown, there is good agreement between the independently computed peak concentrations and peak or long-term concentrations observed on plots of the GoldSim results (Figures 2, 3, and 4 for the West Pit Flowpath and Figures 7, 9, and 11 for the East Pit Cat 2/3 Flowpath). The only significant discrepancy is the cobalt plume associated with the East Pit chemical source, for which the GoldSim concentration of 5.95 ug/L is less than the calculated value of 15.15 ug/L. As shown on Figure 8, the GoldSim East Pit cobalt concentration decreases dramatically during its initial period as an active source (20 to 40 years), and this likely limits the accuracy of the hand calculation. Overall, the independent mixing calculations support the GoldSim results.

Table 3 *Peak Concentration in Groundwater Discharge to the Partridge River*

Source Area	**Constituent**	**Source Flowrate gpm**	**Source Conc ug/L**	**Recharge Flowrate gpm**	**Recharge Conc ug/L**	**Discharge Flowrate gpm**	**Computed Peak Discharge Conc ug/L**	**GoldSim Peak Discharge Conc ug/L**
West Pit	Sulfate	6.09	65,000	10.58	10,125	16.67	30,172	29,500
	Cobalt	6.09	30.0	10.58	0.882	16.67	11.5	11.0
	Aluminum	6.09	1.5	10.58	59.4	16.67	38.2	38.5
Cat 2/3	Sulfate	0.0193	3,800,000	39.17	10,125	39.19	11,991	11,725
	Cobalt	0.0193	4,200	39.17	0.882	39.19	2.9	2.2
	Aluminum	0.0193	133,000	39.17	59.4	39.19	125	112
East Pit	Sulfate	3.75	1,100,000	35.44	10,125	39.19	114,413	118,800
	Cobalt	3.75	150	35.44	0.882	39.19	15.15	5.95
	Aluminum	3.75	0.5	35.44	59.4	39.19	53.8	54.0

CONCLUSIONS

This audit of groundwater transport simulations performed by the Mine Site GoldSim model is “strategic” in that only two flowpaths and three chemical constituents are considered. However, the selected flowpaths (West Pit and East Pit Cat 2/3) are the most important with regard to long-term impacts to the Partridge River and the selected solutes are reasonable surrogates for other chemical constituents in groundwater and surface water. This evaluation does not raise any major concerns regarding algorithms in the Mine Site GoldSim model that are used to simulate chemical migration in the surficial groundwater aquifer.

ATTACHMENT 3: MINE SITE AUDIT - GOLDSIM ESTIMATES OF PARTRIDGE RIVER WATER QUALITY

INTRODUCTION

This attachment performs independent calculations of sulfate, aluminum, and cobalt river concentrations for a selected time and location in the Partridge River, and compares these values with analogous results from the Mine Site GoldSim model. The location selected for analysis was SW-004a. The selected approach was not expected to produce results exactly equivalent to the GoldSim outputs, but rather to determine if a simplified, alternative process of estimating Project impacts would produce estimates of Partridge River Project water quality that are reasonably similar to the GoldSim outputs.

METHODS

With regard to the Project, there are six groundwater-related chemical inputs to the Partridge River at SW-004a: (1) East Pit, (2) Cat 2/3 Stockpile, (3) OSP, (4) WWTP pond, (5) OSLA, and (6) West Pit. Via migration in five groundwater surficial flowpaths, the chemical effects from each of these sources reaches the river at different times, ranging from about 30 years for the Cat 2/3 Stockpile to about 170 years for the East Pit. In addition, effluent from the WWTP (meeting all water quality standards) is discharged to the Partridge River starting at about year 36. The target time for this evaluation (mine year 159.58) was arbitrarily selected with the intent of including some input from most of the mine-related chemical sources. This year, however, was not intended to represent a time when maximum Project impacts are expected.

Based on a deterministic run of the Mine Site GoldSim model (version 4.1) using P50 inputs, background streamflow at SW-004a was determined by reducing the river flow rate at year 159.58 by the sum of flowpath discharge rates for the same year. Background Partridge River water quality (concentration) was taken from Barr's No Action average P50 estimate for each constituent for year 159.58. Project flows and associated water quality for each of the groundwater sources and the WWTP effluent at year 159.58 were taken from output spreadsheets generated by Mine Site GoldSim model. The estimate of Partridge River Project water quality at SW004a for each constituent was estimated by a simple mixing calculation that considered background chemical load (upstream river flow multiplied by concentration) and each of the Project source loads (source flows multiplied by concentrations) and dividing by the sum of background and source-related flow rates. Note that in GoldSim, the flows and concentrations for the Cat 2/3 stockpile and East Pit are mathematically combined because they both enter the same groundwater flowpath.

RESULTS

The calculation of Project water quality at SW-004a includes some input from all six groundwater sources plus the WWTP effluent. As shown in Table 1, the independently calculated sulfate concentration at SW-004a (9,637 µg/L) is very close to the GoldSim estimate (9,531 ug/L) based on a deterministic model run using P50 inputs. Table 2 provides a similar comparison for aluminum, for which there is close agreement between the independently computed value of 63.45 µg/L and the GoldSim estimate of 60.36 µg/L. For cobalt (Table 3), the comparison is also favorable, with a computed concentration of 0.66 µg/L versus the Goldsim estimate of 0.55 µg/L.

