



Groundwater Modeling of the NorthMet Flotation Tailings Basin Containment System

Supporting Document for Water Management Plan – Plant

Prepared for
PolyMet Mining Inc.

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1.0 Introduction

This report describes the technical approach, rationale, and scope for the two-dimensional (i.e., flow path) groundwater modeling that was conducted to support the design of the Flotation Tailings Basin (FTB) Containment System at the PolyMet NorthMet Project (Project) Plant Site and to support the assumptions made in the GoldSim water quality model regarding FTB Containment System capture effectiveness (Reference (1)). Groundwater modeling objectives, methods, and results are presented. The modeling was based on the current understanding of the Plant Site conditions and the Project description (Reference (2)) developed for the Final Environmental Impact Statement (FEIS).

In this report, the FTB is the newly constructed NorthMet Flotation Tailings impoundment, and the Tailings Basin is the existing LTV Steel Mining Company (LTVSMC) Tailings Basin as well as the combined LTVSMC Tailings Basin and the FTB.

Groundwater flow path models were used to assess the effectiveness of the FTB Containment System along the north, northwest, and west flow paths defined in the GoldSim water quality model (Section 5.1.1.2 of Reference (1)). The flow path models originate at the toe of the North, Northwest, and West FTB Dams and terminate at the Embarrass River. Each model simulates groundwater flow along one of these three paths, representing a narrow, cross-sectional slice of aquifer spanning the length of a groundwater flow path. The locations of the flow-path models are shown on Figure 1-1.

Groundwater flow path models for tailings basin seepage to the south and east were not developed. Eastern and southern groundwater flow paths were not modeled in GoldSim (Section 5.1.1.2 of Reference (1)) because the modeling assumes complete capture for these portions of the FTB Containment System (i.e., all water from the FTB that reports to these portions of the FTB Containment System, both surface and/or groundwater, is captured). This assumption for complete capture of seepage to the east was based on the existing topography, inward hydraulic gradients during current conditions and long-term closure, and the design of the FTB Containment System and the swale to control unimpacted water (Section 3.4 of Reference (3)). For seepage to the south, the capture assumption is also based on the existing topography, which causes seepage in this direction to emerge as surface seepage within a short distance of the dam toe rather than being transported via subsurface flow. PolyMet has also committed to collect essentially all seepage to the south (Section 4.4 of Reference (3)).

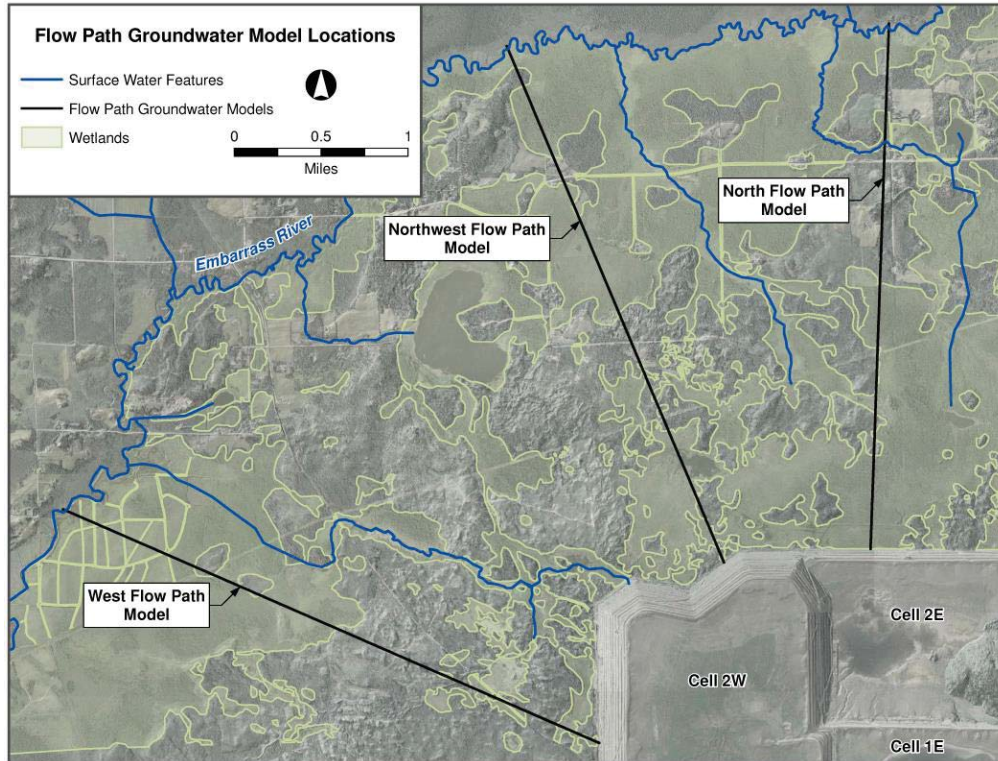


Figure 1-1 Locations of Flow Path Models Used to Evaluate the FTB Containment System

1.1 Objectives

The rate of groundwater seepage from the Tailings Basin was estimated by the Plant Site groundwater flow model (Section 4.2.1 in Attachment A of Reference (1)). The fate of that seepage was then evaluated using the Plant Site GoldSim model (Reference (1)), which assumed capture efficiencies for the FTB Containment System of: 100% of surface water and 90% of groundwater. The flow path models described in this report were developed to support the simplifying assumption that 90% of groundwater will be captured by the FTB Containment System. The objective of the flow path models was to estimate the rate of seepage from the Tailings Basin that will pass beyond the FTB Containment System.

1.2 Background

Estimates of tailings basin seepage entering each of the groundwater flow paths under operations and long-term closure conditions from the three-dimensional Plant Site models were used as input to the flow path models. The three-dimensional Plant Site models were first developed during the Draft Environmental Impact Statement (DEIS) process (Attachment A-6 of Reference (4), Attachment A-6 of Reference (5)). The DEIS versions of the model calibrations were steady-state and did not simulate changes in water levels within the basin. As part of the modeling effort for the Supplemental Draft Environmental Impact Statement (SDEIS), the calibration of the groundwater model was updated to represent transient conditions following LTVSMC closure until present. For the FEIS modeling effort, the groundwater models were updated to incorporate groundwater elevation data collected through 2013 and changes as recommended by the Co-lead Agencies (Attachment A of Reference (1)). The flow path

models were updated using results from the FEIS version of the three-dimensional Plant Site models, and this report documents the current version of the flow path models developed for the FEIS.

