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 bypasses 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.
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

### Sulfate (solubility equation)

\[
\begin{align*}
\text{Mg} & := \frac{0.235127}{24.305} \\
\text{Ca} & := \frac{1.10426}{40.078} \\
\text{K} & := \frac{0.191692}{39.0983} \\
\text{Na} & := \frac{0.227726}{22.989} \\
\text{CAP}_{\text{SO}_4} & := \left[ \frac{1294}{\text{Ca}} \left( \frac{\text{Mg} + 0.5\text{Na} + 0.5\text{K}}{\text{Ca}} + 1760 \right) \right] \text{mg L}^{-1}
\end{align*}
\]

P50 magnesium release rate in mmole/kg/week

\( \text{Mg} = 9.674 \times 10^{-3} \)

(Table 1-24 and GoldSim to compute P50 value)

P50 calcium release rate in mmole/kg/week

\( \text{Ca} = 0.028 \)

(Table 1-24 and GoldSim to compute P50 value)

P50 potassium release rate in mmole/kg/week

\( \text{K} = 4.903 \times 10^{-3} \)

(Table 1-24 and GoldSim to compute P50 value)

P50 sodium release rate in mmole/kg/week

\( \text{Na} = 9.906 \times 10^{-3} \)

(Table 1-24 and GoldSim to compute P50 value)

SO₄ concentration cap computed from P50 values

\( \text{CAP}_{\text{SO}_4} = 2562 \text{ mg L}^{-1} \)

\( 2562 \)

### Copper (based on pH and AMAX data)

\[
\begin{align*}
\text{pH} & := 7.25 \\
\text{CAP}_{\text{Cu}} & := \frac{(0.200 + 0.178 + 0.260 + 0.340)}{4} \text{mg L}^{-1}
\end{align*}
\]

Assumed Cat 1 pH with geomembrane cover

\( \text{pH} = 7.25 \)

P50 copper concentration cap from pH based values (Table 1-30)

\( \text{CAP}_{\text{Cu}} = 0.244 \text{ mg L}^{-1} \)

\( 0.237 \)

### Zinc (based on pH and AMAX data)

\[
\begin{align*}
\text{pH} & := 7.25 \\
\text{CAP}_{\text{Zn}} & := \frac{(0.133 + 0.170 + 0.230 + 0.230)}{4} \text{mg L}^{-1}
\end{align*}
\]

Assumed Cat 1 pH with geomembrane cover

\( \text{pH} = 7.25 \)

P50 zinc concentration cap from pH based values (Table 1-30)

\( \text{CAP}_{\text{Zn}} = 0.191 \text{ mg L}^{-1} \)

\( 0.186 \)

### Nickel (based on pH and AMAX data)

\[
\begin{align*}
\text{pH} & := 7.25 \\
\text{CAP}_{\text{Ni}} & := \frac{(1.62 + 2.08 + 2.29 + 3.42)}{4} \text{mg L}^{-1}
\end{align*}
\]

Assumed Cat 1 pH with geomembrane cover

\( \text{pH} = 7.25 \)

P50 nickel concentration cap from pH based values (Table 1-30)

\( \text{CAP}_{\text{Ni}} = 2.353 \text{ mg L}^{-1} \)

\( 2.267 \)

### Cobalt (based on pH and AMAX data)

\[
\begin{align*}
\text{pH} & := 7.25 \\
\text{CAP}_{\text{Co}} & := \frac{(0.093 + 0.1368 + 0.120 + 0.150)}{4} \text{mg L}^{-1}
\end{align*}
\]

Assumed Cat 1 pH with geomembrane cover

\( \text{pH} = 7.25 \)

P50 cobalt concentration cap from pH based values (Table 1-30)

\( \text{CAP}_{\text{Co}} = 0.125 \text{ mg L}^{-1} \)

\( 0.123 \)

Cat 1 seepage concentrations are at concentration caps at the end of simulation (t = 500 yrs)
## Table 2. Sulfate - Plant Site During Closure

<table>
<thead>
<tr>
<th>Tailings Basin Sub-Area</th>
<th>Tailings Material</th>
<th>Bentonite Amended Area acre</th>
<th>Perc in yr</th>
<th>Flow rate (Q) gpm</th>
<th>Mass rate (MR) mg/m²/week</th>
<th>Flow Distribution</th>
<th>Mass Rate (MR) kg/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Dam banks (outer slopes)</td>
<td>LTV bulk (other)</td>
<td>Operations and closure</td>
<td>249.50</td>
<td>6.07</td>
<td>78.08</td>
<td>24.22</td>
<td>10.44</td>
</tr>
<tr>
<td>East Dam banks (outer slopes)</td>
<td>LTV bulk (other)</td>
<td>Operations and closure</td>
<td>40.00</td>
<td>6.07</td>
<td>12.54</td>
<td>24.22</td>
<td>1.68</td>
</tr>
<tr>
<td>South Dam banks (outer slopes)</td>
<td>LTV bulk (other)</td>
<td>Operations and closure</td>
<td>91.00</td>
<td>6.07</td>
<td>28.54</td>
<td>24.22</td>
<td>3.81</td>
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<tr>
<td>North Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>75.87</td>
<td>6.07</td>
<td>23.73</td>
<td>233.99</td>
<td>30.68</td>
</tr>
<tr>
<td>East Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>45.71</td>
<td>6.07</td>
<td>14.30</td>
<td>233.99</td>
<td>18.48</td>
</tr>
<tr>
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<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>103.58</td>
<td>6.07</td>
<td>32.32</td>
<td>233.99</td>
<td>41.77</td>
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<tr>
<td>North Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>188.64</td>
<td>6.07</td>
<td>59.15</td>
<td>233.99</td>
<td>76.44</td>
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<td>Pond</td>
<td>(va)</td>
<td>Closure (after 30 years)</td>
<td>972.60</td>
<td>6.07</td>
<td>328.59</td>
<td>58.43</td>
<td>0.00</td>
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<tr>
<td>TE coarse</td>
<td>LTV coarse</td>
<td>None</td>
<td>3.38</td>
<td>2.64</td>
<td>0.47</td>
<td>1167.20</td>
<td>6.83</td>
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<tr>
<td>TE fine</td>
<td>LTV fine</td>
<td>None</td>
<td>0.00</td>
<td>2.18</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>TE other</td>
<td>LTV coarse</td>
<td>None</td>
<td>75.29</td>
<td>5.50</td>
<td>21.48</td>
<td>518.25</td>
<td>67.57</td>
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<tr>
<td>NW coarse</td>
<td>LTV coarse</td>
<td>None</td>
<td>220.08</td>
<td>13.27</td>
<td>150.86</td>
<td>1539.87</td>
<td>586.91</td>
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<tr>
<td>NW fine</td>
<td>LTV fine</td>
<td>None</td>
<td>748.07</td>
<td>15.63</td>
<td>615.75</td>
<td>727.96</td>
<td>343.09</td>
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<tr>
<td>South Buttress banks</td>
<td>Assumed Cat 1 waste rock</td>
<td>None</td>
<td>339.18</td>
<td>7.82</td>
<td>136.97</td>
<td>1073.15</td>
<td>630.38</td>
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<tr>
<td>Total GW to Collection Systems</td>
<td>588.49</td>
<td>438.40</td>
<td>328.06</td>
<td>186.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total SW Runoff to Collection Systems</td>
<td>253.47</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue entries are values extracted from the GoldSim model</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Red entries from Mathcad worksheets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All values are independently calculated using inputs and equations mutually agreed upon by the Agencies and Barr.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration to WWTP (mg/L)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Check 1783.40</td>
<td>Check 2655.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Notes:
- GW to Individual Collection Systems: 588.49, 438.40, 328.06, 186.79, 507.74, 934.46, 802.68, 265.67
- GW to Combined Collection: 1541.73
- Total Average to WWTP: 2510.55
- Check 273.18

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### Definitions:
- **NRA**: Mass rate of chemical release per unit map area
- **MR**: Mass rate of chemical release

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### Values:
- **N**: North Toe
- **NW**: Northwest Toe
- **W**: West Toe
- **S**: South Toe

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### Other Details:
- GW to Combined Collection: 2510.55
- Check 2655.70
- Concentration to WWTP (mg/L): 256.55
- Check 273.18
## Table 3. Copper - Plant Site During Closure

<table>
<thead>
<tr>
<th>Falling Basin Sub-Area</th>
<th>Falling Material</th>
<th>Bentonite Amended</th>
<th>Flow Rate (Q) (gpm)</th>
<th>Mass Rate (MR) (kg/day)</th>
<th>Ratio to Sulfur (mg/mg)</th>
<th>Cap Conc (mg/L)</th>
<th>Check</th>
<th>GoldSim Flow Distribution</th>
<th>Check</th>
<th>Fine Rate (Q) (gpm)</th>
<th>Mass Rate (MR) (kg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Dam banks (outer slopes)</td>
<td>LV bulk (other)</td>
<td>Operations and closure</td>
<td>12.54</td>
<td>1.68</td>
<td>0.54</td>
<td>3.10E-02</td>
<td>0.0005</td>
<td>6.86E-06</td>
<td>0.57E-06</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>South Dam banks (outer slopes)</td>
<td>LV bulk (other)</td>
<td>Operations and closure</td>
<td>28.54</td>
<td>3.92</td>
<td>1.21</td>
<td>3.10E-02</td>
<td>0.0005</td>
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<td>100</td>
<td>0</td>
</tr>
<tr>
<td>North Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>25.79</td>
<td>5.19</td>
<td>1.92</td>
<td>3.10E-02</td>
<td>0.0005</td>
<td>6.86E-06</td>
<td>0.57E-06</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>East Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>14.39</td>
<td>2.97</td>
<td>1.02</td>
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<td>4.02E-06</td>
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<tr>
<td>South Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>32.32</td>
<td>5.19</td>
<td>1.87</td>
<td>3.10E-02</td>
<td>0.0005</td>
<td>9.56E-06</td>
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<td>0</td>
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<tr>
<td>North Beach banks</td>
<td>Assumed Cat 1 waste rock</td>
<td>none</td>
<td>10.26</td>
<td>1.83</td>
<td>0.65</td>
<td>3.10E-02</td>
<td>0.0005</td>
<td>9.71E-06</td>
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</tr>
<tr>
<td>South Beach banks</td>
<td>Assumed Cat 1 waste rock</td>
<td>none</td>
<td>10.26</td>
<td>1.83</td>
<td>0.65</td>
<td>3.10E-02</td>
<td>0.0005</td>
<td>9.71E-06</td>
<td>0.57E-06</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Theoretical result over-ridden by concentration cap

GW to Individual Collection Systems: 588.49, 438.40, 328.06, 186.79
GW to Combined Collection: 1541.73
SW Runoff to Combined Collection: 253.47
Total Average to WWTP: 1795.20

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.
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
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 Wallrock, 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 area 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).
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.
Comparison of Sulfate Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation.
Figure 3  
Comparison of Arsenic Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation

arsenic Load from Ore Wall Rock to West Pit

arsenic Load from Cat 4 Duluth Complex Wall Rock to West Pit

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

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**Copper Load from Cat 4 Duluth Complex Wall Rock to West Pit**

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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

![Graph showing comparison of Antimony Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation.]

- Antimony Load from Ore Wall Rock to West Pit
- Antimony Load from Cat 4 Duluth Complex Wall Rock to West Pit
Figure 6  
Comparison of Nickel Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation

![Comparison of Nickel Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation](image-url)
Figure 7  
Comparison of Cobalt Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation
Figure 8  Comparison of Magnesium Load to West Pit from Wall Rock (Cat4 Duluth Complex and Ore): GoldSim Model vs. Audit Calculation
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).
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

\[ K_s := 2.40 \times 10^{-3} \text{ cm} \text{ sec} \]

\[ \beta := 2 \]

\[ \theta_r := 0.041 \]

\[ \phi := 0.412 \]

\[ G := 2.80 \]

\[ \rho_w := 1. \text{ gm} \text{ cm}^{-3} \]

\[ \Lambda := 3.3784 \text{ acre} \]

\[ q := 2.6812 \text{ in} \text{ yr} \]

\[ \tau := 0.273 \]

\[ D_a := 1.8 \times 10^{-5} \text{ m}^2 \text{ sec} \]

\[ c := 3.28 \]

\[ D_w := 2.2 \times 10^{-9} \text{ m}^2 \text{ sec} \]

\[ K_H := 33.9 \]

\[ C_o := 8.89 \text{ mol} \text{ m}^3 \]

\[ W_{SO4} := 96.07 \text{ gm} \text{ mole} \]

\[ W_S := 32.066 \text{ gm} \text{ mole} \]

\[ R_{SO4} := 1.95186 \text{ mg} \text{ day}^{-1} \text{ kg}^{-1} \]

\[ CF := 0.185 \]

\[ TF := 0.228589 \]

\[ FF := \frac{3.4}{12} \]

\[ \text{moleratio} := \frac{4}{9} \]

\[ \text{DTW} := 117.8 \text{ ft} \]

\[ \text{Cont}_S := 329 \text{ mg} \text{ kg}^{-1} \]

\[ \rho_b := G \rho_w (1 - \phi) \]

\[ \mu_g := 10^{-6} \text{ gm} \]

Saturated hydraulic conductivity (Table 1-12a)

vanGenuchten parameter (Table 1-12a)

Residual volumetric water content (Table 1-12a)

Porosity (Table 1-12a)

Specific gravity (Table 1-12a)

Water density (standard value)

Map area (Table 1-33)

Percolation flux (from seepage spreadsheet with Barr edits)

Tortuosity (Table 1-1, sheet 5)

Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)

Empirical constant (Table 1-1, sheet 5)

Free diffusion coeff of oxygen in water (Table 1-1, sheet 5)

Henry's constant for oxygen (Table 1-1, sheet 5)

O2 concentration in air (Table 1-1, sheet 5)

Molecular weight of sulfate (standard value)

Molecular weight of sulfur (standard value)

P50 SO4 distribution paramater for tailings (Table 1-19)

Calibration factor for tailings (Table 1-1, sheet 5)

Temperature factor (computed in GS using numerous inputs)

Freeze factor (from Table 1-1, sheet 3)

FF = 0.28333

mole SO4 / mole O2 = mole S / mole O2

moleratio = 0.444

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)

Sulfur content. Mass of S per unit mass of tailings.