Table 1 Estimated Partridge River Project Sulfate Water Quality at SW-004a

	NON-PROJECT FLOW[1]			PROJECT FLOWS[2]				MIXED FLOWS[3]
	Q, cfs	**Conc, µg/L**	**Relative Load, Q x Conc**	**Source**	**Q, cfs**	**Conc, µg/L**	**Relative Load, Q x Conc**	**Total Load/Total Q vs Project ave P50, µg/L**
$S0_4$	25.23	9,598	242,158	WWTF, Eff	0.635	9000	5,715	
				W. Pit gw	0.0371	23,867	885.47	
				E. Pit/2/3	0.0873	18,661	1629.11	
				OSP	0.0156	10,309	160.82	
				WWTF,gw	0.0076	10,675	81.13	
				OSLA	0.0248	12,919	320.39	
					0.807		8,791.92	25,095/26.04 = 9,637 vs 9,531

[1] Source: SW_Flows and SW_Conc Timeseries Spreadsheets, Barr, Dec2012, No Action
[2] Source: MineSite_CV Spreadsheets, Barr 2012
[3] Source: SW_Concs_Timeseries_MineSite.xlsm, Barr, Dec2012

Table 2 Estimated Partridge River Project Aluminum Water Quality at SW-004a

	NON-PROJECT FLOW[1]			PROJECT FLOWS[2]				MIXED FLOWS[3]
	Q, cfs	**Conc, µg/L**	**Relative Load, Q x Conc**	**Source**	**Q, cfs**	**Conc, µg/L**	**Relative Load, Q x Conc**	**Total Load/Total Q vs Project ave P50, µg/L**
Al	25.23	65.07	1641.7	WWTF, Eff	0.635	1.41	0.895	
				W. Pit gw	0.0371	38.18	1.416	
				E. Pit/2/3	0.0873	57.35	5.007	
				OSP	0.0156	65.84	1.027	
				WWTF,gw	0.0076	76.19	0.581	
				OSLA	0.0248	65.84	1.633	
					0.807		10.56	1652.26/26.04 = 63.45 vs 60.36

[1] Source: SW_Flows and SW_Conc Timeseries Spreadsheets, Barr, Dec2012, No Action
[2] Source: MineSite_CV Spreadsheets, Barr 2012
[3] Source: SW_Concs_Timeseries_MineSite.xlsm, Barr, Dec2012

Table 3 Estimated Partridge River Project Cobalt Water Quality at SW-004a

	NON-PROJECT FLOW[1]			PROJECT FLOWS[2]				MIXED FLOWS[3]
	Q, cfs	**Conc, µg/L**	**Relative Load, Q x Conc**	**Source**	**Q, cfs**	**Conc, µg/L**	**Relative Load, Q x Conc**	**Total Load/Total Q vs Project ave P50, µg/L**
Co	25.23	0.395	9.966	WWTF, Eff	0.635	5.0	3.175	
				W. Pit gw	0.0371	8.64	0.321	
				E. Pit/2/3	0.0873	7.66	0.669	
				OSP	0.0156	1.43	0.022	
				WWTF,gw	0.0076	1.52	0.012	
				OSLA	0.0248	0.859	0.021	
					0.807		3.551	17.07/26.04 = 0.66 vs 0.55

[1] Source: SW_Flows and SW_Conc Timeseries Spreadsheets, Barr, Dec2012, No Action

[2] Source: MineSite_CV Spreadsheets, Barr 2012

[3] Source: SW_Concs_Timeseries_MineSite.xlsm, Barr, Dec2012

CONCLUSION

With regard to river concentrations for three solutes, the independent calculations reasonably reproduce the GoldSim model outputs at location SW-004a for the selected year. This evaluation provides good evidence that the GoldSim model adequately accounts for Project-related chemical inputs to the Partridge River and correctly computes river concentrations using simple mixing.

Appendix C
Project Plant Site Audit (v5) - Goldsim Water-Quality Model

APPENDIX C: PROJECT PLANT SITE AUDIT (V5) - GOLDSIM WATER-QUALITY MODEL

INTRODUCTION

This technical memorandum describes an audit of the version 5 (v5) NorthMet Project Plant Site GoldSim water-quality model that was run during February 2013. This model for the Plant Site was developed by Barr Engineering Company (Barr) to estimate potential environmental effects from the proposed mine on the quality and quantity of water resources. This audit has been conducted by members of the ERM Project Team to provide technical support to the State of Minnesota in preparation of the NorthMet Project Supplemental Draft Environmental Impact Statement (SDEIS).

Previously, the ERM Team conducted an audit of the version 3 (v3) GoldSim model that was run during September 2012. Results of the v3 audit were summarized in an ERM memorandum dated October 30, 2012 (Appendix A this report). The October 2012 audit was not a 100-percent verification of model calculations, but instead focused on evaluating select model components that are critical in the estimates of solute release/transport. This update provides a supplementary audit of additional model components at the Plant Site that were not evaluated previously or have changed due to modified inputs or GoldSim programming. The most important model changes that were made in going from v3 to v5 are the following:

- Revised chemical concentrations in the WWTP effluent based on pilot testing.
- Revised calibration factors for release of sulfate from fine and coarse LTVSMC tailings to provide consistency with previously agreed upon vanGenuchten parameters (CDF055).
- New GoldSim programming that effectively increases the flow rate of tailings-impacted groundwater that by-passes the containment system and enters surficial groundwater flow paths (CDF061)
- Using water from Colby Lake to augment streamflow in tributaries to the Embarrass River (CDF069 and CDF062).
- Modified watershed areas (CDF051).

It was confirmed during this audit that these model changes were appropriately incorporated into the v5 GoldSim model and the changes did not raise any QA concerns.