1.2.1 Containment System Overview

A containment system, comprising a collection trench, drain pipe, and low-permeability cutoff wall, will be installed to capture seepage leaving the northern, northwestern, western and eastern sides of the Tailings Basin (Section 2.1.4 of Reference (6)). This containment system was not included in the three-dimensional Plant Site models, because the three-dimensional Plant Site model was developed to understand the fate and the transport of water that enters the footprint of the Tailings Basin. While the area outside the Tailings Basin (including where the containment system will be installed) was included in the three-dimensional model for continuity, the model was not developed to evaluate transport of the seepage outside the footprint of the Tailings Basin.

By intercepting seepage from the Tailings Basin and returning captured water for reuse or treatment, the system is designed to reduce the constituent load from the Tailings Basin entering the downgradient surface and groundwater system. The cutoff wall will extend through the full thickness of unconsolidated deposits (approximately 10 to 30 feet thick) to the top of bedrock, and will direct groundwater flow toward the collection trench and drain pipe. The collection trench will be installed immediately upgradient of the cutoff wall, i.e., on the side nearest the Tailings Basin, and will be backfilled with granular, transmissive material. A drain pipe will be placed at the base of the collection trench at a depth of approximately five to eight feet below grade.

The FTB Containment System will decrease flows to tributaries of the Upper Embarrass River and to Second Creek (also known locally as Knox Creek), a tributary to the lower Partridge River. The Project will implement stream augmentation measures to prevent potential hydrologic impacts to Unnamed Creek, Mud Lake Creek, Trimble Creek, and Second Creek. Stream flow in Trimble Creek, Unnamed Creek, and Second Creek will be augmented with treated effluent from the WWTP. Stream flow in Mud Lake Creek will be augmented with non-contact stormwater runoff diverted via the drainage swale constructed east of the FTB East Dam. WWTP effluent discharge for stream augmentation will be directed downstream of the FTB seepage capture systems.

1.3 Report Organization

This report is organized into five sections, including this introduction. Section 2.0 presents the conceptual model used to develop the flow path groundwater flow models. Section 3.0 describes the construction of the flow path models, and Section 4.0 presents model results. Summary and conclusions are presented in Section 5.0.

2.0 Conceptual Model

A *hydrogeologic conceptual model* is a schematic description of how water enters, flows through, and leaves the groundwater system. Its purpose is to describe the major sources and sinks of water, the grouping or division of hydrostratigraphic units into aquifers and aquitards, the direction of groundwater flow, the interflow of groundwater between aquifers, and the interflow of water between surface waters and groundwater. The hydrogeologic conceptual model is both scale-dependent (e.g., local conditions may not be identical to regional conditions) and dependent upon the objectives. It is important when developing a conceptual model to strive for an effective balance: the model should be kept as simple as possible while still adequately representing the system to analyze the objectives at hand.

2.1 Geologic Units

This section provides an overview of the Plant Site geology and the hydraulic properties of each geologic unit, particularly as they pertain to the development of the groundwater flow models. A more detailed summary of the current understanding of bedrock structure and hydrogeology at the Mine Site and the Plant Site, and description of the regional and local bedrock geology and hydrogeology, including the nature of fractured bedrock, can be found in Reference (7).

2.1.1 Surficial Deposits

The native unconsolidated deposits in the vicinity of Plant Site are a relatively thin mantle of Quaternary-age glacial till and associated reworked sediments, most of which were deposited and reworked by the retreating Rainy Lobe during the last glacial period in association with the development of the Vermillion moraine complex (Reference (8)). Near the Tailings Basin, unconsolidated deposits have been characterized based on soil borings and monitoring wells, which have been completed to the north and west of the Tailings Basin. The unconsolidated deposits generally consist of discontinuous lenses of silty sand to poorly graded sand with silt, to poorly graded sand with gravel. Very little silt or clay has been encountered, with the exception of the soil boring drilled near monitoring well GW006, where several feet of silt is interbedded with silty sand (Reference (9)). In places, the till is overlain by organic peat deposits. Depth to bedrock in the area surrounding the Tailings Basin is generally less than 50 feet. The unconsolidated deposits generally thicken in a northerly direction toward the Embarrass River. Wetland areas also become more common to the north, off the northern flank of the Giant's Range, the granite outcrops located adjacent to the Tailings Basin. These wetland areas are underlain by thin glacial drift and lacustrine deposits, which were deposited by the retreating Rainy Lobe and associated lakes that were trapped between the retreating ice margin and the Giant's Range.

Siegel and Ericson (Reference (10)) indicate that the till of the Rainy Lobe has an estimated hydraulic conductivity range of 0.1 to 30 feet/day. In-situ pumping tests were conducted at monitoring wells GW001, GW006, GW007, GW009, GW010, GW011, and GW012 to estimate hydraulic conductivity, as described in detail in Attachment F of Reference (11). The data collected during the tests was used to estimate the hydraulic conductivity of the unconsolidated deposits using three different methods; the Moench solution (Reference (12)), the Theis solution (Reference (13)), and using specific capacity data (Reference (14)). The hydraulic conductivity estimates from each solution are different at each location.

Not only is there spatial variability, shown by differences between wells, but there is uncertainty in the hydraulic conductivity at any given well, shown by the differences in the estimates at each well. Table 2-1 shows the estimates of hydraulic conductivity at each well (Reference (9)). GW009 generally has the lowest estimates of hydraulic conductivity (around 0.5 feet/day) and GW010 generally has the highest estimates of hydraulic conductivity (around 50 feet/day). The arithmetic and geometric means of the average hydraulic conductivity estimates at the test locations are approximately 13 feet/day and 5 feet/day, respectively.