(Table 1-22)

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

\[ \rho_b = 1.646 \text{ gm} \text{ cm}^{-3} \]
\[
\gamma := 1 - \frac{1}{\beta}
\]

\[
K_{ss} := K_s \left( \frac{ss \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \left[ 1 - \left( \frac{1}{ss \cdot \phi - \theta_r} \right) \right]^{2} \quad \text{Unsaturated hydraulic conductivity as a function of saturation (ss) based on van Genuchten relationship}
\]

\[
f(ss) := q - K_{ss} \quad \text{Root equation and saturation guess}
\]

\[
SAT := \text{root}(f(ss), ss) \quad \text{Computed saturation associated with flux (q)}
\]

\[
q - K(SAT) = -9.282 \times 10^{-10} \text{ in} \cdot \text{yr}^{-1} \quad \text{Confirm root calculation (result should be approx zero)}
\]

\[
D := \tau \cdot D_a (1 - SAT)^c + \tau \cdot SAT \cdot \frac{D_w}{K_H} \quad \text{Effective O2 diffusion coeff referenced to void volume}
\]

\[
MR_{SO4} := R_{SO4} \cdot CF \cdot TF \cdot (1 - FF) \quad \text{Mass rate of released SO4 per unit mass of tailings solids}
\]

\[
R_{O2} := \frac{M RM_{SO4}}{W_{SO4} \cdot \text{moleratio}} \cdot \frac{\rho_b}{\phi} \quad \text{Effect of three factors} \quad CF \cdot TF \cdot (1 - FF) = 0.030
\]

\[
d := \sqrt{\frac{2 \cdot D \cdot C_0}{R_{O2}}} \quad \text{Molar consumption rate of O2 per unit void volume.}
\]

\[
b := \min(d, DTW) \quad \text{Thickness of sulfate reaction zone if controlled by diffusion}
\]

\[
MR_{SO4} := MR_{SO4} \cdot b \cdot A \cdot \rho_b \quad \text{Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water.}
\]

\[
MR_{S} := MR_{V_{S}} \cdot b \quad \text{Mass rate of released sulfate}
\]

\[
MR_{V_{S}} := R_{O2} \cdot W_{S} \cdot \text{moleratio} \cdot \phi \quad \text{Mass rate of released S per unit bulk volume}
\]

\[
MR_{A_{S}} := MR_{S} \cdot b \quad \text{Mass rate of released S per unit map area (m²)}
\]

\[
M := MR_{S} \cdot A \quad \text{Mass rate of released S}
\]

\[
Q := q \cdot A \quad \text{Seepage flow rate}
\]

\[
C_{SO4} := \frac{MR_{SO4}}{Q} \quad \text{Sulfate concentration in seepage}
\]

\[
t_{\text{end}} := \frac{\text{Cont}_S \cdot \rho_b \cdot A \cdot DTW}{MR_{S}} \quad \text{Time to deplete all sulfur in the reaction zone.}
\]
GoldSim Output

MR$_{SO_4}$ at 100 years is 4.882 kg/day

Other Chemicals

**Arsenic**

\[ RR_{As} := 0.09995 \]
\[ CF_{As} := 0.0001 \]
\[ MR_{As} := MR_S \cdot RR_{As} \cdot CF_{As} \]
\[ C_{As} := \frac{MR_{As}}{Q} \]

Mass rate of released As \( 8.322 \times 10^{-6} \) \( \text{MR}_{As} = 8.322 \times 10^{-6} \text{ tonne yr} \)

As concentration in seepage \( C_{As} = 8.938 \text{ ug L}^{-1} \)

**Cobalt**

\[ RR_{Co} := 0.03076 \]
\[ CF_{Co} := 0.0006 \]
\[ MR_{Co} := MR_S \cdot RR_{Co} \cdot CF_{Co} \]
\[ C_{Co} := \frac{MR_{Co}}{Q} \]

Mass rate of released Co \( 1.536 \times 10^{-5} \) \( \text{MR}_{Co} = 1.537 \times 10^{-5} \text{ tonne yr} \)

Co concentration in seepage \( C_{Co} = 16.505 \text{ ug L}^{-1} \)

**Copper**

\[ RR_{Cu} := 0.030598 \]
\[ CF_{Cu} := 0.0005 \]
\[ MR_{Cu} := MR_S \cdot RR_{Cu} \cdot CF_{Cu} \]
\[ C_{Cu} := \frac{MR_{Cu}}{Q} \]

Mass rate of released Cu \( 1.274 \times 10^{-5} \) \( \text{MR}_{Cu} = 1.274 \times 10^{-5} \text{ tonne yr} \)

Cu concentration in seepage \( C_{Cu} = 13.681 \text{ ug L}^{-1} \)
**Nickel**

\[
\begin{align*}
RR_{Ni} &= 0.014307 & \text{Release ratio of Ni to S} \\
CF_{Ni} &= 0.0027 & \text{Ni calibration factor} \\
MR_{Ni} &= MR_{S} \cdot RR_{Ni} \cdot CF_{Ni} & \text{Mass rate of released Ni} \quad 3.216 \times 10^{-5} \quad MR_{Ni} = 3.216 \times 10^{-5} \text{ tonne yr}^{-1} \\
C_{Ni} &= \frac{MR_{Ni}}{Q} & \text{Ni concentration in seepage} \quad C_{Ni} = 34.544 \text{ mg L}^{-1} \\
\end{align*}
\]

**Zinc**

\[
\begin{align*}
RR_{Zn} &= 5.0629 \times 10^{-5} & \text{Release ratio of Zn to SO4} \\
CF_{Zn} &= 0.2596 & \text{Zn calibration factor} \\
MR_{Zn} &= MR_{SO4} \cdot RR_{Zn} \cdot CF_{Zn} & \text{Mass rate of released Zn} \quad 3.278 \times 10^{-5} \quad MR_{Zn} = 3.279 \times 10^{-5} \text{ tonne yr}^{-1} \\
C_{Zn} &= \frac{MR_{Zn}}{Q} & \text{Zn concentration in seepage} \quad C_{Zn} = 35.214 \text{ mg L}^{-1} \\
\end{align*}
\]
Cell 2E Other - Sulfate - Closure

\[ K_s := 2.24 \times 10^{-3} \text{ cm sec}^{-1} \]
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)

\[ G := 2.80 \]
Specific gravity (Table 1-12a)

\[ \rho_w := 1.0 \frac{\text{gm}}{\text{cm}^3} \]
Water density (standard value)

\[ \Lambda := 304688 \text{ m}^2 \]
Map area (Table 1-33)

\[ q := 5.50 \frac{\text{in}}{\text{yr}} \]
Percolation flux (from seepage spreadsheet with Barr edits)

\[ \tau := 0.273 \]
Tortuosity (Table 1, sheet 5)

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

\[ c := 3.28 \]
Empirical constant (Table 1-1, sheet 5)

\[ D_w := 2.2 \times 10^{-9} \frac{\text{m}^2}{\text{sec}} \]
Free diffusion coeff of oxygen in water (Table 1-1, sheet 5)

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

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

\[ W_{SO_4} := 96.07 \frac{\text{gm}}{\text{mole}} \]
Molecular weight of sulfate (standard value)

\[ W_S := 32.066 \frac{\text{gm}}{\text{mole}} \]
Molecular weight of sulfur (standard value)

\[ R_{SO_4} := 1.95186 \frac{\text{mg}}{\text{kg} \cdot \text{7 day}} \]
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)

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

\[ \text{FF} = 0.28333 \]
moleratio = 0.444

\[ \text{DTW} := 52.3 \text{-ft} \]
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)

\[ \text{Cont}_S := 329 \frac{\text{mg}}{\text{kg}} \]
Sulfur content. Mass of S per unit mass of tailings.
(Table 1-22)

\[ \rho_b := G \rho_w (1 - \phi) \]
Tailings dry bulk density. Mass of solids per unit bulk volume.

\[ \rho_b = 1.646 \frac{\text{gm}}{\text{cm}^3} \]
\[ \gamma := 1 - \frac{1}{\beta} \]

Computed van Genuchten parameter \[ \gamma = 0.5 \]

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

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

Root equation and saturation guess

\[ f(ss) := q - K(ss) \quad ss := 0.6 \]

COMPUTED SATURATION ASSOCIATED WITH FLUX (q) \[ SAT = 0.2828 \quad 0.2816 \]

Confirm root calculation (result should be approx zero) \[ 1.661 \times 10^{-6} \]

Effective O2 diffusion coeff referenced to void volume \[ D = 1.652 \times 10^{-6} \text{ m}^2 \text{ s}^{-1} \]

Mass rate of released SO4 per unit mass of tailings solids \[ \text{MRM}_{SO4} = 0.0592 \frac{\text{mg}}{\text{kg} \cdot 7 \cdot \text{day}} \]

Effect of three factors \[ \text{CF} \cdot \text{TF} \cdot (1 - FF) = 0.030 \]

Molar consumption rate of O2 per unit void volume. \[ \text{RO2} = 0.005536 \frac{\text{mol}}{\text{m}^3 \cdot 7 \cdot \text{day}} \]

Thickness of sulfate reaction zone if controlled by diffusion \[ d = 56.77 \text{ m} \]

Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction zone or depth-to-water. \[ b = 15.941 \text{ m} \]

Mass rate of released sulfate \[ \text{MRSO4} = 67.578 \text{ kg day}^{-1} \]

Mass rate of released S per unit bulk volume \[ \text{MRV}_S = 4.644 \frac{\text{mg}}{\text{m}^3 \cdot \text{day}} \]

Mass rate of released S per unit map area (m^2) \[ \text{MRA}_S = 518.245 \frac{\text{mg}}{\text{m}^2 \cdot \text{day}} \]

Mass rate of released S \[ \text{MR}_S = 22.556 \text{ kg day}^{-1} \]

Seepage flow rate \[ Q = 21.379 \text{ gpm} \]

Sulfate concentration in seepage \[ c_{SO4} = 579.9 \frac{\text{mg}}{\text{liter}} \]

Time to deplete all sulfur in the reaction zone. \[ t_{end} = 319 \text{ yr} \]
Other Chemicals

Arsenic

Release ratio of As to S
\[ \text{RR}_{\text{As}} := 0.09995 \]
As calibration factor
\[ \text{CF}_{\text{As}} := 0.0001 \]
Mass rate of released As
\[ \text{MR}_{\text{As}} := \text{MR}_S \cdot \text{RR}_{\text{As}} \cdot \text{CF}_{\text{As}} \]
As concentration in seepage
\[ \text{C}_{\text{As}} := \frac{\text{MR}_{\text{As}}}{q} \]
\[ \text{C}_{\text{As}} = 1.935 \ \mu\text{g}/\text{L} \]

Cobalt

Release ratio of Co to S
\[ \text{RR}_{\text{Co}} := 0.03076 \]
Co calibration factor
\[ \text{CF}_{\text{Co}} := 0.0006 \]
Mass rate of released Co
\[ \text{MR}_{\text{Co}} := \text{MR}_S \cdot \text{RR}_{\text{Co}} \cdot \text{CF}_{\text{Co}} \]
Co concentration in seepage
\[ \text{C}_{\text{Co}} := \frac{\text{MR}_{\text{Co}}}{q} \]
\[ \text{C}_{\text{Co}} = 3.572 \ \mu\text{g}/\text{L} \]

Copper

Release ratio of Cu to S
\[ \text{RR}_{\text{Cu}} := 0.030598 \]
Cu calibration factor
\[ \text{CF}_{\text{Cu}} := 0.0005 \]
Mass rate of released Cu
\[ \text{MR}_{\text{Cu}} := \text{MR}_S \cdot \text{RR}_{\text{Cu}} \cdot \text{CF}_{\text{Cu}} \]
Cu concentration in seepage
\[ \text{C}_{\text{Cu}} := \frac{\text{MR}_{\text{Cu}}}{q} \]
\[ \text{C}_{\text{Cu}} = 2.961 \ \mu\text{g}/\text{L} \]
Nickel

\[ \text{RR}_{Ni} := 0.014307 \]
\[ \text{CF}_{Ni} := 0.0027 \]
\[ \text{MR}_{Ni} := \text{MR}_{S} \cdot \text{RR}_{Ni} \cdot \text{CF}_{Ni} \]
\[ \text{CN}_{Ni} := \frac{\text{MR}_{Ni}}{Q} \]

Release ratio of Ni to S
Ni calibration factor
Mass rate of released Ni \[ 3.183 \times 10^{-4} \]
Ni concentration in seepage \[ 7.477 \frac{\text{mg}}{\text{L}} \]

Zinc

\[ \text{RR}_{Zn} := 5.0629 \times 10^{-5} \]
\[ \text{CF}_{Zn} := 0.2596 \]
\[ \text{MR}_{Zn} := \text{MR}_{SO4} \cdot \text{RR}_{Zn} \cdot \text{CF}_{Zn} \]
\[ \text{C}_{Zn} := \frac{\text{MR}_{Zn}}{Q} \]

Release ratio of Zn to SO4
Zn calibration factor
Mass rate of released Zn \[ 3.244 \times 10^{-4} \]
Zn concentration in seepage \[ 7.621 \frac{\text{mg}}{\text{L}} \]
**Cell 2W Banks - Sulfur - Transient**