For this QA update, the following specific evaluations were performed using a deterministic run of the v5 GoldSim model with P50 inputs:

- Re-evaluation of chemical release from subareas of the Flotation Tailings Basin (FTB).
- Evaluation of containment system bypass and associated chemical migration in groundwater surficial pathways.
- Evaluation of chemical loading to the Embarrass River caused by discharge of WWTP effluent and Colby Lake augmentation water.

Each of these evaluations is described in subsequent sections of this memorandum.

Overall, the results of this audit provide good evidence that the v5 Plant Site GoldSim model has appropriate and mathematically correct algorithms for (1) estimating flows and chemical concentrations of impacted water leaving the TFB, (2) simulating chemical migration in the surficial groundwater flowpaths, and (3) estimating Embarrass River chemical concentrations by mixing of background and human-affected water sources to the river.

EVALUATION 1 – FTB CHEMICAL SOURCES

In the October 2012 memorandum, a comprehensive set of Mathcad worksheets and Excel spreadsheets were used to independently compute the flows and concentrations of sulfate and copper generated by subareas of the FTB. These calculations were based on v3 calibration factors for fine and course LTVSMC tailings, which were changed in v5 to be consistent with new vanGenuchten parameters presented in CDF055. The calibration factors, documented in Table 1-1 (sheet 5), of the current Plant Site Work Plan, are as follows:

- Input name: “Coarse_Calibration_Fact” v3 value = 0.181 v5 value = 0.151
- Input name: “ Fine_Calibration_Fact” v3 value = 0.360 v5 value = 0.207

This evaluation performed essentially the same calculations, but incorporated the new v5 calibration values. In addition, the trace metal of interest was changed from copper to lead because previous runs of the model showed that the FTB will release lead concentrations that are significantly higher than groundwater background concentrations.

The results of this evaluation for lead are summarized in Table 1. Using flow distributions specified in the GoldSim inputs, mixing calculations were used to compute the post-closure lead concentration in FTB seepage reporting to each of the four FTB toes (see “Independently computed concentration”). For comparison, the analogous post-closure lead concentration at each toe was extracted from the GoldSim output files (see “GoldSim concentration”). Figure 1 is an example of the GoldSim output for lead concentration in seepage reporting to the North Toe, which for long-term post closure conditions has a concentration of about 17 μg/L. As shown in Table 1, there is very good agreement between the independently computed lead concentrations and the analogous concentrations generated by the GoldSim model.

Table 2 is a similar summary of independent calculations performed for sulfate. As shown, there is very good agreement between the independently computed values and the GoldSim estimates.

This evaluation provides good evidence that the GoldSim Plant Site model correctly computes flow rates and chemical concentrations in seepage water reaching the toes of the FTB.

EVALUATION 2 – CONTAINMENT SYSTEM BY-PASS AND GROUNDWATER TRANSPORT

In CDF061, a revised method was presented for estimating the groundwater flow rate approaching different segments of the FTB containment system and the associated bypass that would enter the upgradient end of each adjacent groundwater surficial flowpath. The upper portion of Table 3 summarizes independent calculations of the by-pass flow rate for each flowpath (north, northwest, and west) and compares these values with flow rates extracted from the GoldSim model. As shown, there is exact agreement between the two sets of by-pass flow rates.