Table 2-1 Hydraulic Conductivity Measured During Single-Well Pumping Tests in Unconsolidated Materials.

Monitoring Well	Moench Solution⁽¹⁾ (feet/day)	Theis Solution⁽²⁾ (feet/day)	Specific Capacity (feet/day)
GW001	1.3	1.8	1.6
GW006	9.6	5.7	10.7
GW007	11.5	30.4	14.8
GW009	0.4	0.5	0.6
GW010	52.0	31.9	64.8
GW011	8.6	15.9	11.4
GW012	0.7	2.4	0.7

(1) Reference (12)

(2) Reference (13)

Additional characterization of hydraulic properties of the unconsolidated deposits was conducted as part of a geotechnical investigation during 2014 (Attachment F of Reference (11)). Slug tests were conducted in ten standpipe piezometers and two monitoring wells screened in the native unconsolidated deposits: R14-04, R14-06, R14-08, R14-12, R14-13, R14-15, R14-16, R14-26, R14-27, R14-28, GW001, and GW012. Hydraulic conductivity estimates from the slug tests ranged from 0.15 to 132 feet/day. The results of those analyses are shown in Table 2-2.

Table 2-2 Hydraulic Conductivity Measured in Unconsolidated Materials Using Slug Tests

Well	Test	K feet/day
R14-04	test 3 - in	2.86
	test 3 - out	3.57
R14-06	test 2 - out	131.76
	test 3 - out	88.13
R14-08	test 1 - in	1.19
	test 2 - out	1.42
R14-12	test 1 - out	0.15
	test 2 - out	0.16
R14-13	test 2 - out	2.12
	test 3 - in	1.53
R14-15	test 1 - in	20.84
	test 2 - out	31.04
R14-16	test 2 - out	18.52
	test 3 - in	16.77
R14-26	test 2 - out	51.65
	test 3 - in	24.45
R14-27	test 2 - out	114.65
	test 3 - out	104.54
R14-28	test 1 - in	0.38
	test 2 - out	0.77
GW001	test 1 - in	0.99
	test 3 - out	1.24
GW012	test 1 - in	0.44
	test 2 - in	0.33

2.1.2 Bedrock

The uppermost bedrock at the Plant Site consists of quartz monzonite and monzodiorite of the Neoproterozoic Giant's Range batholith. These pink to dark-greenish gray, hornblende-bearing, coarse-grained rocks are referred to collectively as the "Giant's Range granite". The granite locally outcrops as a northeast-southwest trending ridge and drainage divide that makes up the highest topography in the area; the Giant's Range. The Giant's Range granite has been scoured by glaciers, creating local

depressions and linear valleys. In this report, “bedrock hills” is used to describe the Giant’s Range granite outcrops located adjacent to the Tailings Basin.

Groundwater flow within the bedrock is primarily through fractures and other secondary porosity features, as the rock has low primary hydraulic conductivity. The upper portions of the rock are more likely than rock at depth to contain a fracture network capable of transmitting water. The literature-based assessment of the upper fractured zone suggests that groundwater flow in the Giants Range granite likely occurs mostly in the upper 300 feet of the bedrock; however, the site-specific fracture data indicate that the amount of fracturing decreases significantly in the upper 20 feet of the bedrock surface (Reference (7)).

Siegel and Ericson (Reference (10)) measured specific capacity in one well in the upper 200 feet of the Giant’s Range granite and measured hydraulic conductivity of 2.6×10^{-2} feet/day. This well was located less than 1 mile to the east of the Plant Site. Specific capacity data from a residential well located north of the Plant Site suggests that the hydraulic conductivity of the upper 47 feet of the granite at that location is approximately 42 feet/day. The log for this well indicates that the top of bedrock is at 18 feet below grade, and the casing also extends to 18 feet below grade. Because the well casing apparently does not extend into bedrock, it is possible that the higher hydraulic conductivity estimate at this well may reflect some degree of hydraulic connection with the unconsolidated deposits.

Packer testing was conducted at five boreholes in the uppermost portions (<20 feet) of the Giant’s Range granite during a 2014 geotechnical investigation in the Plant Site area (Attachment F of Reference (11)). The results from that testing are shown on Table 2-3. Hydraulic conductivity values for the upper portion of the Giant’s Range granite at the Plant Site range from effectively zero (i.e., no water was produced in three of the packer test intervals) to 3 feet/day, with a geometric mean of 0.14 feet/day (for the purposes of calculating a geometric mean, the lowest hydraulic conductivity value measured during the investigation was used for the three intervals that did not produce water).

Table 2-3 Hydraulic conductivity measured in bedrock during packer tests.

Boring	Test Interval (feet)	Kr feet/day
B14- 36	14 - 18.5	<0.00411
	20.5 - 26.5	0.0041
B14-55	37 - 41.5	3.1
	41.5 - 46.5	<0.00411
	46 - 50.5	<0.00411
B14-44	34 - 42	0.11
	42 - 46	0.23
B14-65	24 - 30	0.15
	27.5 - 33.5	0.65
B14-76	37 - 42	0.29

(1) For packer test results where zero inflow was observed during testing, permeability values were selected based on inference from lowest packer test result obtained.

2.2 Sources and Sinks for Water

The Tailings Basin receives water from direct precipitation and runoff from watershed areas to the east. Water falling within the tailings basin watershed collects in the ponds in Cell 1E and Cell 2E or infiltrates through dams and beaches. The ponds lose water to evaporation from the water surface and to seepage through the pond bottom. Most groundwater in the Plant Site vicinity flows to the north and northwest toward the Embarrass River; however, some portion of the water entering the Tailings Basin flows south and discharges to Second Creek, a tributary of the Partridge River.