- **Map area (Table 1-33)**: \( A = 339.183 \text{ acre} \)
- **Percolation flux (from seepage spreadsheet with Barr edits)**: \( q = 7.82 \text{ in} / \text{yr} \)
- **Saturated hydraulic conductivity of tailings (Table 1-12a)**: \( K_s = 1.17 \times 10^{-3} \text{ cm} / \text{sec} \)
- **vanGenuchten parameter of tailings (Table 1-12a)**: \( \beta = 2 \)
- **Residual volumetric water content of tailings (Table 1-12a)**: \( \theta_r = 0.041 \)
- **Porosity of tailings (Table 1-12a)**: \( \phi = 0.412 \)
- **Specific gravity of tailings solids (Table 1-12a)**: \( G = 2.8 \)
- **Water density (standard value)**: \( \rho_w = 1.0 \text{ gm/cm}^3 \)
- **Tortuosity (Table 1-1, sheet 5)**: \( \tau = 0.273 \)
- **Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)**: \( D_a = 1.8 \times 10^{-5} \text{ m}^2 / \text{sec} \)
- **Empirical constant (Table 1-1, sheet 5)**: \( c = 3.28 \)
- **Free diffusion coeff of oxygen in water (Table 1-1, sheet 5)**: \( D_w = 2.2 \times 10^{-9} \text{ m}^2 / \text{sec} \)
- **Henry's constant for oxygen (Table 1-1, sheet 5)**: \( K_H = 33.9 \)
- **O2 concentration in air. Moles of O2 per unit volume of air (Table 1-1, sheet 5)**: \( C_o = 8.89 \text{ mol/m}^3 \)
- **Molecular weight of sulfate (standard value)**: \( W_{SO_4} = 96.07 \text{ gm/mole} \)
- **Molecular weight of sulfur (standard value)**: \( W_S = 32.066 \text{ gm/mole} \)
- **P50 SO4 distribution parameter for tailings (Table 1-19; P50 from GoldSim)**: \( R_{SO_4} = 1.95186 \text{ mg/kg/7 day} \)
- **Calibration factor for tailings (Table 1-1, sheet 5)**: \( CF = 0.185 \)
- **Temperature factor (computed in GS using numerous inputs)**: \( TF = 0.228589 \)
- **Freeze factor (from Table 1-1, sheet 3)**: \( FF = 0.28333 \)
- **mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6)**: \( \text{moleratio} = 0.444 \)
- **Sulfur content. Mass of S per unit mass of tailings. (Table 1-22)**: \( \text{Cont}_S = 329 \text{ mg/kg} \)
- **Initial concentration in tailings pore water** (Table 1-22): \( C_{O_{SO_4}} = 728 \text{ mg/L} \)

**LT VSMC coarse tailings**

- **Piecewise linear function to approximate DTW vs time**

\[
\begin{align*}
A &= 1372626 \text{ m}^2 \\
q &= 7.82 \text{ in/yr} \\
K_s &= 1.17 \times 10^{-3} \text{ cm/sec} \\
\beta &= 2 \\
\theta_r &= 0.041 \\
\phi &= 0.412 \\
G &= 2.8 \\
\rho_w &= 1.0 \text{ gm/cm}^3 \\
\tau &= 0.273 \\
D_a &= 1.8 \times 10^{-5} \text{ m}^2/\text{sec} \\
c &= 3.28 \\
D_w &= 2.2 \times 10^{-9} \text{ m}^2/\text{sec} \\
K_H &= 33.9 \\
C_o &= 8.89 \text{ mol/m}^3 \\
W_{SO_4} &= 96.07 \text{ gm/mole} \\
W_S &= 32.066 \text{ gm/mole} \\
R_{SO_4} &= 1.95186 \text{ mg/kg/7 day} \\
CF &= 0.185 \\
TF &= 0.228589 \\
FF &= 0.28333 \\
molaratio &= 0.444 \\
\text{Cont}_S &= 329 \text{ mg/kg} \\
C_{O_{SO_4}} &= 728 \text{ mg/L} \\
t_1 &= 0 \text{ yr} \\
t_2 &= 2 \text{ yr} \\
t_3 &= 7 \text{ yr} \\
D_1 &= 96.4 \text{ ft} \\
D_2 &= 89.0 \text{ ft} \\
D_3 &= 91.4 \text{ ft} \\
\end{align*}
\]
\[ t_4 := 10 \text{ yr} \quad D_4 := 90.6 \text{ ft} \]
\[ t_5 := 45 \text{ yr} \quad D_5 := 104.3 \text{ ft} \]
\[ t_6 := 50 \text{ yr} \quad D_6 := 108.3 \text{ ft} \]
\[ t_7 := 200 \text{ yr} \quad D_7 := 108.3 \text{ ft} \]

\[ \text{DTW}(t) := \begin{cases} 
D_1 + \frac{D_2 - D_1}{t_2 - t_1} (t - t_1) & \text{if } t_1 \leq t \leq t_2 \\
D_2 + \frac{D_3 - D_2}{t_3 - t_2} (t - t_2) & \text{if } t_2 < t \leq t_3 \\
D_3 + \frac{D_4 - D_3}{t_4 - t_3} (t - t_3) & \text{if } t_3 < t \leq t_4 \\
D_4 + \frac{D_5 - D_4}{t_5 - t_4} (t - t_4) & \text{if } t_4 < t \leq t_5 \\
D_5 + \frac{D_6 - D_5}{t_6 - t_5} (t - t_5) & \text{if } t_5 < t \leq t_6 \\
D_6 + \frac{D_7 - D_6}{t_7 - t_6} (t - t_6) & \text{if } t_6 < t \leq t_7 
\end{cases} \]

\[ \rho_b := G \rho_w (1 - \phi) \quad \text{Tailings dry bulk density. Mass of solids per unit bulk volume.} \]
\[ \gamma := 1 - \frac{1}{\beta} \quad \text{Computed vanGenuchten parameter} \]

\[ K_{ss} := K_s \left( \frac{ss \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \left[ 1 - \left( \frac{ss \phi - \theta_r}{\phi - \theta_r} \right) \right]^{2} \quad \text{Unsaturated hydraulic conductivity as a function of saturation (ss) based on vanGenuchten relationship} \]

\[ f(ss) := q - K(ss) \quad ss := 0.4 \quad \text{Root equation and saturation guess} \]

\[ \text{SAT} := \text{root}(f(ss), ss) \quad \text{Computed saturation associated with flux (q)} \]

\[ q - K(\text{SAT}) = -3.452 \times 10^{-7} \text{ in. yr}^{-1} \quad \text{Confirm root calculation (result should be approx zero)} \]

\[ D := \tau D'' (1 - \text{SAT})^c + \tau \text{SAT} \frac{D_w}{K_H} \quad \text{Effective O2 diffusion coeff used in GS.} \]

\[ 1.335 \times 10^{-6} \quad D = 1.335 \times 10^{-6} \text{ m}^2 \text{ s}^{-1} \quad \text{This diffusion coeff is referenced to void volume.} \]

\[ \text{MRM}_{SO4} := R_{SO4} CF \cdot TF \cdot (1 - FF) \quad \text{Mass rate of released SO4 per unit mass of tailings solids} \]

\[ R_{SO4} = 1.952 \text{ mg kg}^{-1} \text{ day}^{-1} \quad \text{Effect of three factors} \]

\[ \text{CF} \cdot \text{TF} \cdot (1 - FF) = 0.030 \]

\[ R_{O2} := \frac{\text{MRM}_{SO4}}{W_{SO4} \text{ molaratio}} \frac{\rho_b}{\phi} \quad \text{Molar consumption rate of O2 per unit void volume} \]

\[ 0.00554 R_{O2} = 0.00554 \text{ mol m}^{-3} \text{ day}^{-1} \]
Thickness of sulfate reaction zone if controlled by diffusion. Note: both $D$ and $R_{O_2}$ are referenced to void volume.

$$d := \sqrt{\frac{2 \cdot D \cdot C_0}{R_{O_2}}}$$

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

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

Mass rate of released sulfate

$$MR_{SO_4}(t) := MRM_{SO_4} \cdot b(t) \cdot A \cdot \rho_b$$

Mass rate of released S per unit bulk volume

$$MR_V := R_{O_2} \cdot W_S \cdot \text{moleratio} \cdot \phi$$

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

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

Mass rate of released S

$$M_S(t) := \int_{0}^{t} MR_S(t) \, dt$$

Total mass of available sulfur

$$MT_S := \text{Cont}_S \cdot \rho_b \cdot A \cdot DTW(200-yr)$$

Root equation and time guess

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

Sulfate depletion time > 200 yr

$$\begin{align*}
MR_{AS}(t) & := \begin{cases} 
MR_S(t) \cdot b(t) & \text{if } 0 \leq t < t_{end} \\
0 & \text{if } t \geq t_{end}
\end{cases} \\
MR_S(t) & := \begin{cases} 
MRA_S(t) \cdot A & \text{if } 0 \leq t < t_{end} \\
0 & \text{if } t \geq t_{end}
\end{cases}
\end{align*}$$

Seepage flow rate

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

Water volume in unsat zone

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

$$\begin{align*}
d & = 50.923 \, \text{m} \\
& = 167.07 \, \text{ft}
\end{align*}$$

$$MR_S = 5.375 \times 10^{-11} \, \frac{\text{kg}}{\text{m}^3 \cdot \text{s}}$$

$$MT_S = 2.454 \times 10^4 \, \text{tonne}$$

$$Q_{seep} = 136.942 \, \text{gpm}$$

$$V_w = 6.12 \times 10^6 \, \text{m}^3$$
Set up dimensionless equations using m-kg-day units

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

\[ \text{MR}(t) := \frac{\text{MR}_\text{SO}_4(t \cdot \text{day})}{\text{kg} \cdot \text{day}^{-1}} \]  
Mass rate of sulfate generation in kg/day

\[ \text{MR}(t) := \text{MR}(t) \text{ if } t < t_{\text{end}} \]  
\[ = 0 \text{ otherwise} \]  
Sulfate mass generation function

\[ V := \frac{V_w}{m^3} \]  
Water volume in m$^3$  \[ V = 6.12 \times 10^6 \]

\[ Q := \frac{Q_{\text{seep}}}{m^3 \cdot \text{day}^{-1}} \]  
Seepage flow rate in m$^3$/day  \[ Q = 746.469 \]

\[ \text{Co} := \frac{\text{Co}_\text{SO}_4}{\text{kg} \cdot m^{-3}} \]  
Initial sulfate conc in kg/m$^3$  \[ \text{Co} = 0.728 \]

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

\[ C_{\text{SO}_4}(t) := \left( \frac{t}{\text{day}} \right) \cdot \text{kg} \cdot m^{-3} \]  
Seepage sulfate conc as a function of time  \[ t_{\text{e}} := 0, 1 \cdot \text{yr}., 200 \cdot \text{yr} \]
Sulfate Generation - Cell 2W Coarse

\[ A := 890625 \, \text{m}^2 \]
\[ q := 13.27 \, \frac{\text{in}}{\text{yr}} \]
\[ K_s := 1.17 \times 10^{-3} \, \frac{\text{cm}}{\text{sec}} \]
\[ \beta := 2 \]
\[ \theta_r := 0.041 \]
\[ \phi := 0.412 \]
\[ G := 2.8 \]
\[ \rho_w := 1. \, \frac{\text{gm}}{\text{cm}^3} \]
\[ \tau := 0.273 \]
\[ D_a := 1.8 \times 10^{-5} \, \frac{\text{m}^2}{\text{sec}} \]
\[ c := 3.28 \]
\[ D_w := 2.2 \times 10^{-9} \, \frac{\text{m}^2}{\text{sec}} \]
\[ K_H := 33.9 \]
\[ C_o := 8.89 \, \frac{\text{mol}}{\text{m}^3} \]
\[ W_{SO4} := 96.07 \, \frac{\text{gm}}{\text{mole}} \]
\[ W_S := 32.066 \, \frac{\text{gm}}{\text{mole}} \]
\[ R_{SO4} := 1.95186 \, \frac{\text{mg}}{\text{kg} \cdot \text{7 day}} \]
\[ \text{CF} := 0.185 \]
\[ \text{TF} := 0.228589 \]
\[ \text{FF} := 3.4 \]
\[ \text{moleratio} := \frac{4}{9} \]
\[ \text{Cont}_S := 329 \, \frac{\text{mg}}{\text{kg}} \]
\[ \text{Co}_{SO4} := 560 \, \frac{\text{mg}}{\text{L}} \]
\[ t_1 := 0 \, \text{yr} \]
\[ t_2 := 18 \, \text{yr} \]
\[ t_3 := 45 \, \text{yr} \]

LTVSMC coarse tailings

Map area (Table 1-33)
\[ A = 220.078 \, \text{acre} \]

Percolation flux (from seepage spreadsheet with Barr edits)

Saturated hydraulic conductivity of tailings (Table 1-12b)

vanGenuchten parameter of tailings (Table 1-12a)

Residual volumetric water content of tailings (Table 1-12a)

Porosity of tailings (Table 1-12a)

Specific gravity of tailings (Table 1-12a)

Water density (standard value)

Tortuosity (Table 1-1, sheet 5)

Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)

Empirical constant (Table 1-1, sheet 5)

Free diffusion coeff of oxygen in water (Table 1-1, sheet 5)

Henry's constant for oxygen (Table 1-1, sheet 5)

O2 concentration in air. Moles of O2 per unit volume of air (Table 1-1, sheet 5)

Molecular weight of sulfate (standard value)

Molecular weight of sulfur (standard value)

P50 SO4 distribution parameter of tailings (Table 1-19; P50 from GoldSim)

Calibration factor for tailings (Table 1-1, sheet 5)

Temperature factor (computed in GS using numerous inputs)

Freeze factor (from Table 1-1, sheet 3)

mole SO4 / mole O2 = mole S / mole O2

moleratio = 0.444

Sulfur content. Mass of S per unit mass of tailings.