Table 1. *Lead Concentration in Groundwater at FTB Toes*

Tailings Basin Sub-Area	Tailings Material	Bentonite Amended	From Sulfate Table Flow gpm	From Sulfate Table MR kg/day	Sulfur MR kg/day	Ratio Lead to Sulfur R mg/mg	Calib Factor C	Conc Cap if used Cap mg/L	Lead MR kg/day	Flow Distribution N %	Flow Distribution NW %	Flow Distribution W %	Flow Distribution S %	Flow Rate (Q) N gpm	Flow Rate (Q) NW gpm	Flow Rate (Q) W gpm	Flow Rate (Q) S gpm	Mass Rate (MR) N kg/day	Mass Rate (MR) NW kg/day	Mass Rate (MR) W kg/day	Mass Rate (MR) S kg/day
North Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	78.08	8.37	2.79	5.800E-03	0.0003		4.86E-06	100	0	0	0	78.08	0.00	0.00	0.00	4.86E-06	0.00E+00	0.00E+00	0.00E+00
East Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	12.54	1.35	0.45	5.800E-03	0.0003		7.84E-07	100	0	0	0	12.54	0.00	0.00	0.00	7.84E-07	0.00E+00	0.00E+00	0.00E+00
South Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	28.54	3.06	1.02	5.800E-03	0.0003		1.78E-06	0	0	0	100	0.00	0.00	0.00	28.54	0.00E+00	0.00E+00	0.00E+00	1.78E-06
North Beach	35% NM fine, 65% NM coarse	Closure only	23.73					0.100	1.29E-02	100	0	0	0	23.73	0.00	0.00	0.00	1.29E-02	0.00E+00	0.00E+00	0.00E+00
East Beach	35% NM fine, 65% NM coarse	Closure only	14.30					0.100	7.80E-03	100	0	0	0	14.30	0.00	0.00	0.00	7.80E-03	0.00E+00	0.00E+00	0.00E+00
South Beach	35% NM fine, 65% NM coarse	Closure only	32.32					0.100	1.76E-02	3.8	0	0	96.2	1.23	0.00	0.00	31.10	6.70E-04	0.00E+00	0.00E+00	1.69E-02
Closure Beach	35% NM fine, 65% NM coarse	Closure only	59.15					0.100	3.22E-02	84.8	0	0	15.2	50.16	0.00	0.00	8.99	2.73E-02	0.00E+00	0.00E+00	4.90E-03
Pond	LTV	Closure (after 30 years)	326.59		9.89	5.800E-03	0.0003		1.72E-05	81	0	0	19	264.54	0.00	0.00	62.05	1.39E-05	0.00E+00	0.00E+00	3.27E-06
1E coarse	LTV coarse	none	0.47	5.57	1.86	5.800E-03	0.0003		3.24E-06	0	0	0	100	0.00	0.00	0.00	0.47	0.00E+00	0.00E+00	0.00E+00	3.24E-06
1E fine	LTV fine	none								1.5	31.7	7	59.8	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2E coarse	LTV coarse	none								1.5	98.5	0	0	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2E fine	LTV fine	none								100	0	0	0	0.00	0.00	0.00	0.00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2E other	LTV coarse	none	21.40	55.15	18.41	5.800E-03	0.0003		3.20E-05	98.6	1.4	0	0	21.10	0.30	0.00	0.00	3.16E-05	4.48E-07	0.00E+00	0.00E+00
2W coarse	LTV coarse	none	150.86	479.01	159.89	5.800E-03	0.0003		2.78E-04	14.6	31.1	35.2	19.1	22.03	46.92	53.10	28.81	4.06E-05	8.65E-05	9.79E-05	5.31E-05
2W fine	LTV fine	none	615.75	715.48	238.83	5.800E-03	0.0003		4.16E-04	8.9	55.5	35.4	0.2	54.80	341.74	217.97	1.23	3.70E-05	2.31E-04	1.47E-04	8.31E-07
2W banks	LTV coarse	none	136.97	514.49	171.74	5.800E-03	0.0003		2.99E-04	11.1	36.1	41.6	11.2	15.20	49.45	56.98	15.34	3.32E-05	1.08E-04	1.24E-04	3.35E-05
South Buttress banks	Assumed Cat 1 waste rock	none	10.26					0.1000	5.59E-03	0.0	0.0	0.0	100.0	0.00	0.00	0.00	10.26	0.00E+00	0.00E+00	0.00E+00	5.59E-03
North Buttress banks	Assumed Cat 1 waste rock	none	30.78					0.1000	1.68E-02	100.0	0.0	0.0	0.0	30.78	0.00	0.00	0.00	1.68E-02	0.00E+00	0.00E+00	0.00E+00

Total GW to Collection System
SW Runoff to Collection Systems

Total Average to WWTP

	Flow Rate (Q) N gpm	Flow Rate (Q) NW gpm	Flow Rate (Q) W gpm	Flow Rate (Q) S gpm	Mass Rate (MR) N kg/day	Mass Rate (MR) NW kg/day	Mass Rate (MR) W kg/day	Mass Rate (MR) S kg/day
GW to Individual Collection Systems	588.49	438.40	328.06	186.79	6.568E-02	4.255E-04	3.693E-04	2.754E-02

	N	NW	W	S
Independently computed concentration (ug/L) ->	20.476	0.178	0.207	27.048
GoldSim concentration (ug/L) ->	17.280	0.178	0.207	23.504

All values are independently calculated using inputs and equations mutually agreed upon by the Agencies and Barr.

R Ratio of copper mass to sulfur mass
MR Mass rate of chemical release

🟦 Theoretical result over-ridden by concentration cap

🟩 Based on dissolved oxygen brought in with pond seepage

N North Toe
NW Northwest Toe

From From
Sulfate Sulfate Ratio Lead Calib Conc Cap

Table 2. Sulfate Concentration in Groundwater at FTB Toes

P50 rainfall = 27.818

						Sulfur	Sulfate	Flow Distribution				Flow Rate (Q)				Mass Rate (MR)			
Tailings Basin Sub-Area	Tailings Material	Bentonite Amended	Area acre	Perc in/yr	Flow gpm	MRA mg/m2/week	MR kg/day	N %	NW %	W %	S %	N gpm	NW gpm	W gpm	S gpm	N kg/day	NW kg/day	W kg/day	S kg/day
North Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	249.00	6.07	78.08	19.421	8.37	100	0	0	0	78.08	0.00	0.00	0.00	8.37	0.00	0.00	0.00
East Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	40.00	6.07	12.54	19.421	1.35	100	0	0	0	12.54	0.00	0.00	0.00	1.35	0.00	0.00	0.00
South Dam banks (outer slopes)	LTV bulk (other)	Operations and closure	91.00	6.07	28.54	19.421	3.06	0	0	0	100	0.00	0.00	0.00	28.54	0.00	0.00	0.00	3.06
North Beach	35% NM fine, 65% NM coarse	Closure only	75.67	6.07	23.73	233.990	30.66	100	0	0	0	23.73	0.00	0.00	0.00	30.66	0.00	0.00	0.00
East Beach	35% NM fine, 65% NM coarse	Closure only	45.61	6.07	14.30	233.990	18.48	100	0	0	0	14.30	0.00	0.00	0.00	18.48	0.00	0.00	0.00
South Beach	35% NM fine, 65% NM coarse	Closure only	103.08	6.07	32.32	233.990	41.77	3.8	0	0	96.2	1.23	0.00	0.00	31.10	1.59	0.00	0.00	40.18
Closure Beach	35% NM fine, 65% NM coarse	Closure only	188.64	6.07	59.15	233.990	76.44	84.8	0	0	15.2	50.16	0.00	0.00	8.99	64.82	0.00	0.00	11.62
Pond	n/a	Closure (after 30 years)	972.60	6.50	326.59		58.43	81	0	0	19	264.54	0.00	0.00	62.05	47.33	0.00	0.00	11.10
1E coarse	LTV coarse	none	3.38	2.68	0.47	952.688	5.57	0	0	0	100	0.00	0.00	0.00	0.47	0.00	0.00	0.00	5.57
1E fine	LTV fine	none	0.00	2.19				1.5	31.7	7	59.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2E coarse	LTV coarse	none	0.00	5.04				1.5	98.5	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2E fine	LTV fine	none	0.00	3.92				100	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2E other	LTV coarse	none	75.29	5.50	21.40	422.968	55.15	98.6	1.4	0	0	21.10	0.30	0.00	0.00	54.38	0.77	0.00	0.00
2W coarse	LTV coarse	none	220.08	13.27	150.86	1256.772	479.01	14.6	31.1	35.2	19.1	22.03	46.92	53.10	28.81	69.94	148.97	168.61	91.49
2W fine	LTV fine	none	748.07	15.93	615.75	552.262	715.48	8.9	55.5	35.4	0.2	54.80	341.74	217.97	1.23	63.68	397.09	253.28	1.43
2W banks	LTV coarse	none	339.18	7.82	136.97	875.858	514.49	11.1	36.1	41.6	11.2	15.20	49.45	56.98	15.34	57.11	185.73	214.03	57.62
South Buttress banks	Assumed Cat 1 waste rock	none	15.00	13.24	10.26		7.53	0.0	0.0	0.0	100.0	0.00	0.00	0.00	10.26	0.00	0.00	0.00	7.53
North Buttress banks	Assumed Cat 1 waste rock	none	45.00	13.24	30.78		26.51	100.0	0.0	0.0	0.0	30.78	0.00	0.00	0.00	26.51	0.00	0.00	0.00