2.3 Local Flow System

Regionally, groundwater flows primarily northward, from the bedrock hills to the Embarrass River (Reference (10)). Groundwater elevations in the network of monitoring wells located around the Tailings Basin indicate that groundwater in the unconsolidated deposits flows primarily to the north and northwest, toward the Embarrass River. Groundwater flow to the south and east is constricted by bedrock outcrops of the Giant's Range granite (Reference (15)). However, a gap in the bedrock hills near the southern end of the Tailings Basin allows some water to flow southward (south seeps), forming the headwaters of Second Creek, a tributary to the lower Partridge River. A second gap in the bedrock hills is present near the eastern side of the Tailings Basin. Under current conditions, seepage does not flow from the Tailings Basin to the east, because the Cell 1E pond is topographically lower than the surface water features to the east. Groundwater in the native unconsolidated material currently flows to the northwest toward the Tailings Basin. Following the completion of the FTB East Dam, groundwater within the unconsolidated deposits is generally expected to continue to flow from the east toward the Tailings Basin. The presence of the FTB Pond will not alter the existing regional groundwater flow direction, but may result in radial flow away from the Tailings Basin area on a local scale. Some water could seep through the

unconsolidated material below the East Dam. Based on topography and the inferred groundwater divides to the area east of the Tailings Basin, this seepage would likely discharge near the toe of the East Dam, and it is not anticipated to flow east toward the Area 5NW pit or Spring Mine Lake (Reference (16)). The eastern segment of the FTB Containment System will be constructed in this area to capture any seepage that would discharge in this area (Reference (6)).

As the Tailings Basin was built up over time, a groundwater mound formed beneath the basin due to seepage from the basin ponds, altering local flow directions and rates. Therefore, the Tailings Basin determines patterns of runoff and infiltration at the Plant Site. Under current conditions, water that infiltrates through the Tailings Basin (from precipitation and seepage from the existing ponds) seeps downward to the native unconsolidated deposits.

Beneath the unconsolidated deposits, low-permeability crystalline bedrock impedes further downward groundwater flow; based on the contrast in hydraulic conductivity between the unconsolidated deposits and bedrock described above, groundwater flow through the bedrock is likely negligible relative to flow through the unconsolidated deposits. Because the unconsolidated deposits are thin and have relatively low hydraulic conductivity, and because the water table is close to the ground surface (which effectively limits the hydraulic gradient), the unconsolidated deposits have a limited capacity to transport Tailings Basin seepage. Therefore, a large portion of that seepage discharges to wetland areas near the Tailings Basin dams, while a small portion remains in the unconsolidated deposits and flows away from the basin laterally as groundwater.

2.4 Hydrologic Model Selection

The flow path models were developed using MODFLOW-NWT (Reference (17)), a formulation of the industry-standard finite-difference groundwater modeling code MODFLOW (Reference (18); Reference (19); Reference (20)). MODFLOW solves the following three-dimensional, differential equation of groundwater flow for saturated steady-state and transient conditions Equation 2-1:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) - W = S_s \frac{\partial h}{\partial t} \quad \text{Equation 2-1}$$

Where K_{xx} , K_{yy} , and K_{zz} are the three principal directions of the hydraulic conductivity tensor, W represents sources and sinks, S_s represents specific storage, h is hydraulic head, and t is time. MODFLOW was developed by the U.S. Geological Survey and is in the public domain. MODFLOW-NWT was selected over other MODFLOW formulations because it is more stable for nonlinear hydrogeologic conditions, such as the drying of model cells near the FTB Containment System drain. Due to the way the models were set up (using ground surface as the top of the model) and the vertical discretization used, it was anticipated that some cells would be located near or above the water table and may be dry during some simulations. MODFLOW-NWT accommodates drying and rewetting by using the Newton method for solving nonlinear equations (described in Reference (17)). Hereinafter, MODFLOW-NWT will be referred to as MODFLOW.

The particle-tracking code MODPATH (Reference (21)) was used to estimate the rate of seepage bypassing the FTB Containment System. MODPATH uses output files from MODFLOW simulations to compute three-dimensional flow paths by tracking particles throughout the model domain until they reach a boundary, enter an internal source or sink, or are terminated in a process specified by the modeler. MODPATH also keeps track of the time-of-travel for simulated particles as they move through the model domain.

The models were developed using the graphical user interface Groundwater Vistas (Version 6; Reference (22)).

3.0 Model Construction

For each of the three groundwater flow path models, six simulations were completed. Each flow path was simulated under two seepage conditions (operations and long-term closure), using three assumed values for the thickness of the upper fractured zone in the granite bedrock (25, 50, and 100 feet) as shown on Figure 3-1.

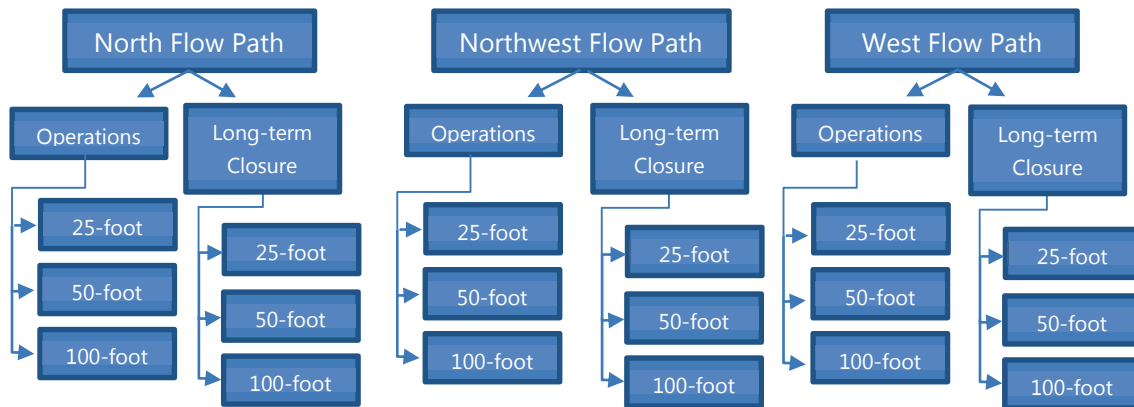


Figure 3-1 Model Simulations for the Flow Path Groundwater Models for Two Different Flow Conditions and Three Different Bedrock Thicknesses

Cross-sectional diagrams of the three flow paths, detailing model discretization and key model parameter values are shown in Large Figure 1 through Large Figure 3. In each figure, the model cells are shown in gray outline, and individual cells are colored to indicate either a boundary condition or hydraulic conductivity zone. The figures each depict three surfaces for the bottom of the model: one surface corresponding to the model with a bedrock thickness of 25 feet, one for the model with a bedrock thickness of 50 feet, and one for the model with a bedrock thickness of 100 feet. Model discretization is discussed in detail in Section 3.1, boundary conditions in Section 3.2, model parameters in Section 3.3, and simulated components of the FTB Containment System in Section 3.4.