Initial concentration in tailings pore water

Piecewise linear function to approximate DTW vs time
\[ t_4 := 50 \text{ yr} \quad D_4 := 155.4 \text{ ft} \]
\[ t_5 := 200 \text{ yr} \quad D_5 := 155.4 \text{ ft} \]

\[
DTW(t) := \begin{cases} 
D_1 + \frac{D_2 - D_1}{t_2 - t_1} (t - t_1) & \text{if } t_1 \leq t \leq t_2 \\
D_2 + \frac{D_3 - D_2}{t_3 - t_2} (t - t_2) & \text{if } t_2 < t \leq t_3 \\
D_3 + \frac{D_4 - D_3}{t_4 - t_3} (t - t_3) & \text{if } t_3 < t \leq t_4 \\
D_4 + \frac{D_5 - D_4}{t_5 - t_4} (t - t_4) & \text{if } t_4 < t \leq t_5 
\end{cases}
\]

\[ \rho_b := G \rho_w (1 - \phi) \quad \text{Tailings dry bulk density. Mass of solids per unit bulk volume.} \]
\[ \gamma := 1 - \frac{1}{\beta} \quad \text{Computed van Genuchten parameter} \]

\[ K_{(ss)} := K_s \left( \frac{SS \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \left[ \frac{1}{1 - \left( \frac{SS \cdot \phi - \theta_r}{\phi - \theta_r} \right)^2} \right] \quad \text{Unsaturated hydraulic conductivity as a function of saturation (ss) based on van Genuchten relationship} \]

\[ f(ss) := q - K_{(ss)} \quad ss := 0.5 \quad \text{Root equation and saturation guess} \]

\[ SAT := \text{root}(f(ss), ss) \quad \text{Computed saturation associated with flux (q)} \]

\[ q - K(SAT) = -3.36 \times 10^{-6} \text{ in yr}^{-1} \quad \text{Confirm root calculation (result should be approx zero)} \]

\[ D := \tau \cdot D_a \cdot (1 - SAT)^c + \tau \cdot SAT \cdot \frac{D_w}{K_s} \quad \text{Effective O2 diffusion coeff used in GS.} \]

\[ \text{This diffusion coeff is referenced to void volume.} \]

\[ R_{SO4} := R_{SO4} \cdot \text{CF-TF} \cdot (1 - \text{FF}) \quad \text{Mass rate of released SO4 per unit mass of tailings solids} \]

\[ R_{O2} := \frac{MRM_{SO4}}{W_{SO4} \cdot \text{molaratio}} \cdot \frac{\rho_b}{\phi} \quad \text{Molar consumption rate of O2 per unit void volume} \]

\[ d := \sqrt{\frac{2 \cdot D \cdot C_0}{R_{O2}}} \quad \text{Thickness of sulfate reaction zone if controlled by diffusion. Note: both D and R_{O2} are referenced to void volume.} \]

\[ b(t) := \text{min}(d, DTW(t)) \quad \text{Actual thickness of sulfate reaction zone. Minimum of diffusion controlled reaction} \]
Mass rate of released sulfate

$$MR_{SO_4}(t) := MRM_{SO_4} b(t) \cdot A \cdot \rho_b$$

Mass rate of released S per unit bulk volume

$$MRV_S := R_{O_2} \cdot W_S \cdot \text{molaratio} \cdot \phi$$

Mass rate of released S per unit map area (m²)

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

Mass rate of released S

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

Total mass of available sulfur

$$MT_S := \text{Cont}_S \cdot \rho_b \cdot A \cdot DTW(200 \text{ yr})$$

Root equation and time guess

$$ff(tt) := M_S(tt) - MT_S \quad tt := 100 \text{ yr}$$

Sulfate depletion time > 200 yr

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

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

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

$$MR_S(t) := \begin{cases} MR_A(t) \cdot A & \text{if } 0 \leq t < t_{\text{end}} \\ 0 & \text{if } t \geq t_{\text{end}} \end{cases}$$

Seepage flow rate

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

Water volume in unsat zone

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

$$Q_{\text{seep}} = 150.78 \text{ gpm}$$

$$V_w = 6.184 \times 10^6 \text{ m}^3$$
Set up dimensionless equations using m-kg-day units

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

$$\text{MR}(t) := \frac{\text{MRSO}_4(t \cdot \text{day})}{\text{kg} \cdot \text{day}^{-1}}$$  
Mass rate of sulfate generation in kg/day

$$M(t) := \begin{cases} \text{MR}(t) & \text{if } t < t_{\text{end}} \\ 0 & \text{otherwise} \end{cases}$$  
Sulfate mass generation function

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

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

$$C_{\text{SO}_4} := \frac{C_{\text{SO}_4}}{\text{kg} \cdot \text{m}^{-3}}$$  
Initial sulfate conc in kg/m$^3$  
$$C_{\text{SO}_4} = 0.56$$

Given  
$$\frac{d}{dt} C(t) = \frac{M(t) - Q \cdot C(t)}{V}$$  
$$C(0) = C_0$$  
$$C := \text{Odesolve}(t, 197, 365)$$  
Governing ODE and IC

$$C_{\text{SO}_4}(t) := C \left( \frac{t}{\text{day}} \right) \text{kg} \cdot \text{m}^{-3}$$  
Seepage sulfate conc as a function of time  
$$t := 0, 1\cdot\text{yr}.. 200\cdot\text{yr}$$
Sulfate Generation - Cell 2W Fine

Map area (Table 1-33)  \( A = 748.073 \text{ acre} \)

Percolation flux (from seepage spreadsheet with Barr edits)

Saturated hydraulic conductivity of tailings (Table 1-12b)

van Genuchten parameter of tailings (Table 1-12a)

Residual volumetric water content of tailings (Table 1-12a)

Porosity of tailings (Table 1-12a)

Specific gravity of tailings solids (Table 1-12a)

Water density (standard value)

Tortuosity (Table 1-1, sheet 5)

Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)

Empirical constant (Table 1-1, sheet 5)

Free diffusion coefficient of oxygen in water (Table 1-1, sheet 5)

Henry's constant for oxygen (Table 1-1, sheet 5)

O2 concentration in air. Moles of O2 per unit volume of air (Table 1-1, sheet 5)

Molecular weight of sulfate (standard value)

Molecular weight of sulfur (standard value)

P50 SO4 distribution parameter for tailings (Table 1-19; P50 from GoldSim)

Calibration factor for tailings (Table 1-1, sheet 5)

Temperature factor (computed in GS using numerous inputs)

Freeze factor (from Table 1-1, sheet 3)

mole SO4 / mole O2 = mole S / mole O2 (Table 1-1, sheet 6)

moleratio = 0.444

Sulfur content. Mass of S per unit mass of tailings. (Table 1-22)

Initial concentration in tailings pore water

Piecewise linear function to approximate DTW vs time
t_4 := 18 \text{ yr} & \quad D_4 := 59.8 \text{ ft} \\
 t_5 := 45 \text{ yr} & \quad D_5 := 81.5 \text{ ft} \\
 t_6 := 50 \text{ yr} & \quad D_6 := 89.4 \text{ ft} \\
 t_7 := 200 \text{ yr} & \quad D_7 := 89.4 \text{ ft} \\
 DTW(t) := \\
 D_1 & + \left( \frac{D_2 - D_1}{t_2 - t_1} \right)(t - t_1) \quad \text{if} \quad t_1 \leq t \leq t_2 \\
 D_2 & + \left( \frac{D_3 - D_2}{t_3 - t_2} \right)(t - t_2) \quad \text{if} \quad t_2 < t \leq t_3 \\
 D_3 & + \left( \frac{D_4 - D_3}{t_4 - t_3} \right)(t - t_3) \quad \text{if} \quad t_3 < t \leq t_4 \\
 D_4 & + \left( \frac{D_5 - D_4}{t_5 - t_4} \right)(t - t_4) \quad \text{if} \quad t_4 < t \leq t_5 \\
 D_5 & + \left( \frac{D_6 - D_5}{t_6 - t_5} \right)(t - t_5) \quad \text{if} \quad t_5 < t \leq t_6 \\
 D_6 & + \left( \frac{D_7 - D_6}{t_7 - t_6} \right)(t - t_6) \quad \text{if} \quad t_6 < t \leq t_7 \\
 \\
 \rho_b := G \rho_w (1 - \phi) & \quad \text{Tailings dry bulk density. Mass of solids per unit bulk volume.} \\
 \gamma := 1 - \frac{1}{\beta} & \quad \text{Computed vanGenuchten parameter} \\
 K_{ss}(ss) := K_s \left( \frac{ss \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \left[ 1 - \left[ 1 - \left( \frac{ss \phi - \theta_r}{\phi - \theta_r} \right) \right]^{-\gamma} \right]^{2} & \quad \text{Unsaturated hydraulic conductivity as a function of saturation (ss) based on vanGenuchten relationship} \\
 f(ss) := q - K(ss) & \quad ss := 0.8 \\
 SAT := \text{root}(f(ss), ss) & \quad \text{Root equation and saturation guess} \\
 q - K(SAT) = -4.179 \times 10^{-9} \text{ in} \text{ yr}^{-1} & \quad \text{Computed saturation associated with flux (q) SAT = 0.6741} \\
 D := \tau \cdot D_a (1 - SAT)^c + \tau \cdot SAT \cdot \frac{D_w}{K_H} & \quad \text{Effective O2 diffusion coeff used in GS. D = 1.243 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}} \\
 MRM_{SO4} := R_{SO4} \cdot CF \cdot TF \cdot (1 - FF) & \quad \text{Mass rate of released SO4 per unit mass of tailings solids} \\
 \text{MRM}_{SO4} & = R_{SO4} 1.952 \text{ mg kg}^{-1} \text{ day}^{-1} \\
 \text{Effect of three factors} & \quad \text{CF} \cdot \text{TF} \cdot (1 - FF) = 0.059 \\
 RO_2 := \frac{\text{MRM}_{SO4}}{\rho_b \cdot W_{SO4} \cdot \text{molaratio}} & \quad \text{Molar consumption rate of O2 per unit void volume} \\
 RO_2 & = 0.00805 \text{ mol m}^{-3} \text{ day}^{-1}
Thickness of sulfate reaction zone if controlled by diffusion. Note: both D and $R_{O2}$ are referenced to void volume.

$$d := \sqrt{\frac{2 \cdot D \cdot C_0}{R_{O2}}}$$

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

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

$$\text{Mass rate of released sulfate}$$

$$\text{Mass rate of released S per unit bulk volume}$$

$$\text{Mass rate of released S per unit map area (m}^2)$$

$$\text{Total mass of available sulfur}$$

$$\text{Sulfate depletion time > 200 yr Set}$$

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

$$V_w := SAT \cdot \phi \cdot A \cdot DTW(200\text{-yr})$$
Set up dimensionless equations using m-kg-day units

\[ t_{\text{end}} := \frac{t_{\text{end}}}{\text{day}} \]
End of sulfate generation in days \( t_{\text{end}} = 7.341 \times 10^4 \)

\[ \text{MR}(t) := \frac{\text{MRSO}_4(t \cdot \text{day})}{\text{kg} \cdot \text{day}^{-1}} \]
Mass rate of sulfate generation in kg/day

\[ M(t) := \begin{cases} \text{MR}(t) & \text{if } t < t_{\text{end}} \\ 0 & \text{otherwise} \end{cases} \]
Sulfate mass generation function

\[ V := \frac{V_w}{m^3} \]
Water volume in m\(^3\) \( V = 2.741 \times 10^7 \)

\[ Q := \frac{Q_{\text{seep}}}{m^3 \cdot \text{day}^{-1}} \]
Seepage flow rate in m\(^3\)/day \( Q = 3.354 \times 10^3 \)

\[ C_0 := \frac{C_{\text{SO}_4}}{\text{kg} \cdot \text{m}^{-3}} \]
Initial sulfate conc in kg/m\(^3\) \( C_0 = 0.272 \)

Given
\[ \frac{d}{dt} C(t) = \frac{M(t) - Q \cdot C(t)}{V} \]
\[ C(0) = C_0 \]
\[ C := \text{Odesolve}(t, 196.365) \]
Governing ODE and IC

\[ C_{\text{SO}_4}(t) := \left( C \left( \frac{t}{\text{day}} \right) \right) \cdot \text{kg} \cdot \text{m}^{-3} \]
Seepage sulfate conc as a function of time \( t := 0, 1 \cdot \text{yr}., 200 \cdot \text{yr} \)
North Beach - Misc Chemicals - Closure

Mixture of fine and coarse NM tailings with bentonite amendment

\[ q := 6.07 \text{ in yr} \]

\[ A := 75.67 \text{ acre} \]

Tailings

\[ F := 0.35 \]

\[ R_{SO4}^{\text{coarse}} := 11.83451 \frac{\text{mg}}{\text{kg} \cdot \text{day}} \]

\[ R_{SO4}^{\text{fine}} := 19.32669 \frac{\text{mg}}{\text{kg} \cdot \text{day}} \]

\[ CF := 1 \]

\[ \text{DTW} := 137.3 \text{ ft} \]

\[ G := 3.0 \]

\[ \phi := 0.41 \]

\[ K_s := 1.04961 \times 10^{-3} \frac{\text{cm}}{\text{sec}} \]

\[ \theta_r := 0.0113 \]

\[ \alpha := 0.008775 \cdot \text{cm}^{-1} \]

\[ \beta := 2.6944 \]

Bentonite-Amended Layer

\[ \phi_{bn} := 0.36 \]

\[ K_{sbn} := 5.56 \times 10^{-6} \frac{\text{cm}}{\text{sec}} \]

\[ \theta_{rbn} := 0.07 \]

\[ \beta_{bn} := 1.09 \]

\[ \alpha_{bn} := 0.005 \cdot \text{cm}^{-1} \]

General Inputs

\[ \tau := 0.273 \]

\[ D_a := 1.8 \times 10^{-5} \frac{\text{m}^2}{\text{sec}} \]

\[ c := 3.28 \]

\[ D_w := 2.2 \times 10^{-9} \frac{\text{m}^2}{\text{sec}} \]

\[ K_H := 33.9 \]

\[ C_o := 8.89 \frac{\text{mol}}{\text{m}^3} \]

\[ W_{SO4} := 96.07 \frac{\text{gm}}{\text{mole}} \]

\[ W_S := 32.066 \frac{\text{gm}}{\text{mole}} \]

\[ \mu_g := 10^{-6} \text{ gm} \]

Blue values are generated by GoldSim model
Temperature factor (computed in GS using numerous inputs)

Freeze factor (from Table 1-1, sheet 3)

mole SO4 / mole O2 = mole S / mole O2

Molecular weight of O2

Water density (standard value)

Calcs for LTV Bulk Tailings

Bulk density

Computed vanGenuchten parameter

Saturation

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

For unit gradient conditions

Suction head in tailings for unit gradient conditions

Calcs for Bentonite-Amended Tailings

Computed vanGenuchten parameter

Saturation at bottom of the bentonite layer. Assumed to apply to entire layer.