Total GW to Collection System

SW Runoff to Collection Systems

Total Average to WWTP

	N	NW	W	S	N	NW	W	S
GW to Individual Collection Systems	588.49	438.40	328.06	186.79	444.21	732.57	635.92	229.61

	N	NW	W	S
Independently computed concentration (ug/L) ->	138,478	306,549	355,614	225,517
GoldSim concentration (ug/L) ->	144,300	306,700	355,800	238,400

All values are independently calculated using inputs and equations mutually agreed upon by the Agencies and Barr.

MRA Mass rate of chemical release per unit map area
MR Mass rate of chemical release

N North Toe
NW Northwest Toe
W West Toe
S South Toe

🟧 Based on Mathcad worksheets for oxygen diffusion

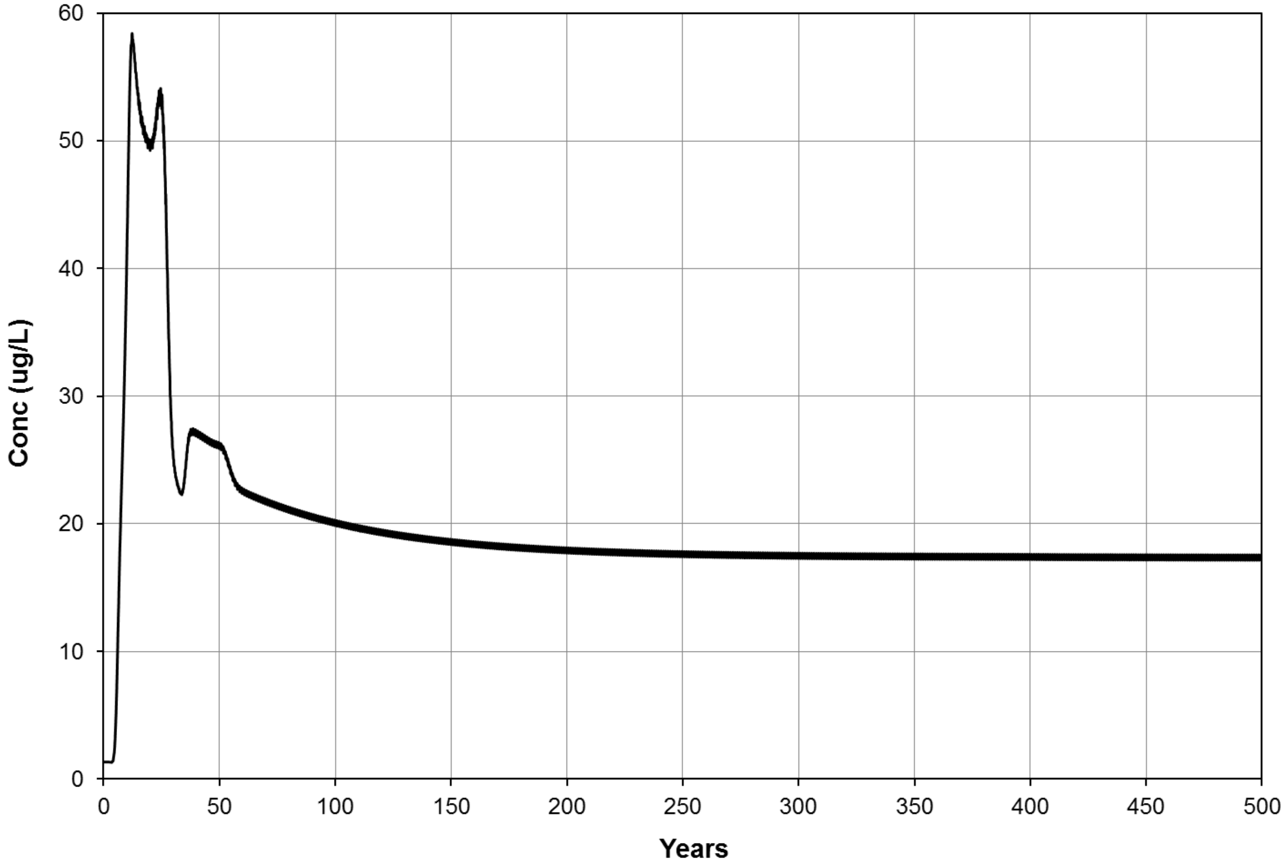
🟩 Based on pond sulfate and dissolved oxygen concentrations