3.1 Model Domain and Discretization

Each flow-path model grid consists of a single row, oriented approximately parallel to groundwater flow in one of the three flow paths defined in the GoldSim model (Reference (1)). The origin of each grid is located at the toe of the Tailings Basin dam, and the last column of each model intersects the Embarrass River; see Section 3.2 for a discussion of the boundary conditions used to represent these endpoints. Column spacing varies over the length of each model. A two-foot spacing is used in the primary area of interest, i.e., the 500 feet nearest the Tailings Basin; this is followed by a gradual transition over 50 cells to a 150-foot spacing, which is used over the remaining distance to the Embarrass River. Each model's single row is one foot wide.

The domain of each model is bounded at the top by the ground surface and at the bottom by a specified depth below the bedrock surface. Several GIS datasets were used to define the ground and bedrock

surfaces. A LiDAR-based, three-meter resolution Digital Elevation Model (DEM), available through the Minnesota Elevation Mapping Project (Reference (23)), was used to calculate ground elevations. Bedrock elevations were calculated using a combined bedrock dataset, derived from a regional, 30-meter resolution Minnesota Geological Survey (MGS) bedrock surface (Reference (24)), into which local bedrock data were incorporated. Groundwater wells and borings completed in the vicinity of the Tailings Basin, for which estimated bedrock elevations were available, were buffered a distance of 3,280.4 feet (or 1,000 meters). The area within the buffer was then clipped from the MGS bedrock surface. Finally, the coordinates of each well, its associated bedrock elevation and the remaining regional grid data were provided as input to a new surface interpolation. The resulting surface matches the regional grid outside the 1,000-meter buffer and within, smoothly transitions to match the field-measured site data.

To calculate the ground surface and bedrock surface elevation in each column, centerlines spanning each model's single row were generated and divided into segments corresponding to model columns. These centerlines were then intersected with ground and bedrock raster datasets; in the process, the one or more cells in each raster dataset coincident with each column segment were identified. Length-weighted average elevations for each model column were calculated by applying Equation 3-1 to the intersected ground and bedrock datasets in turn:

$$E_a = \sum_{i=1}^n \frac{E_i \times L_i}{L_t} \quad \text{Equation 3-1}$$

Where E_i is the elevation of a given coincident raster cell, L_i is the length of the column segment within that raster cell, L_t is the total length of the column segment and E_a is the average elevation of the column segment.

The upper portion of each flow path model representing the unconsolidated deposits was discretized vertically into layers of equal thickness, evenly subdividing the thickness of unconsolidated deposits. During the SDEIS modeling, the number of layers was selected such that layers were approximately two feet thick at the end of the model nearest the Tailings Basin. This target thickness matched the two-foot column spacing used within the first 500 feet and resulted in regular grid geometry over this area of primary interest. For the FEIS modeling, the depth to bedrock was updated, resulting in thinner model layers for the northwest flow path. The average thickness of unconsolidated deposits between the Tailings Basin and the FTB Containment System cutoff wall, as well as vertical discretization of the unconsolidated deposits, are summarized in Table 3-1.

Table 3-1 Vertical Discretization of Unconsolidated Deposits between the Tailings Basin and the FTB Containment System

Flow Path Model	Average Thickness of Unconsolidated Deposits between Tailings Basin and FTB Containment System Cutoff Wall	Number of Model Layers Representing Unconsolidated Deposits	Average Thickness of Layers Representing Unconsolidated Deposits between Tailings Basin and FTB Containment System Cutoff Wall
North	21.2 Feet	10	2.1 Feet
Northwest	16.5 Feet	14	1.2 Feet
West	14.4 Feet	7	2.1 Feet

The bedrock was divided into layers of equal thickness, each approximately 2 feet thick, for each flow-path model set. The number of layers was selected to match the target bedrock thickness with layers approximately two feet thick at the end of the model nearest the Tailings Basin. This target thickness matched the two-foot column spacing used within the first 500 feet and resulted in regular grid geometry over this area of primary interest. Vertical discretization of bedrock is summarized in Table 3-2.

Table 3-2 Number of Model Layers Representing Bedrock

Bedrock Thickness	North	Northwest	West
25 feet	10	11	13
50 feet	20	22	26
100 feet	40	44	52

3.2 Boundary Conditions

Seepage from the Tailings Basin and distributed meteoric recharge, described in Sections 3.2.1 and 3.2.2, respectively, are the primary groundwater sources in each flow path model. Groundwater is allowed to leave the modeled system via wetlands, described in Section 3.2.3, and the containment system drain pipe, described in Section 3.4. The Embarrass River, described in Section 3.2.4, comprises the downgradient flow boundary in the flow path models.

3.2.1 Representation of Tailings Basin Seepage

Specified-flux cells were used to represent tailings basin seepage; this boundary condition is implemented using Well Package in MODFLOW, used to inject or extract water from a model at a specified rate (Reference (18)). The first column of each model is coincident with the toe of a tailings basin dam; therefore, one specified-flux cell was placed in each layer of the first column, as shown in Large Figure 1 through Large Figure 3.