Effective O2 diffusion coeff used in GS. This parameter is referenced to the void volume.

Diffusion Related Calcs

Mass rate of released SO4 per unit mass of tailings solids

MRM SO4 = RSO4 CF · TF · (1 - FF)
Effect of three factors

\[ CF \cdot TF \cdot (1 - FF) = 0.164 \]

Molar consumption rate of \( \text{O}_2 \) per unit volume of voids

\[ r_{nm} = 0.23956 \text{ mol m}^{-3} \cdot \text{day}^{-1} \]

Thickness of sulfate reaction zone if controlled by diffusion

\[ d = 0.166 \text{ m} \]

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

\[ b = 0.166 \text{ m} \]

**Sulfate Calcs**

\[ \text{MRV}_{\text{SO}_4} := \text{MRM}_{\text{SO}_4} \cdot \rho \]

\[ \text{MR}_{\text{SO}_4} := \text{MRV}_{\text{SO}_4} \cdot A \cdot b \]

\[ q := q \cdot A \]

\[ C_{\text{SO}_4} := \frac{\text{MR}_{\text{SO}_4}}{Q} \]

\[ d := \sqrt{\frac{2 \cdot D_{bn} \cdot C_0}{r_{nm}}} \]

\[ b := \min(d, DTW) \]

**Sulfur Calcs**

\[ \text{MRV}_S := \text{MRV}_{\text{SO}_4} \frac{W_S}{W_{\text{SO}_4}} \]

\[ \text{MR}_{SA} := \text{MRV}_S \cdot b \]

\[ \text{MR}_S := \text{MR}_{SA} \cdot A \]

\[ \text{MR}_{V_H} := \text{MR}_{V_H}\frac{W_{\text{H}_2\text{O}}}{W_{\text{H}_2\text{O}}} \]

\[ \text{MR}_{S_H} := \text{MR}_{V_H} \cdot A \]

\[ q := q \cdot A \]

\[ C_{\text{H}_2\text{O}} := \frac{\text{MR}_{V_H}}{Q} \]

\[ \text{N}_1 := \text{N}_1 \cdot A \]

\[ \text{N}_2 := \text{N}_2 \cdot A \]

\[ \text{T}_{\text{H}_2\text{O}} := \text{T}_{\text{H}_2\text{O}} \cdot A \]

**GoldSim Output**

- **Sulfate Concentration in Seepage**
  - Initial: 237.5 mg/liter
  - Final: 235.79 mg/liter

- **Seepage Flow Rate**
  - Initial: 23.714 gpm
  - Final: 233.99 mg/m²/day

- **Mass Rate of Sulfur Generation**
  - Initial: 10.173 kg/day
  - Final: 232.552 mg/m²·day
Other Chemicals

Arsenic

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

$$CF_{As} := 1$$ \quad \text{As calibration factor}

$$MR_{As} := MR_S \cdot RR_{As} \cdot CF_{As}$$ \quad \text{Mass rate of released As} \quad 6.822 \times 10^{-3} \quad \text{MR}_{As} = 6.780 \times 10^{-3} \cdot \text{tonne yr}^{-1}

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

Copper

$$RR_{Cu} := F \cdot 0.09250 + (1 - F) \cdot 0.208367$$ \quad \text{Release ratio of Cu to S}

$$CF_{Cu} := 1$$ \quad \text{Cu calibration factor}

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

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

Nickel

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

$$CF_{Ni} := 1$$ \quad \text{Ni calibration factor}

$$MR_{Ni} := MR_S \cdot RR_{Ni} \cdot CF_{Ni}$$ \quad \text{Mass rate of released Ni} \quad 1.018 \times 10^{-2} \quad \text{MR}_{Ni} = 1.012 \times 10^{-2} \cdot \text{tonne yr}^{-1}

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

Cobalt

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

$$CF_{Co} := 1$$ \quad \text{Co calibration factor}

$$MR_{Co} := MR_{Ni} \cdot RR_{Co} \cdot CF_{Co}$$ \quad \text{Mass rate of released Co} \quad 7.851 \times 10^{-4} \quad \text{MR}_{Co} = 7.803 \times 10^{-4} \cdot \text{tonne yr}^{-1}

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

Zinc

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

$$CF_{Zn} := 1$$ \quad \text{Zn calibration factor}

$$MR_{Zn} := MR_{Ni} \cdot RR_{Zn} \cdot CF_{Zn}$$ \quad \text{Mass rate of released Zn} \quad 1.713 \times 10^{-3} \quad \text{MR}_{Zn} = 1.702 \times 10^{-3} \cdot \text{tonne yr}^{-1}

$$C_{Zn} := \frac{MR_{Zn}}{Q}$$ \quad \text{Zn concentration in seepage} \quad C_{Zn} = 36.051 \cdot \frac{\mu g}{L}
North Dam - Misc Chemicals - Closure

LTV bulk tailings

\[ q := 6.07 \frac{\text{in}}{\text{yr}} \]
\[ A := 249 \text{ acre} \]

LTVSMC bulk tailings with bentonite amendment

\[ \mu g := 10^{-6} \text{ gm} \]

Map area of North Dam

Blue values are generated by GoldSim model

### LTV bulk tailings

- **R\text{SO}_4 := 1.95186 \frac{\text{mg}}{\text{kg} \cdot \text{day}}**
- **CF_{\text{coarse}} := 0.185**
- **CF_{\text{fine}} := 0.360**
- **DTW := 152 \text{ ft}**
- **G := 2.85**
- **\phi := 0.440**
- **K_s := 8.02 \times 10^{-5} \frac{\text{cm}}{\text{sec}}**
- **\theta_r := 0.048**
- **\alpha := 0.011 \cdot \text{cm}^{-1}**
- **\beta := 2.0**

### Bentonite-Amended Layer

- **\phi_{bn} := 0.36**
- **K_{sbn} := 5.56 \times 10^{-6} \frac{\text{cm}}{\text{sec}}**
- **\theta_{rbn} := 0.07**
- **\beta_{bn} := 1.09**
- **\alpha_{bn} := 0.005 \cdot \text{cm}^{-1}**

### General Inputs

- **\tau := 0.273**
- **D_a := 1.8 \times 10^{-5} \frac{\text{m}^2}{\text{sec}}**
- **c := 3.28**
- **D_w := 2.2 \times 10^{-9} \frac{\text{m}^2}{\text{sec}}**
- **K_H := 33.9**
- **C_o := 8.89 \frac{\text{mol}}{\text{m}^3}**
- **W_{SO_4} := 96.07 \frac{\text{gm}}{\text{mole}}**
- **W_S := 32.066 \frac{\text{gm}}{\text{mole}}**
- **TF := 0.228589**

P50 SO4 distribution parameter (GS for P50 value)

SO4 calibration factor for coarse tailings (Table 1-1, sheet 5)

SO4 calibration factor for fine tailings (Table 1-1, sheet 5)

Depth to water table during closure (Table 1-29)

Specific gravity (Table 1-12a)

Porosity (Table 1-12a)

Saturated hydraulic conductivity (Table 1-12a)

Residual water content (Table 1-12a)

vanGenuchten parameter (Table 1-12a)

vanGenuchten parameter for bentonite amended tailings (Table 1-1, sheet 4)

Porosity of bentonite amended tailings (Table 1-1, sheet 4)

Saturated hydraulic conductivity of bentonite amended tailings (Table 1-1; sheet 4)

Residual volumetric water content for bentonite amended tailings (Table 1-1, sheet 4)

vanGenuchten parameter for bentonite amended tailings (Table 1-1, sheet 4)

vanGenuchten parameter for bentonite amended tailings (Table 1-1, sheet 4)

Tortuosity (Table 1-1, sheet 5)

Free diffusion coefficient of oxygen in air (Table 1-1, sheet 5)

Empirical constant (Table 1-1, sheet 5)

Free diffusion coeff of oxygen in water (Table 1-1, sheet 5)

Henry's constant for oxygen (Table 1-1, sheet 5)

O2 concentration in air (Table 1-1, sheet 5)

Molecular weight of sulfate (standard value)

Molecular weight of sulfur (standard value)

Temperature factor (computed in GS using numerous inputs)
\[
\begin{align*}
FF & := \frac{3.4}{12} \quad \text{Freeze factor (from Table 1-1, sheet 3)} \\
moleratio & := \frac{4}{9} \quad \text{mole SO}_4 / \text{mole O}_2 = \text{mole S / mole O}_2 \quad \text{(Table 1-1, sheet 6)} \\
W_{O2} & := 32 \frac{\text{gm}}{\text{mole}} \quad \text{Molecular weight of O}_2 \\
\rho_w & := 1 \frac{\text{gm}}{\text{cm}^3} \quad \text{Water density (standard value)}
\end{align*}
\]

**Calcs for LTV Bulk Tailings**

\[
\begin{align*}
\rho & := G\rho_w(1 - \phi) \quad \text{Bulk density} \\
\gamma & := 1 - \frac{1}{\beta} \quad \text{Computed vanGenuchten parameter} \\
Sat & := 0.490864 \quad \text{Saturation} \\
\end{align*}
\]

\[
\begin{align*}
K_{tv} & := K_s \left( \frac{\text{Sat} \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{0.5} \left[ 1 - \left( \frac{1}{\gamma} \frac{\text{Sat} \cdot \phi - \theta_r}{\phi - \theta_r} \right)^{1/\gamma} \right]^2 \quad \text{Unsaturated hydraulic conductivity as a function of saturation (Sat) based on vanGenuchten relationship and unit hydraulic gradient}
\end{align*}
\]

\[
\begin{align*}
h & := \frac{1}{\alpha} \left[ \frac{1}{\gamma} \left( \frac{\phi - \theta_r}{\text{Sat} \cdot \phi - \theta_r} \right) \right]^{1/\gamma} - 1 \quad \text{Suction head in tailings for unit gradient conditions}
\end{align*}
\]

**Calcs for Bentonite-Amended Tailings**

\[
\begin{align*}
\gamma_{bn} & := 1 - \frac{1}{\beta_{bn}} \quad \text{Computed vanGenuchten parameter} \\
\text{Sat}_{bn} & := \frac{1}{\phi_{bn}} \left[ \theta_{rbn} + \frac{\phi_{bn} - \theta_{rbn}}{1 + \left( \alpha_{bn} h \right)^{\beta_{bn}}} \right]^{\gamma_{bn}} \quad \text{Saturation at bottom of the bentonite layer. Assumed to apply to entire layer.} \quad \text{Sat}_{bn} = 0.9566 \quad 0.9563
\end{align*}
\]

\[
\begin{align*}
D_{bn} & := \tau \cdot D_a \left( 1 - \text{Sat}_{bn} \right)^\psi + \tau \cdot \text{Sat}_{bn} \frac{D_w}{K_H} \quad \text{Effective O}_2 \text{ diffusion coeff used in GS. This parameter is referenced to the void volume.} \quad D_{bn} = 1.835 \times 10^{-10} \text{ m}^2 / \text{s} \quad 1.876 \times 10^{-10}
\end{align*}
\]

**Diffusion Related Calcs**

\[
\begin{align*}
\text{CF} & := \frac{\text{CF}_{fine} + \text{CF}_{coarse}}{2} \quad \text{Sulfate calibration factor} \\
\text{MRM}_{SO4} & := R_{SO4} \cdot \text{CF} \cdot \text{TF} \cdot (1 - \text{FF}) \quad \text{Mass rate of released SO}_4 \text{ per unit mass of tailings solids} \quad \text{MRM}_{SO4} = 0.087 \frac{\text{mg}}{\text{kg} \cdot \text{day}}
\end{align*}
\]
Effect of three factors

Molar consumption rate of O2 per unit volume of voids

\[ r_{nm} := \frac{\text{MRM}_\text{SO}_4}{\text{W}_\text{SO}_4 \cdot \text{moleratio} \cdot \phi} \]

\[ d := \sqrt{\frac{2 \cdot D_{bn} \cdot C_o}{r_{nm}}} \]

b := min(d, DTW)

\[ r_{nm} = 0.00740 \text{ mol m}^3 \text{ mol}^{-1} \text{ s}^{-1} \]

\[ d = 0.516 \text{ m} \]

\[ b = 0.516 \text{ m} \]

\[ b_{\text{min}} = 0.522 \]

Sulfate Calcs

\[ \text{MRV}_\text{SO}_4 := \text{MRM}_\text{SO}_4 \cdot \rho \]

\[ \text{MRSO}_4 := \text{MRV}_\text{SO}_4 \cdot A \cdot b \]

\[ Q := q \cdot A \]

\[ C_{\text{SO}_4} := \frac{\text{MRSO}_4}{Q} \]

\[ \text{MRV}_\text{SO}_4 = 2.299 \times 10^{-10} \text{ kg m}^3 \text{ s}^{-1} \]

\[ \text{MRSO}_4 = 10.335 \text{ kg m}^{-3} \text{ s}^{-1} \]

\[ Q = 78.034 \text{ gpm} \]

Sulfate concentration in seepage

\[ 24.5 \text{ mg liter}^{-1} \]

Sulfur Calcs

\[ \text{MRV}_S := \text{MRV}_\text{SO}_4 \cdot \frac{W_S}{W_{\text{SO}_4}} \]

\[ \text{MRA}_S := \text{MRV}_S \cdot b \]

\[ \text{MR}_S := \text{MRA}_S \cdot A \]

\[ \text{MRV}_S = 7.675 \times 10^{-11} \text{ kg m}^3 \text{ s}^{-1} \]

\[ \text{MRA}_S = 23.962 \text{ mg m}^2 \text{ s}^{-1} \]

\[ \text{MR}_S = 3.449 \text{ kg day}^{-1} \]