🟦 Based on Category 1 sulfate oxidation and LAM scale factor

Table 3. *Plant Site Surficial Flowpaths - Flow Rates and Travel Times*

Description	Units	Surficial Aquifer Pathway		
		West	Northwest	North
Flowpath width	m	2920	2090	1920
Flowpath thickness	m	7	7	7
Hydraulic gradient	---	0.00736	0.00514	0.00444
Hydraulic conductivity	m/d	3.7139	3.7139	3.7139
Groundwater flow rate approaching containment system	gpm	102.50	51.23	40.66
Containment system capture efficiency	%	90	90	90
Indpendently computed groundwater flow rate by-passing containment system	gpm	10.25	5.12	4.07
GoldSim result based on deterministic run with P50 inputs		10.25	5.12	4.07
Net meteoric recharge	in/yr	0.765	0.765	0.765
Aquifer porosity	---	0.30	0.30	0.30
Distance from containment system to mine property boundary (groundwater compliance point)	m	3023	1250	1132
Distance from containment system to location of groundwater discharge to surface water	m	5331	3645	3191
Independently computed groundwater discharge rate to surface water	gpm	162.31	79.54	63.92
GoldSim result based on deterministic run with P50 inputs		162.18	79.45	63.87
Independently computed sharp-front chemical arrival time at the property boundary	yr	242.2	193.3	197.5
GoldSim result - apparent travel time for lead based on 50th percentile conc from Monte Carlo simulation		225	175	200
Independenly computed sharp-front chemical arrival time at the location of groundwater discharge to surface water	yr	298.5	296.3	297.7
GoldSim result - apparent travel time for lead based on deterministic run with P50 inputs		290	290	290

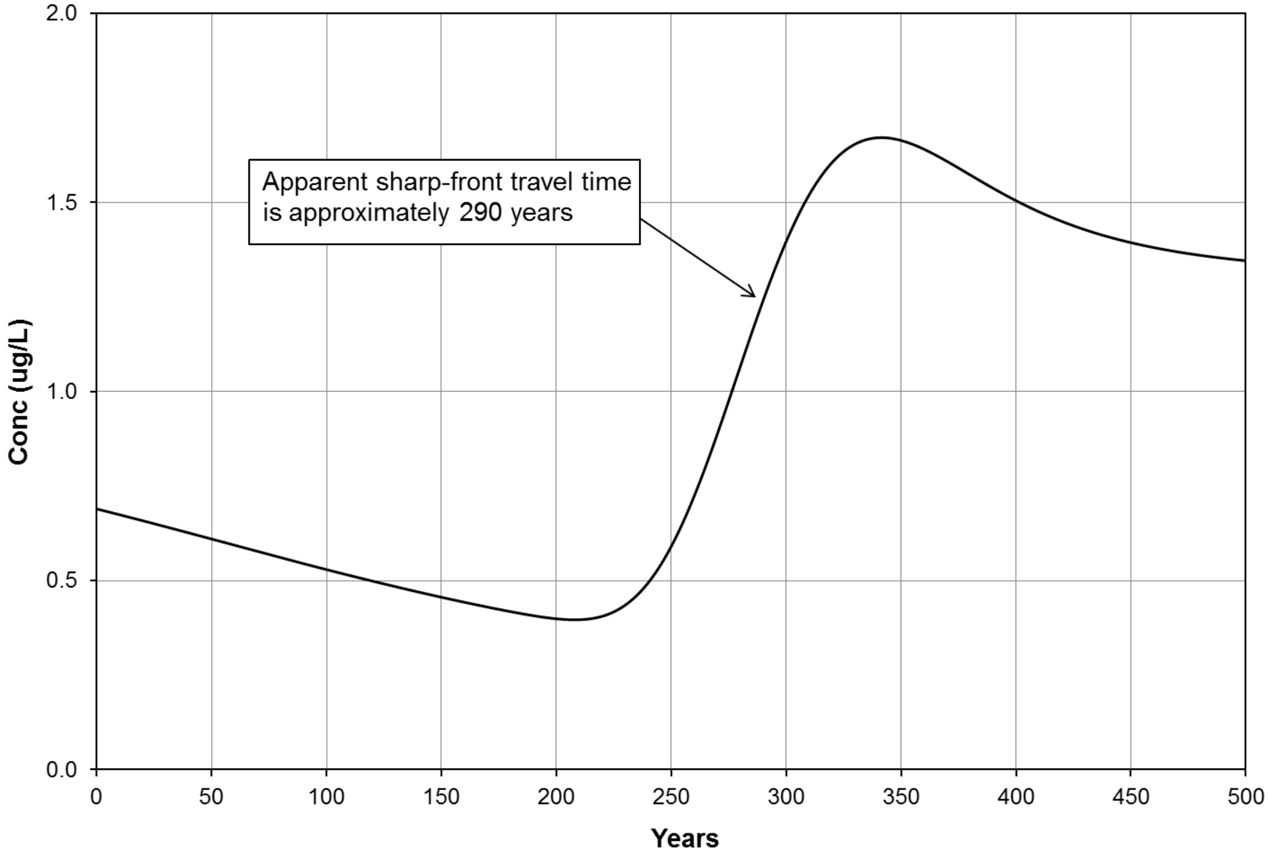
Figure 1. GoldSim Lead Concentration at Upgradient (containment) end of North Flowpath Based on Deterministic Run with P50 Inputs