The rate of seepage from the Tailings Basin at each flow path was estimated using the Plant Site groundwater model (Attachment A of Reference (1)). The seepage rates used in operations simulations

represent Mine Year 7 conditions; these rates were selected in order to evaluate the performance of the FTB Containment System under conditions during which the maximum seepage is expected. The seepage rates used in long-term closure simulations represent conditions after the reclamation of the Tailings Basin. These rates are lower due to the planned application of the FTB cover system, cessation of tailings deposition on the FTB beaches, and gradual dissipation of the groundwater mound beneath the Tailings Basin. Output from the Plant Site model which was used as input to the flow-path models consisted of a seepage rate from the Tailings Basin in units of cubic length per time, i.e., gpm, which corresponds to a length along the perimeter of the Tailings Basin. Because the flow-path models represent a one-foot-wide segment of the flow path, the seepage rate was divided by the flow path width (i.e., the corresponding length along the perimeter of the Tailings Basin) to obtain the rate per linear foot, which was the total seepage rate used as input in the model. Seepage rates used in each model are summarized in Table 3-3.

Table 3-3 Seepage Estimates under Operations and Long-Term Closure Conditions

Flow Path	Flow Path Width (Feet)	Seepage from Tailings Basin Dam (GPM)		Seepage from Tailings Basin Dam (GPM / Linear Foot of Dam)	
		Operations (Mine Year 7)	Long-term Closure	Operations (Mine Year 7)	Long-term Closure
North	8460	1600	570	0.19	0.067
Northwest	5415	580	410	0.11	0.076
West	11065	960	690	0.087	0.062

Seepage rates applied in the model were scaled to reflect the differences in hydraulic conductivity and thickness of the unconsolidated deposits and bedrock. To calculate the scaled seepage rate in the unconsolidated deposits, Equation 3-2 was applied:

$$q_s = q_{total} \frac{K_s t_s}{(K_s t_s + K_b t_b)} \quad \text{Equation 3-2}$$

Where q_s is the scaled seepage rate in the unconsolidated deposits, q_{total} is the total seepage rate, K_s is the hydraulic conductivity of the unconsolidated deposits, t_s is the thickness of the unconsolidated deposits, K_b is the hydraulic conductivity of the bedrock, and t_b is the thickness of the bedrock. The same equation, with the bedrock and surficial values reversed, is used to calculate the scaled seepage rate in bedrock. These rates were then divided by the number of layers (unconsolidated or bedrock) to obtain the rate assigned to each specified-flux cell in the model. The scaled seepage rates applied in the model are shown on Table 3-4.

Table 3-4 Seepage Estimates Applied to the North, Northwest, and West Flow Paths, Scaled by Transmissivity

Flow Path Model	Bedrock Thickness (feet)	Unconsolidated Deposits Scaled Seepage Rate gpm/linear ft		Bedrock Scaled Seepage Rate gpm/linear ft	
		Operations (Mine Year 7)	Long-term Closure	Operations (Mine Year 7)	Long-term Closure
North	25	0.187	0.0667	0.002	0.0007
	50	0.185	0.0660	0.004	0.0014
	100	0.181	0.0646	0.008	0.0028
Northwest	25	0.106	0.0750	0.001	0.0007
	50	0.105	0.0743	0.002	0.0015
	100	0.103	0.0729	0.004	0.0029
West	25	0.0854	0.0614	0.0014	0.0010
	50	0.0841	0.0604	0.0027	0.0020
	100	0.0815	0.0586	0.0053	0.0038

3.2.2 Recharge

Distributed recharge was applied uniformly across the top of each model via the Recharge Package in MODFLOW (Reference (18)); the median recharge rate of 0.61 inches/year, which was calculated based on the watershed area and baseflow in the Embarrass River (Reference (1)), was used for both operations and long-term closure simulations.

3.2.3 Representation of Wetlands

Wetland areas were represented in the MODFLOW models using river cells downgradient of the FTB Containment System and drain cells upgradient of the system (i.e., between the Tailings Basin and the FTB Containment System). A river cell, implemented via the River Package in MODFLOW, is a head-dependent boundary condition. If the modeled hydraulic head in the aquifer is higher than the river cell control elevation, the cell removes water from the aquifer. Conversely, if the head in the aquifer is lower than the control elevation, the cell contributes water to the aquifer. This flux is regulated by the river cell conductance, a function of the hydraulic conductivity, area and thickness of the riverbed deposits represented by the boundary condition (Reference (18)). A drain cell, implemented via the Drain Package in MODFLOW, functions similarly to a river cell but cannot contribute water to the aquifer (Reference (18)). Because the containment system drain pipe induces a strong downward hydraulic gradient, drain cells were selected to represent wetlands between the Tailings Basin and the FTB Containment System; this prevented the modeled wetlands from contributing more water to the FTB Containment System than would actually be available in the wetlands.

Wetland locations in each MODFLOW model were determined using a combined wetlands dataset, derived from National Wetlands Inventory data (Reference (25)), into which site wetland delineations were

incorporated. Model centerlines (described in Section 3.1) were used to determine wetland placement in the models; the centerlines were intersected with the wetlands dataset, and the length of each column segment within wetland areas was calculated. A river or drain cell was placed in the top model layer in columns fully or partly coincident with wetlands, with the exception of model cells downgradient of the FTB Containment System for the northwest flow path. Though delineated wetlands are not present there, river cells were added from the cutoff wall to 50 feet downgradient of the wall to represent the head control that will be realized from flow augmentation downgradient of the FTB Containment System. Delineated wetlands are present downgradient of the FTB Containment System for the north and west flow paths, and additional boundary conditions were not necessary to represent the head control that will be realized from flow augmentation in these locations.

To calculate each cell's conductance, the length of overlap between column segment and wetland was used in Equation 3-3:

$$C = K \frac{LW}{M} \quad \text{Equation 3-3}$$

Where K is the hydraulic conductivity of the riverbed or drain material, L is length of the cell within wetland areas, W is the cell width and M is the thickness of the riverbed or drain material. A constant value was specified for all variables other than length: a hydraulic conductivity of 49.2 feet/day (representative of relatively conductive material) and a width and thickness of one foot were used. Groundwater flux to or from the aquifer is regulated by this conductance and is dependent on the difference between the hydraulic head in the aquifer and the river or drain control elevation; to represent wetland areas, control elevations were set to the ground surface elevation of each river or drain cell.