Other Chemicals

GoldSim Output
RR_{As} := 0.09995 \quad \text{Release ratio of As to S}

CF_{As} := 0.0001 \quad \text{As calibration factor}

MR_{As} := MR_S \cdot RR_{As} \cdot CF_{As} \quad \text{Mass rate of released As } 1.273 \times 10^{-5} \quad MR_{As} = 1.259 \times 10^{-5} \text{ tonne yr}^{-1}

C_{As} := \frac{MR_{As}}{Q} \quad \text{As concentration in seepage} \quad C_{As} = 0.081 \mu g \text{ L}^{-1}

RR_{Co} := 0.03076 \quad \text{Release ratio of Co to S}

CF_{Co} := 0.0006 \quad \text{Co calibration factor}

MR_{Co} := MR_S \cdot RR_{Co} \cdot CF_{Co} \quad \text{Mass rate of released Co } 2.350 \times 10^{-5} \quad MR_{Co} = 2.325 \times 10^{-5} \text{ tonne yr}^{-1}

C_{Co} := \frac{MR_{Co}}{Q} \quad \text{Co concentration in seepage} \quad C_{Co} = 0.150 \mu g \text{ L}^{-1}

RR_{Cu} := 0.030598 \quad \text{Release ratio of Cu to S}

CF_{Cu} := 0.0005 \quad \text{Cu calibration factor}

MR_{Cu} := MR_S \cdot RR_{Cu} \cdot CF_{Cu} \quad \text{Mass rate of released Cu } 1.948 \times 10^{-5} \quad MR_{Cu} = 1.928 \times 10^{-5} \text{ tonne yr}^{-1}

C_{Cu} := \frac{MR_{Cu}}{Q} \quad \text{Cu concentration in seepage} \quad C_{Cu} = 0.124 \mu g \text{ L}^{-1}

RR_{Ni} := 0.014307 \quad \text{Release ratio of Ni to S}

CF_{Ni} := 0.0027 \quad \text{Ni calibration factor}

MR_{Ni} := MR_S \cdot RR_{Ni} \cdot CF_{Ni} \quad \text{Mass rate of released Ni } 4.920 \times 10^{-5} \quad MR_{Ni} = 4.867 \times 10^{-5} \text{ tonne yr}^{-1}

C_{Ni} := \frac{MR_{Ni}}{Q} \quad \text{Ni concentration in seepage} \quad C_{Ni} = 0.313 \mu g \text{ L}^{-1}

RR_{Zn} := 5.0629 \times 10^{-5} \quad \text{Release ratio of Zn to SO4}

CF_{Zn} := 0.2596 \quad \text{Zn calibration factor}

MR_{Zn} := MR_{SO4} \cdot RR_{Zn} \cdot CF_{Zn} \quad \text{Mass rate of released Zn } 5.014 \times 10^{-5} \quad MR_{Zn} = 4.961 \times 10^{-5} \text{ tonne yr}^{-1}

C_{Zn} := \frac{MR_{Zn}}{Q} \quad \text{Zn concentration in seepage} \quad C_{Zn} = 0.319 \mu g \text{ L}^{-1}
Pond Area - Sulfate - Bentonite Amended - Closure at t = 100 yrs

\[ A := 972.6 \text{ acre} \]

Pond area (GS output)

\[ q := 6.5 \frac{\text{in}}{\text{yr}} \]

Seepage flux for bentonite amended pond bottom (Table 1-31)

\[ C_o := 12.48 \frac{\text{mg}}{\text{L}} \]

Average annual pond DO concentration (Table 1-18)

\[ W_{O2} := 32 \frac{\text{gm}}{\text{mole}} \]

O2 molecular weight

\[ W_{SO4} := 96.07 \frac{\text{gm}}{\text{mole}} \]

SO4 molecular weight

\[ W_S := 32.07 \frac{\text{gm}}{\text{mole}} \]

S molecular weight

\[ C_{SO4p} := 16.19 \frac{\text{mg}}{\text{L}} \]

Sulfate concentration in pond water (GS output table)

\[ \text{moleratio} := \frac{4}{9} \]

moles of SO4 generated per mole of O2 consumed

\[ Q := q \cdot A \]

Seepage flow rate

\[ Q := 326.4 \text{ gpm} \]

\[ Q = 326.394 \text{ gpm} \]

\[ M_{RO2} := C_o \cdot Q \]

Mass rate of O2 brought in with pond seepage water

\[ M_{RO2} = 1.554 \times 10^8 \frac{\text{mg}}{7\text{ day}} \]

\[ M_{O2} = 1.554 \times 10^8 \frac{\text{mg}}{7\text{ day}} \]

\[ M_S := M_{RO2} \left( \frac{W_S}{W_{O2}} \right) \cdot \text{moleratio} \]

Mass rate of S produced by tailings oxidation

\[ M_S = 6.923 \times 10^7 \frac{\text{mg}}{7\text{ day}} \]

\[ M_{SO4o} := M_{RO2} \left( \frac{W_{SO4}}{W_{O2}} \right) \cdot \text{moleratio} \]

Mass rate of SO4 produced by tailings oxidation

\[ M_{SO4o} = 29.627 \text{ kg day} \]

\[ M_{SO4o} = 29.627 \text{ kg day} \]

\[ M_{SO4p} := C_{SO4p} \cdot Q \]

Mass rate of SO4 brought in with pond seepage

\[ M_{SO4p} = 28.805 \text{ kg day} \]

\[ M_{SO4} := M_{SO4o} + M_{SO4p} \]

Mass rate of SO4 in pond area seepage. This value is transferred to Table 2.

\[ M_{SO4} = 58.432 \text{ kg day} \]

\[ C_{SO4} := \frac{M_{SO4}}{Q} \]

Sulfate concentration in seepage water to toes

\[ C_{SO4} = 32.842 \frac{\text{mg}}{\text{L}} \]
\( A := 45 \text{-acre} \) Map area (Table 1-23)
\( q := 13.241 \text{-in} / \text{yr} \) Percolation rate
\( V_{\text{tail}} := 1145900 \text{-yd}^3 \) Volume of tailings (Table 1-23)
\( \text{Cont}_S := 0.063 \text{-\%} \) Sulfur content (Table 1-1, sheet 7)
\( \rho_b := 140 \text{-lbm/ft}^3 \) Dry bulk density (Table 1-1, sheet 7)
\( \text{MRMP}_{\text{SO}_4} := 13.92 \frac{\text{mg}}{\text{kg} \cdot \text{day} \cdot \%} \) 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)
\( \text{SF} := 0.107685 \) P50 LAM scale factor (Table 1-1, sheet 6, P50 from GS)
\( \text{MRM}_{\text{SO}_4} := \text{MRMP}_{\text{SO}_4} \cdot \text{Cont}_S \cdot \text{SF} \) Mass rate of produced sulfate per unit mass of tailings
\( M_{\text{tail}} := \rho_b \cdot V_{\text{tail}} \) Mass tailings
\( Q := A \cdot q \) Percolation rate
\( \text{MR}_{\text{SO}_4} := \text{MRM}_{\text{SO}_4} \cdot M_{\text{tail}} \) Mass rate of sulfate generated by buttress
\( C_{\text{SO}_4} := \frac{\text{MR}_{\text{SO}_4}}{Q} \) Sulfate concentration in bottom drainage

\( M_{\text{tail}} = 1.965 \times 10^6 \text{-tonne} \)
\( Q = 30.763 \text{-gpm} \)
\( \text{MR}_{\text{SO}_4} = 26.506 \frac{\text{kg}}{\text{day}} \)
\( C_{\text{SO}_4} = 158.066 \frac{\text{mg}}{\text{L}} \)
**Buttress South - Sulfate - Closure**