Between the upgradient (containment system) end and downgradient (discharge) end of each flowpath, there is a systematic increase in the groundwater flow rate due to net recharge of meteoric water into the groundwater system. In Table 1, the downgradient groundwater discharge flow rate is computed for each flowpath and is shown to be in excellent agreement with the analogous value extracted from the GoldSim model. These rates represent the discharge of groundwater to surface water at the end of the surficial flowpaths, which are constant in the GodlSim model. Groundwater discharges from the North and Northwest Flowpaths go to the Embarrass River via tributaries Mud Lake Creek and Trimble Creek, respectively. Discharge from the West Flowpath goes directly into the Embarrass River.

Figure 2 shows the GoldSim lead concentration at the discharge (downgradient) end of the North Flowpath over time. Lead is a good tracer in the GoldSim model because its concentration in the containment system by-pass water is much larger than the background concentration in groundwater. The increase in the discharge concentration on Figure 2 results from groundwater transport through the flowpath beginning at the containment system. As shown on Figure 2, the concentration begins to rise at about 225 years and reaches a peak at about 340 years. Due to longitudinal dispersion, the GoldSim plume arrival is gradual, but the shape of the curve indicates an effective "sharp-front" travel time of about 290 years. The sharp-front travel time is the theoretical travel time that would occur if there was no dispersion in the system. For the physical system considered in the GoldSim model, an independent estimate of the sharp-front travel time can be made using the equation presented in the Mine Site QA Update (Appendix B this report). This equation accounts for effect of recharge on the groundwater seepage velocity, which increases in the downgradient direction. In the lower portion of Table 1, the equation is used to independently compute the sharp-front travel time to the property boundary and to the discharge point for each flowpath. As shown, there is good agreement between the apparent sharp-front travel times interpreted form the GoldSim outputs and the theoretical sharp-front travel times predicted from the analytical equation.

Figure 2. GoldSim lead concentration at downgradient (discharge) end of North Flowpath based on deterministic run with P50 inputs



As summarized in Table 4, an additional check was performed using independent mixing calculations to estimate the long-term chemical concentrations in groundwater discharging to surface water. These calculations generally considered chemical concentrations in the upgradient end of the flowpath at 100 to 200 years, when concentrations tend to be steady or slowly changing. The calculation then mixed the flow/concentration at the upstream end of the flow path with the recharge flow/concentration along the flowpath to compute the concentration at the downstream end. This was considered the downgradient concentration that would occur at 400 to 500 years, because there is a 300-year travel time through the entire flowpath. The computed value was then compared to the GoldSim concentration at the downstream end of the flowpath at 400 to 500 years.

As an example, Figure 1 shows that the upgradient lead concentration in the North Flowpath is about 17.6 µg/L at 200 years. The independent calculation gives a computed downgradient concentration of 1.35 µg/L. Figure 2 shows that the GoldSim lead concentration at the downstream end of the North Flowpath is about 1.35 at 500 years, which compares favorably with the computed value. As shown in Table 4, there is generally good agreement between the independently computed sulfate and lead concentrations at the downgradient end of each flowpath and analogous values extracted from the GoldSim outputs.

This evaluation provides good evidence that the GoldSim Plant Site model correctly simulates chemical transport and meteoric dilution in the groundwater surficial flowpaths.

Table 4. Plant Site Flowpaths - Discharge Concentrations

						Compare Values			
Flowpath	Constituent	Containment System Bypass		Recharge		Flow Rate of GW Discharge to SW		Concentration in GW Discharge to SW	
		Flow Rate gpm	Conc ug/L	Flow Rate gpm	Conc ug/L	Computed gpm	GoldSim gpm	Computed ug/L	GoldSim ug/L
North	Sulfate	4.07	156400	59.85	7920	63.92	63.87	17374	17100
	Lead	4.07	17.6	59.85	0.250	63.92	63.87	1.35	1.35
Northwest	Sulfate	5.12	307000	74.42	7920	79.54	79.45	27172	26600
	Lead	5.12	0.179	74.42	0.250	79.54	79.45	0.245	0.246
West	Sulfate	10.25	355700	152.06	7920	162.31	162.18	29883	28200
	Lead	10.25	0.207	152.06	0.250	162.31	162.18	0.247	0.211

EVALUATION 3 – CONSERVATION OF FLOW AND CHEMICAL MASS IN THE EMBARRASS RIVER

Review of the GoldSim Plant Site model has indicated that when reduced to average annual values, the flow rates and chemical mass rates associated with natural components are generally uniform. In the GoldSim model, natural components affecting the Embarrass River include upstream river water entering the Plant Site area, groundwater baseflow, and storm runoff. Some tributary flows and mass rates are variable from the beginning of operations to about year 42 due to variations in WWTP discharge and water from Colby Lake used to augmentation. There is also a systematic variation of chemical concentrations in groundwater discharging from the surficial flowplaths to surface water during this period. In the Embarrass River, noticeable fluctuations in flow and mass rates occur at PM-13 between zero and 42 years due to these factors. An integrated check of how the model accounts for flow and chemical mass entering the river is to compare the system components with variable flow/concentration against GoldSim computed variations at PM-13. The zero to 42 year time frame is chosen because it is during this period that WWTP effluent and Colby Lake augmentation have large annual variations.