3.2.4 Representation of the Embarrass River

Specified-head cells were used to represent the Embarrass River in the MODFLOW models. The location of the river was determined using the National Hydrography Dataset (Reference (26)), and each model was extended from the Tailings Basin such that the last model column intersected the river. Specified-head cells were placed in all model layers in the last column; these cells maintain a specific hydraulic head in the aquifer below the river (Reference (18)). In each model, the ground surface elevation of the last column, representative of the stage of the Embarrass River, was used to set the boundary's hydraulic head. The distance from the Tailings Basin to the river, and the river stage used in each model, are listed in Table 3-5.

Table 3-5 Embarrass River Parameters

Model	Distance from Tailings Basin to Embarrass River (Feet)	Embarrass River Elevation (Feet Mean Sea Level)
North	15,820	1428.3
Northwest	16,870	1425.6
West	17,620	1411.9

3.2.5 No-Flow Boundaries

The bottoms of the flow path models, as well as the long sides of each model's single row, are no-flow boundaries. While these boundaries constrain and simplify the modeled groundwater flow fields, they conceptually represent general flow conditions. The long sides of each model's single row are parallel to the flow paths, and the bottom model boundary conceptually represents the depth at which the bedrock can be considered impermeable, as it has significantly lower hydraulic conductivity than the unconsolidated deposits and the more shallow portions of the bedrock. . Simulation of three different bedrock thicknesses was completed to capture the uncertainty in the range at which this depth may be encountered.

3.3 Hydraulic Conductivity and Porosity

Hydraulic conductivity and porosity (needed for particle tracking simulations) in the unconsolidated deposits and the bedrock, were simulated in the model as two homogeneous zones: one zone representing the unconsolidated deposits, and one zone representing bedrock. At the direction of the co-lead agencies, a horizontal hydraulic conductivity value of 13 feet per day, the representative average value from single-well pumping tests near the perimeter of the Tailings Basin (Reference (9)), and an assumed porosity value of 0.3 was assigned to the unconsolidated deposits in the model. The ratio of horizontal to vertical hydraulic conductivity was assumed to be 2.5:1, which is consistent with Freeze and Cherry (Reference (27)). A horizontal hydraulic conductivity value of 0.14 feet per day, the geometric mean value from packer tests conducted in borings near the Tailings Basin (Reference (11)), and an assumed porosity value of 0.05 was assigned to bedrock in the model. Because bedrock in the model represents the upper, fractured portion of bedrock, it was assumed to be isotropic. For the model realizations with bedrock thicknesses of 50 and 100 feet, applying the geometric mean hydraulic conductivity throughout the bedrock interval is a conservative assumption. In reality, the hydraulic conductivity of the bedrock likely decreases significantly with depth. RQD data from the bedrock that underlies the area to the north and west of the Plant Site indicate the influence of the upper fractured bedrock: average RQD increases from about 60% to 85% from the bedrock surface to 20 feet below the top of bedrock (Reference (7)).

3.4 Representation of the Containment System

Three primary components of the FTB Containment System were explicitly represented in the MODFLOW models: the cutoff wall, the drain pipe and the collection trench containing the drain pipe. The cutoff wall

was implemented in each model via the Horizontal-Flow Barrier (HFB) Package in MODFLOW, used to simulate thin, vertical features with low hydraulic conductivity. Consistent with the FTB Containment System design, the wall was extended through model layers representing the unconsolidated deposits, from the ground surface to the bedrock; the hydraulic conductivity of the wall was set to 0.0028 feet/day, and a thickness of one foot was specified.

The distance between the Tailings Basin and the cutoff wall in each model was based on the proposed barrier alignment and is listed in Table 3-6. These distances may be longer than the direct distance between the perimeter of the Tailings Basin and the FTB Containment System, as they represent measurements along the groundwater flow paths, which are not necessarily orthogonal to the Tailings Basin.

Table 3-6 FTB Containment System Parameters

Model	Cutoff Wall Depth (Feet)	Distance from Tailings Basin to Cutoff Wall (Feet)	Drain Pipe Depth (Feet)
North	21.3	262	8
Northwest	15.0	334	8
West	11.7	364	5

The FTB Containment System drain pipe was represented in each flow-path model using a single drain cell, with a control elevation set five to eight feet below the ground surface; drain depths, listed in Table 3-6 are consistent with the FTB Containment System design, intended to prevent the system from freezing in winter (Reference (6)). Because the unconsolidated deposits are generally thinner in the vicinity of the FTB Containment System along the western groundwater flow path, the drain was placed closer to the ground surface in the west flow path model. In each model, the drain cell was positioned immediately inside the cutoff wall, in the model layer corresponding to the control elevation. The drain cell was assigned a hydraulic conductivity of 567 feet/day, which was used to calculate the drain cell conductance. The cells immediately above the drain were assigned a hydraulic conductivity of 284 feet/day, representative of the gravel backfill material to be used in the collection trench.

4.0 Results

Two simulations were conducted for each set of flow path models using MODFLOW: one representative of groundwater flow conditions during operations and one of conditions during long-term closure. The seepage rates were determined using the Plant Site groundwater model, as described in Attachment A of Reference (1) The models were run in steady-state.

Following the MODFLOW simulation, particle tracking was completed with MODPATH. One particle was started in the first column of each model layer in each model, where seepage is specified, and tracked forward through the modeled groundwater flow fields. In all simulations, the particles that originated in the model layers representing the unconsolidated deposits were captured by the FTB Containment System. The seepage from the Tailings Basin to bedrock was divided equally between the model layers representing bedrock. To calculate the seepage rate bypassing the FTB Containment System, the number of bedrock particles that bypassed the FTB Containment System were counted. The number of particles bypassing was then divided by the total number of bedrock particles and this proportion was multiplied by the total seepage from the Tailings Basin to bedrock to obtain the flow bypassing the FTB Containment System. Because the models were run in steady-state, the MODPATH results represent the long-term conditions; in reality, operations conditions may not be maintained for long enough for the system to reach steady-state. Particle tracking results under operations conditions are shown in Large Figure 4 through Large Figure 6; results under long-term closure conditions are shown in Large Figure 7 through Large Figure 9.