**Assume Cat 1 Waste Rock**

\[
\begin{align*}
A &:= 15\text{-acre} & \text{Map area (Table 1-23)} \\
q &:= 13.241\text{-in yr}^{-1} & \text{Percolation rate} \\
V_{\text{tail}} &:= 325500\text{-yd}^3 & \text{Volume of tailings (Table 1-23)} \\
\text{Cont}_{S} &:= 0.063\% & \text{Sulfur content (Table 1-1, sheet 7)} \\
\rho_{b} &:= 140\text{-lbm ft}^{-3} & \text{Dry bulk density (Table 1-1, sheet 7)} \\
\text{MRMP}_{SO_4} &:= 13.92\text{-mg kg}^{-1}\text{-day}^{-1}\%^{-1} & \text{Cat 1 sulfate release rate as function of \% sulfur. Mass rate per unit mass of tailings per \% sulfur. (Table 1-1, sheet 10; also see Mine Site Worklan Table 1-27)} \\
SF &:= 0.107685 & \text{P50 LAM scale factor (Table 1-1, sheet 6, P50 from GS)} \\
\text{MRM}_{SO_4} &:= \text{MRMP}_{SO_4}\text{Cont}_{S}\text{SF} & \text{Mass rate of produced sulfate per unit mass of tailings} \\
\text{M}_{\text{tail}} &:= \rho_{b}V_{\text{tail}} & \text{Mass tailings} \\
Q &:= A\cdot q & \text{Percolation rate} \\
\text{MR}_{SO_4} &:= \text{MRM}_{SO_4}\cdot \text{M}_{\text{tail}} & \text{Mass rate of sulfate generated by buttress} \\
C_{SO_4} &:= \frac{\text{MR}_{SO_4}}{Q} & \text{Sulfate concentration in bottom drainage} \\
\text{MRM}_{SO_4} &:= 0.094435\text{-mg kg}^{-1}\text{-day}^{-1} & \\
\text{MRM}_{SO_4} &:= 7.529\text{-kg day}^{-1} & \\
\text{M}_{\text{tail}} &:= 5.581 \times 10^5\text{-tonne} & \\
Q &:= 10.254\text{-gpm} & \\
C_{SO_4} &:= 134.699\text{-mg L}^{-1} & \\
\end{align*}
\]
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 issue 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.
<table>
<thead>
<tr>
<th>Item</th>
<th>Date</th>
<th>Model / AWMP Version</th>
<th>Problem / Issue</th>
<th>Change (changes affecting input tables in BOLD)</th>
<th>Updated Model Version</th>
<th>Previous change, status in AWMP V3.0 Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8/2/2012</td>
<td>MS V1.0 / AWMPV2.0</td>
<td>ERM found that the pH used in the model did not match that proposed in Version 2 of the AWMP</td>
<td>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</td>
<td>MS AWMPV2.1</td>
<td>Unchanged from V2.1</td>
</tr>
<tr>
<td>2</td>
<td>8/2/2012</td>
<td>MS V1.0 / AWMPV2.0</td>
<td>ERM identified a greater-than-expected mass removal in the Cat 1 PRB</td>
<td>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</td>
<td>MS AWMPV2.1</td>
<td>Cat 1 PRB no longer modeled</td>
</tr>
<tr>
<td>3</td>
<td>8/2/2012</td>
<td>MS V1.0 / AWMPV2.0</td>
<td>Additional model outputs are necessary to facilitate the impacts analysis</td>
<td>Barr added additional results reporting and standards checking functionality in the surface water portion of the model.</td>
<td>MS AWMPV2.1</td>
<td>Additional outputs added</td>
</tr>
<tr>
<td>4</td>
<td>8/2/2012</td>
<td>MS V1.0 / AWMPV2.0</td>
<td>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.</td>
<td>Barr corrected the West Pit water balance equations.</td>
<td>MS AWMPV2.1</td>
<td>Unchanged from V2.1</td>
</tr>
<tr>
<td>5</td>
<td>8/2/2012</td>
<td>MS V1.0 / AWMPV2.0</td>
<td>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.</td>
<td></td>
<td>MS AWMPV2.1</td>
<td>Unchanged from V2.1</td>
</tr>
<tr>
<td>6</td>
<td>8/2/2012</td>
<td>MS V1.0 / AWMPV2.0</td>
<td>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.</td>
<td>Barr updated the calculations relating to limestone dissolution.</td>
<td>MS AWMPV2.1</td>
<td>West Pit limestone / wetland treatment no longer modeled</td>
</tr>
<tr>
<td>7</td>
<td>8/2/2012</td>
<td>MS V1.0 / PS V1.0 / AWMPV2.0</td>
<td>Internal QA/QC has identified several small inconsistencies in the model flowcharts (not the models themselves).</td>
<td>Barr marked up the flowcharts used for the Task 2 QA/QC control volume identification.</td>
<td>MS AWMPV2.1 / PS AWMPV2.1</td>
<td>Updated for V3.0</td>
</tr>
<tr>
<td>8</td>
<td>8/2/2012</td>
<td>PS V1.0 / AWMPV2.0</td>
<td>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</td>
<td>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.</td>
<td>PS AWMPV2.1</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>8/2/2012</td>
<td>PS V1.0 / AWMPV2.0</td>
<td>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.</td>
<td>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.</td>
<td>PS AWMPV2.1</td>
<td></td>
</tr>
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<tr>
<td>10</td>
<td>8/2/2012</td>
<td>PS V1.0 / AWMPV2.0</td>
<td>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).</td>
<td>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.</td>
<td>PS AWMPV2.1</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>8/2/2012</td>
<td>PS V1.0 / AWMPV2.0</td>
<td>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.</td>
<td>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.</td>
<td>PS AWMPV2.1</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>8/2/2012</td>
<td>PS V1.0 / AWMPV2.0</td>
<td>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).</td>
<td>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.</td>
<td>PS AWMPV2.1</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>8/8/2012</td>
<td>MS AWMPV2.1</td>
<td>Barr found during internal QA/QC that the West Pit outflow mass balance model combines the controlled outflow and any pit overtopping.</td>
<td>Barr changed the mass balance of the West Pit so that overtopping flows (unlikely) bypass the passive treatment and contribute directly to SW-004a.</td>
<td>MS AWMPV2.2</td>
<td>Unchanged from V2.2</td>
</tr>
<tr>
<td>14</td>
<td>8/8/2012</td>
<td>MS AWMPV2.1</td>
<td>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).</td>
<td>Barr edited the cell flows vector calculation in the West Pit surficial aquifer (\Flowpath_Models\WP_Surf\Cell_Flows\Flows)</td>
<td>MS AWMPV2.2</td>
<td>Unchanged from V2.2</td>
</tr>
<tr>
<td>15</td>
<td>8/9/2012</td>
<td>MS AWMPV2.1</td>
<td>Based on comments from reviewers and Barr staff, PRB modeling was determined to be overly complicated.</td>
<td>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.</td>
<td>MS AWMPV2.2</td>
<td>Cat 1 PRB no longer modeled</td>
</tr>
<tr>
<td>16</td>
<td>8/10/2012</td>
<td>MS AWMPV2.1</td>
<td>During detailed West Pit treatment wetland design it was determined that the West Pit water elevation needs to be increased slightly.</td>
<td>Barr added a new variable representing the elevation that the West Pit water returns to after annual discharge. <em>WP_Outlet_Elev_New value set to 1575'</em> Barr also edited the equation for WP_Seasonal_Discharge to account for the current timestep inflows in calculating the desired outflow</td>
<td>MS AWMPV2.2</td>
<td>West Pit limestone / wetland treatment no longer modeled; elevation returned to previous value</td>
</tr>
<tr>
<td>17</td>
<td>8/15/2012</td>
<td>MS AWMPV2.2</td>
<td>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</td>
<td>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.</td>
<td>MS AWMPV2.3</td>
<td>Unchanged from V2.3</td>
</tr>
<tr>
<td>18</td>
<td>8/15/2012</td>
<td>PS AWMPV2.1</td>
<td>Mitigation measure at Tailings Basin</td>
<td>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</td>
<td>PS AWMPV2.2</td>
<td>Unchanged from V2.2</td>
</tr>
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<tr>
<td>19</td>
<td>8/15/2012</td>
<td>PS AWMPV2.1</td>
<td>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.</td>
<td>The areas which were under Cell 2W were divided into Cell 2W and Cell 2E. See Table 1-49.</td>
<td>PS AWMPV2.2</td>
<td>Unchanged from V2.2</td>
</tr>
<tr>
<td>20</td>
<td>8/15/2012</td>
<td>PS AWMPV2.1</td>
<td>During review of the tailings humidity cells, it was determined that the rates currently being used were not appropriate.</td>
<td>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 &quot;proposal&quot; stage; current distributions are as discussed with LAM on 9/28/12. See tables 1-13 and 1-14</td>
<td>PS AWMPV2.2</td>
<td>Updated for V3.0</td>
</tr>
<tr>
<td>21</td>
<td>8/15/2012</td>
<td>PS AWMPV2.1</td>
<td>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.</td>
<td>The error in the model was fixed.</td>
<td>PS AWMPV2.2</td>
<td>Unchanged from V2.2</td>
</tr>
<tr>
<td>22</td>
<td>8/16/2012</td>
<td>MS AWMPV2.2</td>
<td>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.</td>
<td>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.</td>
<td>MS AWMPV2.3</td>
<td>Unchanged from V2.3</td>
</tr>
<tr>
<td>23</td>
<td>8/16/2012</td>
<td>MS AWMPV2.2</td>
<td>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.</td>
<td>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.</td>
<td>MS AWMPV2.3</td>
<td>Unchanged from V2.3</td>
</tr>
<tr>
<td>24</td>
<td>8/16/2012</td>
<td>MS AWMPV2.2</td>
<td>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.</td>
<td>Barr changed the calculations for the source zone recharge (&quot;S&quot;) terms for the following flowpaths: EPCat23_Surf, OSP_Surf, OSLA_Surf. Flow into the flowpath now equals the stockpile outflow rate.</td>
<td>MS AWMPV2.3</td>
<td>Unchanged from V2.3</td>
</tr>
<tr>
<td>25</td>
<td>8/21/2012</td>
<td>PS AWMPV2.3</td>
<td>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).</td>
<td>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.</td>
<td>PS AWMPV3.0</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>8/22/2012</td>
<td>MS AWMPV2.3</td>
<td>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.</td>
<td>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.</td>
<td>MS AWMPV3.0</td>
<td></td>
</tr>
<tr>
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</table>
| 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 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_Lean 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 |                                                        |
<table>
<thead>
<tr>
<th>Item</th>
<th>Date</th>
<th>Model / AWMP Version</th>
<th>Problem / Issue</th>
<th>Change</th>
<th>Updated Model Version</th>
<th>Previous change, status in AWMP V3.0 Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>34</td>
<td>9/24/2012</td>
<td>MS AWMPV2.3</td>
<td>Updated Plant Site modeling has changed the water quality available to flood the West Pit</td>
<td>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</td>
<td>MS AWMPV3.0</td>
<td></td>
</tr>
</tbody>
</table>
| 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          |                                          |
<p>| 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           | No input that controls the drainage time of the Hydrometallurgical Residue Facility.                                                                 | 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           |                                                                                                                                                |                                                                                                                                             | 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          |                                          |</p>
<table>
<thead>
<tr>
<th>Item</th>
<th>Date</th>
<th>Model / AWMP Version</th>
<th>Problem / Issue</th>
<th>Change (changes affecting input tables in BOLD)</th>
<th>Updated Model Version</th>
<th>Previous change, status in AWMP V3.0 Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>9/28/2012</td>
<td>MS AWMPV2.3</td>
<td>Barr found during internal QA/QC that there was an over-release of constituents in the first timestep from all stockpiles, due to an attempt to prevent divide-by-zero errors.</td>
<td>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.</td>
<td>PS AWMPV3.0</td>
<td>PS AWMPV3.0</td>
</tr>
<tr>
<td>48</td>
<td>9/28/2012</td>
<td>PS AWMPV2.3</td>
<td>During Task 2 QA/QC review, Barr found that the initial conditions of the existing basin did not seem correct.</td>
<td>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.</td>
<td>PS AWMPV3.0</td>
<td></td>
</tr>
<tr>
<td>49</td>
<td>9/28/2012</td>
<td>PS AWMPV2.3</td>
<td>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.</td>
<td>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.</td>
<td>PS AWMPV3.0</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>9/28/2012</td>
<td>PS AWMPV2.3</td>
<td>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.</td>
<td>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.</td>
<td>PS AWMPV3.0</td>
<td></td>
</tr>
</tbody>
</table>
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>
<thead>
<tr>
<th>Constituent</th>
<th>GoldSim Model v 3</th>
<th>Model v 4.1</th>
<th>Change in Model Result</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GoldSim Audit</td>
<td>Discrepancy</td>
<td>GoldSim</td>
</tr>
<tr>
<td></td>
<td>[tonne]</td>
<td>Rel. % Diff. [tonne]</td>
<td></td>
</tr>
<tr>
<td>Sulfate</td>
<td>355</td>
<td>361</td>
<td>317</td>
</tr>
<tr>
<td></td>
<td>1.69%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt</td>
<td>1.41</td>
<td>1.43</td>
<td>1.02</td>
</tr>
<tr>
<td></td>
<td>1.67%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.109</td>
<td>0.111</td>
<td>0.097</td>
</tr>
<tr>
<td></td>
<td>1.67%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td>36.4</td>
<td>37.1</td>
<td>31.6</td>
</tr>
<tr>
<td></td>
<td>1.80%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td>18.3</td>
<td>18.6</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>1.67%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antimony</td>
<td>0.040</td>
<td>0.041</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>1.67%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>21.8</td>
<td>60.7</td>
<td>19.6</td>
</tr>
<tr>
<td></td>
<td>94.30%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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:

\[
\text{Inflow entering flowpath at upgradient boundary} + \text{recharge along flowpath} = \text{groundwater discharge to Partridge River}
\]

**Figure 1**

![Diagram](image-url)

**West Pit Groundwater Flowpath - Flow**

- Flow Rate (gpm): 16.66 gpm, 10.57 gpm, 6.09 gpm
- Year: 0 to 300

- Red: West Pit Water Entering Flowpath
- Green: Recharge
- Blue: Groundwater Discharge to Partridge River
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**

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

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

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

West Pit Groundwater Flowpath - Sulfate

Year
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300

0 10000 20000 30000 40000 50000 60000 70000 80000 90000 100000

West Pit Water Entering Flowpath
Groundwater Discharge to Partridge River

Figure 4

West Pit Groundwater Pathway - Cobalt

Years
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250 260 270 280 290 300

0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34

West Pit Water Entering Flowpath
Groundwater Discharge to Partridge River
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

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Flowpath</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>West Pit</td>
</tr>
<tr>
<td>Groundwater flow rate at chemical source</td>
<td>gpm</td>
<td>6.09</td>
</tr>
<tr>
<td>Net meteoric recharge rate</td>
<td>in/yr</td>
<td>0.828</td>
</tr>
<tr>
<td>Flowpath width</td>
<td>m</td>
<td>665</td>
</tr>
<tr>
<td>Flowpath thickness</td>
<td>m</td>
<td>5</td>
</tr>
<tr>
<td>Aquifer porosity</td>
<td>(--)</td>
<td>0.30</td>
</tr>
<tr>
<td>Distance from chemical source to mine property boundary (groundwater compliance point)</td>
<td>m</td>
<td>860</td>
</tr>
<tr>
<td>Distance from chemical source to Partridge River (surface water discharge)</td>
<td>m</td>
<td>1505</td>
</tr>
<tr>
<td>Groundwater travel time from chemical source to mine property boundary</td>
<td>yr</td>
<td>49</td>
</tr>
<tr>
<td>Groundwater travel time from chemical source to Partridge River</td>
<td>yr</td>
<td>72</td>
</tr>
<tr>
<td>Chemical source begin time</td>
<td>yr</td>
<td>33</td>
</tr>
<tr>
<td>Chemical source end time</td>
<td>yr</td>
<td>Contin-</td>
</tr>
<tr>
<td>Sharp front chemical arrival time at property boundary (based on chemical source begin time)</td>
<td>yr</td>
<td>82</td>
</tr>
<tr>
<td>Computed sharp front chemical arrival time at the Partridge River (based on chemical source begin time)</td>
<td>yr</td>
<td>105</td>
</tr>
<tr>
<td>GoldSim sharp front chemical arrival time at the Partridge River (based on chemical source begin time)</td>
<td>yr</td>
<td>105</td>
</tr>
</tbody>
</table>

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**

![East Pit Cat 2/3 Groundwater Flowpath - Source Areas - Sulfate](image-url)
Figure 7

East Pit Cat 2/3 Groundwater Flowpath - Discharge - Sulfate

Sulfate Concentration (ug/L)

Year

Groundwater Discharge to Partridge River

Figure 8

East Pit Cat 2/3 Groundwater Flowpath - Source Areas - Cobalt

Cobalt Concentration (ug/L)

Year

Cat 2/3 Stockpile Leakage

East Pit Water Entering Flowpath
**Figure 9**

*East Pit Cat 2/3 Groundwater Flowpath - Discharge - Cobalt*

**Figure 10**

*East Pit Cat 2/3 Groundwater Flowpath - Source Areas - Aluminum*
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**

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

**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

<table>
<thead>
<tr>
<th></th>
<th>NON-PROJECT FLOW¹</th>
<th>PROJECT FLOWS²</th>
<th>MIXED FLOWS³</th>
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</thead>
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<tr>
<td></td>
<td>Q, cfs</td>
<td>Conc, µg/L</td>
<td>Q x Conc</td>
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<tr>
<td>$\text{SO}_4$</td>
<td>25.23</td>
<td>9,598</td>
<td>242,158</td>
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</tr>
</tbody>
</table>

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

Table 2

<table>
<thead>
<tr>
<th></th>
<th>NON-PROJECT FLOW¹</th>
<th>PROJECT FLOWS²</th>
<th>MIXED FLOWS³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q, cfs</td>
<td>Conc, µg/L</td>
<td>Q x Conc</td>
</tr>
<tr>
<td>$\text{Al}$</td>
<td>25.23</td>
<td>65.07</td>
<td>1641.7</td>
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</tr>
</tbody>
</table>

¹Source: SW_Flows and SW_Conc Timeseries Spreadsheets, Barr, Dec2012, No Action
²Source: MineSite_CV Spreadsheets, Barr 2012
³Source: SW_Concs_Timeseries_MineSite.xlsm, Barr, Dec2012
### Table 3  Estimated Partridge River Project Cobalt Water Quality at SW-004a

<table>
<thead>
<tr>
<th>Source</th>
<th>Q, cfs (Q x Conc)</th>
<th>Conc, µg/L</th>
<th>Relative Load, Q x Conc</th>
<th>Conc, µg/L</th>
<th>Relative Load, Q x Conc</th>
<th>Total Load/Total Q vs Project ave P50, µg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>WWTF, Eff</td>
<td>0.635</td>
<td>5.0</td>
<td>3.175</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W. Pit gw</td>
<td>0.0371</td>
<td>8.64</td>
<td>0.321</td>
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<td></td>
</tr>
<tr>
<td>E. Pit/2/3</td>
<td>0.0873</td>
<td>7.66</td>
<td>0.669</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSP</td>
<td>0.0156</td>
<td>1.43</td>
<td>0.022</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WWTF,gw</td>
<td>0.0076</td>
<td>1.52</td>
<td>0.012</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSLA</td>
<td>0.0248</td>
<td>0.859</td>
<td>0.021</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.807</td>
<td>3.551</td>
<td>17.07/26.04 =</td>
<td>0.66 vs 0.55</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

¹Source: SW_Flows and SW_Conc Timeseries Spreadsheets, Barr, Dec2012, No Action
²Source: MineSite.CV Spreadsheets, Barr 2012
³Source: 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