The GoldSim flow chart indicates that WWTP effluent and Colby Lake augmentation water are discharged to three tributaries of the Embarrass River. These locations are designated in the model as Mudlake Creek (MLC3), Trimble Creek (TC1), and unnamed creek (PM-11). When water is discharged to these tributaries, the model assumes that the flow reaches the Embarrass River instantaneously. GoldSim output indicates that the discharge from each groundwater surficial flowpath exhibits a constant flow rate, but variable chemical concentrations.

For operations and initial closure, Figure 3 shows the sum of WWTP discharge, Colby Lake augmentation, and groundwater flowpath discharge (WWTP+CL+FP) as annual average flow rates, which are shown to vary between 3.4 and 5.1 cfs (left scale). Also shown is the Embarrass River (ER) annual average flow rate at PM-13, which varies from 53.4 to 55.4 cfs (right scale). If natural river inputs (other than WWTP+CL+FP) are uniform, there should be a 1-to-1 relationship between WWTP+CL+FP flow variations and PM-13 flow variations. To provide a comparison, the PM-13 scale on Figure 3 is shifted to bring the two curves into closer proximity. As shown, after year 8 there is an exact correspondence between the two curves. If the WWTP+CL+FP annual average flow rate changes by ΔQ, there is an exact corresponding change in flow at PM-13. This provides good evidence that the GoldSim model properly accounts for human-affected (WWTP+CL+FP) flows entering the Embarrass River and that all other river inputs are uniform after year 8.

Figure 3. *Embarrass River annual average flow rates based on GoldSim deterministic run with P50 inputs*

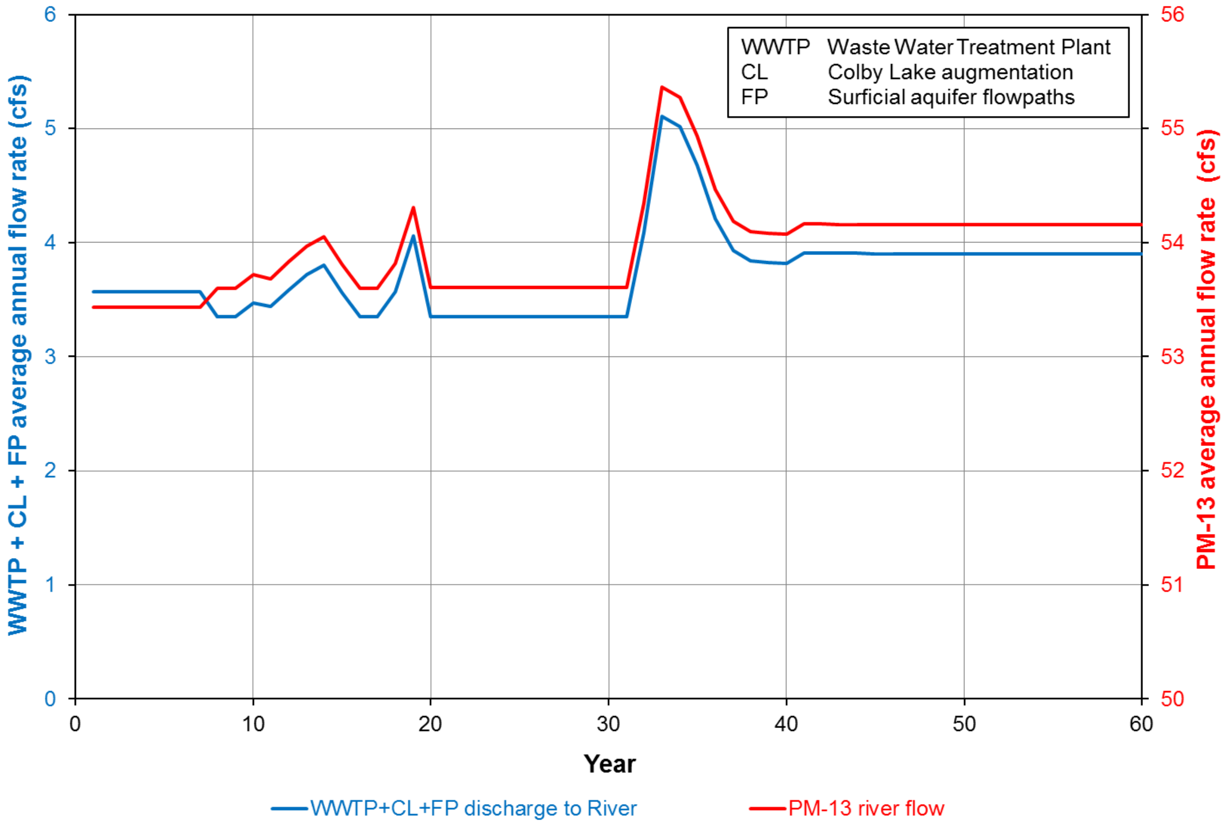


Figure 4 is a similar plot, except it is based on sulfate annual average mass rates. As shown, there is a very good correspondence between fluctuations in WWTP+CL+FP mass rates entering the river and PM-13 mass rate variations.

This evaluation provides good evidence that the GoldSim Plant Site model correctly accounts for human-affected flow and chemical loading to the Embarrass River.

Figure 4. *Embarrass River annual average sulfate mass rates based on GoldSim deterministic run with P50 inputs*