<table>
<thead>
<tr>
<th>Tailings Basin Sub-Area</th>
<th>Tailings Material</th>
<th>Bentonite Amended</th>
<th>Flow Rate (Q)</th>
<th>Mass Rate (MR)</th>
<th>Mass Rate (MR)</th>
<th>Mass Rate (MR)</th>
<th>R</th>
<th>Ratio Lead to Sulfate</th>
<th>Calib Factor</th>
<th>Core Cap</th>
<th>Lead Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>gpm kg/day kg/day mg/L</td>
<td>mg /L</td>
<td>mg /L</td>
<td>% % % %</td>
<td>gpm kg/day kg/day</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Dam banks (outer slopes) LTV bulk (other) Operations and closure</td>
<td>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</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>East Dam banks (outer slopes) LTV bulk (other) Operations and closure</td>
<td>12.54 1.38 0.45 5.800E-03 0.0003 1.70E-06 40 0 0 0 12.54 0.00 0.00 0.00 1.70E-06 0.00E+00 0.00E+00 0.00E+00</td>
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</tr>
<tr>
<td>South Dam banks (outer slopes) LTV bulk (other) Operations and closure</td>
<td>28.54 3.06 1.02 5.800E-03 0.0003 1.70E-06 0 0 0 0 28.54 0.00 0.00 0.00 1.70E-06 0.00E+00 0.00E+00 0.00E+00</td>
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</tr>
<tr>
<td>North Beach 5% NM fine, 40% NM coarse Closure only</td>
<td>33.72 0.00 0.00 0.00 33.72 0.00 0.00 0.00 4.86E-06 0.00E+00 0.00E+00 0.00E+00</td>
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</tr>
<tr>
<td>East Beach 5% NM fine, 40% NM coarse Closure only</td>
<td>33.72 0.00 0.00 0.00 33.72 0.00 0.00 0.00 4.86E-06 0.00E+00 0.00E+00 0.00E+00</td>
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<tr>
<td>South Beach 5% NM fine, 40% NM coarse Closure only</td>
<td>33.72 0.00 0.00 0.00 33.72 0.00 0.00 0.00 4.86E-06 0.00E+00 0.00E+00 0.00E+00</td>
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<td>Closure Beach 5% NM fine, 40% NM coarse Closure only</td>
<td>33.72 0.00 0.00 0.00 33.72 0.00 0.00 0.00 4.86E-06 0.00E+00 0.00E+00 0.00E+00</td>
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</tr>
<tr>
<td>Pond LTV Closure (after 30 years)</td>
<td>36.90 9.00 0.00 0.00 3.69E-02 9.00 0.00 0.00 4.86E-06 0.00E+00 0.00E+00 0.00E+00</td>
<td></td>
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<tr>
<td>1E coarse LTV coarse none</td>
<td>4.05 5.59 1.00 5.800E-03 0.0003 1.20E-06 0 0 0 120 0.00 0.00 0.00 1.20E-06 0.00E+00 0.00E+00 0.00E+00</td>
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<tr>
<td>1E fine LTV fine none</td>
<td>4.05 5.59 1.00 5.800E-03 0.0003 1.20E-06 0 0 0 120 0.00 0.00 0.00 1.20E-06 0.00E+00 0.00E+00 0.00E+00</td>
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<tr>
<td>1E other LTV coarse none</td>
<td>4.05 5.59 1.00 5.800E-03 0.0003 1.20E-06 0 0 0 120 0.00 0.00 0.00 1.20E-06 0.00E+00 0.00E+00 0.00E+00</td>
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</tr>
<tr>
<td>1W fine LTV fine none</td>
<td>4.05 5.59 1.00 5.800E-03 0.0003 1.20E-06 0 0 0 120 0.00 0.00 0.00 1.20E-06 0.00E+00 0.00E+00 0.00E+00</td>
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<tr>
<td>1W other LTV coarse none</td>
<td>4.05 5.59 1.00 5.800E-03 0.0003 1.20E-06 0 0 0 120 0.00 0.00 0.00 1.20E-06 0.00E+00 0.00E+00 0.00E+00</td>
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<tr>
<td>2E coarse LTV coarse none</td>
<td>1.50 31.70 7.00 59.8 0.00 0.00 0.00 0.00 0.00E+00 0.00E+00 0.00E+00 0.00E+00</td>
<td></td>
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<tr>
<td>2E fine LTV fine none</td>
<td>1.50 31.70 7.00 59.8 0.00 0.00 0.00 0.00 0.00E+00 0.00E+00 0.00E+00 0.00E+00</td>
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<td>1.50 31.70 7.00 59.8 0.00 0.00 0.00 0.00 0.00E+00 0.00E+00 0.00E+00 0.00E+00</td>
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<td>2W coarse LTV coarse none</td>
<td>150.86 479.01 159.89 5.800E-03 0.0003 2.78E-03 14.3 31.1 35.2 19.1 22.03 46.92 53.10 28.81 3.27E-03 1.08E-04 1.24E-04 5.31E-05</td>
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<td>2W fine LTV fine none</td>
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<tr>
<td>2W banks LTV coarse none</td>
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<td></td>
</tr>
<tr>
<td>South Buttress banks Assumed Cat 1 waste rock none</td>
<td>13.24 0.00 0.00 0.00 13.24 0.00 0.00 0.00 4.86E-06 0.00E+00 0.00E+00 0.00E+00</td>
<td></td>
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<tr>
<td>North Buttress banks Assumed Cat 1 waste rock none</td>
<td>13.24 0.00 0.00 0.00 13.24 0.00 0.00 0.00 4.86E-06 0.00E+00 0.00E+00 0.00E+00</td>
<td></td>
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</tr>
</tbody>
</table>

Total GW to Collection System 588.49 438.40 328.06 186.79 6.56E-02 4.25E-04 3.84E-04 2.75E-02

GW to Individual Collection Systems

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
N - North Toe
NW - Northwest Toe

Theoretical result overridden by concentration cap
Based on dissolved oxygen brought in with pond seepage

QUALITY ASSURANCE MEMORANDUM
Appendix C-4
February 25, 2013
Table 2. Sulfate Concentration in Groundwater at FTB Toes

<table>
<thead>
<tr>
<th>Tailings Basin Sub-Area</th>
<th>Tailings Material</th>
<th>Bentonite Amended</th>
<th>Area in acre</th>
<th>Flow rate (Q) gpm</th>
<th>Flow rate (Q) gpm</th>
<th>Flow rate (Q) gpm</th>
<th>Flow rate (Q) gpm</th>
<th>Mass rate (MR) N kg/day</th>
<th>Mass rate (MR) NW kg/day</th>
<th>Mass rate (MR) W kg/day</th>
<th>Mass rate (MR) S kg/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Dam banks (outer slopes)</td>
<td>LTV bulk (other)</td>
<td>Operations and closure</td>
<td>249.00</td>
<td>6.07</td>
<td>78.08</td>
<td>19.42</td>
<td>8.37</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>East Dam banks (outer slopes)</td>
<td>LTV bulk (other)</td>
<td>Operations and closure</td>
<td>400.00</td>
<td>6.07</td>
<td>12.54</td>
<td>19.42</td>
<td>1.35</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>South Dam banks (outer slopes)</td>
<td>LTV bulk (other)</td>
<td>Operations and closure</td>
<td>91.00</td>
<td>6.07</td>
<td>28.53</td>
<td>19.42</td>
<td>3.08</td>
<td>0.00</td>
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<td>0.00</td>
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<tr>
<td>North Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>75.62</td>
<td>6.07</td>
<td>23.72</td>
<td>233.99</td>
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<td>0.00</td>
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<tr>
<td>East Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>45.61</td>
<td>6.07</td>
<td>14.30</td>
<td>233.99</td>
<td>16.48</td>
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<tr>
<td>South Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>243.00</td>
<td>6.07</td>
<td>52.31</td>
<td>233.99</td>
<td>41.75</td>
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<tr>
<td>Closure Beach</td>
<td>35% NM fine, 65% NM coarse</td>
<td>Closure only</td>
<td>188.64</td>
<td>6.07</td>
<td>59.15</td>
<td>233.99</td>
<td>74.44</td>
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<td>Pond</td>
<td>LTV, Closure (after 30 years)</td>
<td>972.60</td>
<td>6.07</td>
<td>326.59</td>
<td>58.43</td>
<td>81</td>
<td>0.00</td>
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<td>1E coarse</td>
<td>LTV coarse</td>
<td>none</td>
<td>5.35</td>
<td>2.68</td>
<td>0.47</td>
<td>952.68</td>
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<td>1E fine</td>
<td>LTV fine</td>
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<td>0.00</td>
<td>2.19</td>
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<td>0.00</td>
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<td>2E coarse</td>
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<tr>
<td>2E fine</td>
<td>LTV fine</td>
<td>none</td>
<td>0.00</td>
<td>3.92</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>LTV coarse</td>
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<td>5.61</td>
<td>21.40</td>
<td>422.96</td>
<td>53.15</td>
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<tr>
<td>SW coarse</td>
<td>LTV coarse</td>
<td>none</td>
<td>220.08</td>
<td>13.24</td>
<td>10.26</td>
<td>7.53</td>
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<td>0.00</td>
<td>0.00</td>
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<td>0.00</td>
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<td>LTV fine</td>
<td>none</td>
<td>748.09</td>
<td>15.92</td>
<td>615.78</td>
<td>582.82</td>
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<td>0.00</td>
<td>0.00</td>
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</tr>
<tr>
<td>SW banks</td>
<td>LTV coarse</td>
<td>none</td>
<td>429.18</td>
<td>7.82</td>
<td>36.97</td>
<td>870.65</td>
<td>51.48</td>
<td>0.00</td>
<td>0.00</td>
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</tr>
<tr>
<td>South Buttress banks</td>
<td>Assumed Cat 1 waste rock</td>
<td>none</td>
<td>15.00</td>
<td>13.24</td>
<td>10.26</td>
<td>7.53</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>13.24</td>
<td>30.78</td>
<td>26.51</td>
<td>30.78</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Total G W to Collection System

GW to Individual Collection Systems

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

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>Surficial Aquifer Pathway</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>West</td>
</tr>
<tr>
<td>Flowpath width</td>
<td>m</td>
<td>2920</td>
</tr>
<tr>
<td>Flowpath thickness</td>
<td>m</td>
<td>7</td>
</tr>
<tr>
<td>Hydraulic gradient</td>
<td>---</td>
<td>0.00736</td>
</tr>
<tr>
<td>Hydraulic conductivity</td>
<td>m/d</td>
<td>3.7139</td>
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<tr>
<td>Groundwater flow rate approaching containment system</td>
<td>gpm</td>
<td>102.50</td>
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<tr>
<td>Containment system capture efficiency</td>
<td>%</td>
<td>90</td>
</tr>
<tr>
<td>Independently computed groundwater flow rate by-passing containment system</td>
<td>gpm</td>
<td>10.25</td>
</tr>
<tr>
<td><strong>GoldSim result based on deterministic run with P50 inputs</strong></td>
<td></td>
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</tr>
<tr>
<td>Net meteoric recharge</td>
<td>in/yr</td>
<td>0.765</td>
</tr>
<tr>
<td>Aquifer porosity</td>
<td>---</td>
<td>0.30</td>
</tr>
<tr>
<td>Distance from containment system to mine property boundary (groundwater compliance point)</td>
<td>m</td>
<td>3023</td>
</tr>
<tr>
<td>Distance from containment system to location of groundwater discharge to surface water</td>
<td>m</td>
<td>5331</td>
</tr>
<tr>
<td>Independently computed groundwater discharge rate to surface water</td>
<td>gpm</td>
<td>162.31</td>
</tr>
<tr>
<td><strong>GoldSim result based on deterministic run with P50 inputs</strong></td>
<td></td>
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<tr>
<td>Independently computed sharp-front chemical arrival time at the property boundary</td>
<td>yr</td>
<td>242.2</td>
</tr>
<tr>
<td><strong>GoldSim result - apparent travel time for lead based on 50th percentile conc from Monte Carlo simulation</strong></td>
<td>yr</td>
<td>225</td>
</tr>
<tr>
<td>Independently computed sharp-front chemical arrival time at the location of groundwater discharge to surface water</td>
<td>yr</td>
<td>298.5</td>
</tr>
<tr>
<td><strong>GoldSim result - apparent travel time for lead based on deterministic run with P50 inputs</strong></td>
<td>yr</td>
<td>290</td>
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</table>
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 GoldSim 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**

<table>
<thead>
<tr>
<th>Flowpath</th>
<th>Constituent</th>
<th>Containment System Bypass</th>
<th>Recharge</th>
<th>Flow Rate of GW Discharge to SW</th>
<th>Concentration in GW Discharge to SW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Flow Rate gpm</td>
<td>Conc ug/L</td>
<td>Flow Rate gpm</td>
<td>Conc ug/L</td>
</tr>
<tr>
<td>North</td>
<td>Sulfate</td>
<td>4.07</td>
<td>156400</td>
<td>59.85</td>
<td>7920</td>
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<tr>
<td></td>
<td>Lead</td>
<td>4.07</td>
<td>17.6</td>
<td>59.85</td>
<td>0.250</td>
</tr>
<tr>
<td>Northwest</td>
<td>Sulfate</td>
<td>5.12</td>
<td>307000</td>
<td>74.42</td>
<td>7920</td>
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<tr>
<td></td>
<td>Lead</td>
<td>5.12</td>
<td>0.179</td>
<td>74.42</td>
<td>0.250</td>
</tr>
<tr>
<td>West</td>
<td>Sulfate</td>
<td>10.25</td>
<td>355700</td>
<td>152.06</td>
<td>7920</td>
</tr>
<tr>
<td></td>
<td>Lead</td>
<td>10.25</td>
<td>0.207</td>
<td>152.06</td>
<td>0.250</td>
</tr>
</tbody>
</table>

**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 flowpaths 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

Legend:
- WWTP: Waste Water Treatment Plant
- CL: Colby Lake augmentation
- FP: Surficial aquifer flowpaths

Graph showing annual average sulfate mass rates with years on the x-axis and mass rates (kg/day) on the y-axis.