The results of the modeling indicate nearly all seepage from the Tailings Basin is captured by the FTB Containment System, as summarized in Table 4-1.

Table 4-1 Tailings Basin Seepage in GPM Bypassing the Containment System

Bedrock Fracture Zone Thickness	North Flow Path		Northwest Flow Path		West Flow Path	
	Operations (Mine Year 7)	Long-Term Closure	Operations (Mine Year 7)	Long-term Closure	Operations (Mine Year 7)	Long-Term Closure
25 feet	0	0	0	0	0	0
50 feet	0	0	0	0	0	0
100 feet	0	0	0	0	8	7

5.0 Summary and Conclusions

Groundwater modeling of groundwater seepage from the Tailings Basin to the north, northwest, and west flow paths was conducted to support the GoldSim water quantity and quality modeling. The objective of the flow-path models was to estimate the rate of seepage from the Tailings Basin that will pass beyond the FTB Containment System, thereby determining the effectiveness of the capture system.

Three MODFLOW flow path models, north, northwest, and west, corresponding to groundwater flow paths defined in the GoldSim model, were constructed. The flow path models originate at the toe of the tailings basin dams and terminate at the Embarrass River. Each model simulates groundwater flow along one of these three paths, representing a narrow, cross-sectional slice of aquifer spanning the length of a groundwater flow path. Model parameters and boundary conditions were set using data from onsite investigations and Project description; seepage from the Tailings Basin to each flow path was determined using the Plant Site model (Attachment A of Reference (1)).

Steady-state model simulations were completed for each flow path under operations and long-term closure conditions and for each of three assumed thicknesses of the more permeable fractured zone at the top of the bedrock. In total, 18 model simulations were completed. Model results indicated that all seepage from the Tailings Basin will be captured from the north and northwest flow paths under all assumptions of bedrock fracture zone thickness. From the west flow path all seepage is captured for bedrock fracture zone thicknesses of 25 feet and 50 feet; however, when the bedrock fracture zone thicknesses is assumed to be 100 feet, the model estimates that 8 gpm of seepage bypasses the FTB Containment System under operations conditions, and 7 gpm of seepage bypasses the FTB Containment System under long-term closure conditions. These flow rates correspond to 0.8% and 1% of total seepage toward the west flow path for operations and long-term closure conditions, respectively. Relative to the average aquifer capacity of the west flow path (110 gpm; Reference (1)), the rate of bypassing seepage is approximately 7% and 6% for operations and closure, respectively.

These results indicate that the Plant Site GoldSim model assumption (that seepage equal to 10% of the aquifer capacity bypasses the FTB Containment System) (Section 5.2.2. of Reference (1)) is conservative. The modeling shows that, at most, seepage equal to 7% of the aquifer capacity bypasses the system.

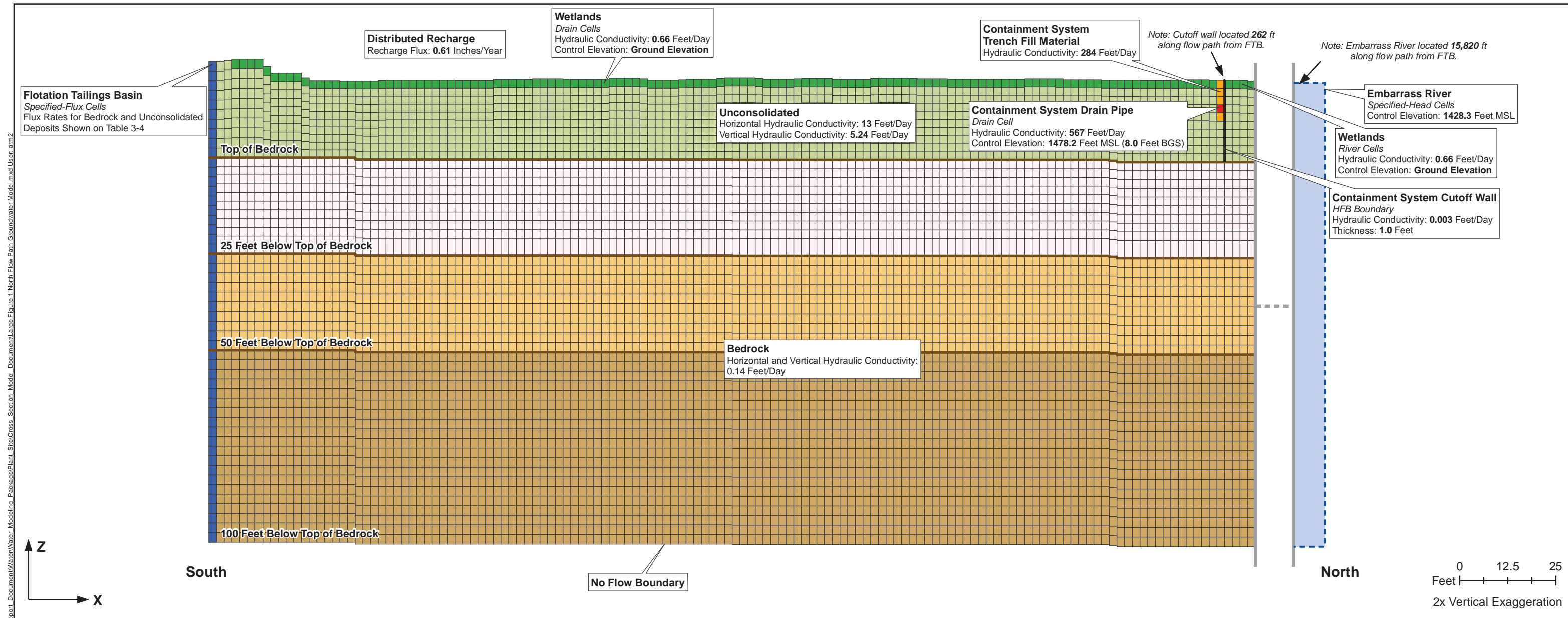
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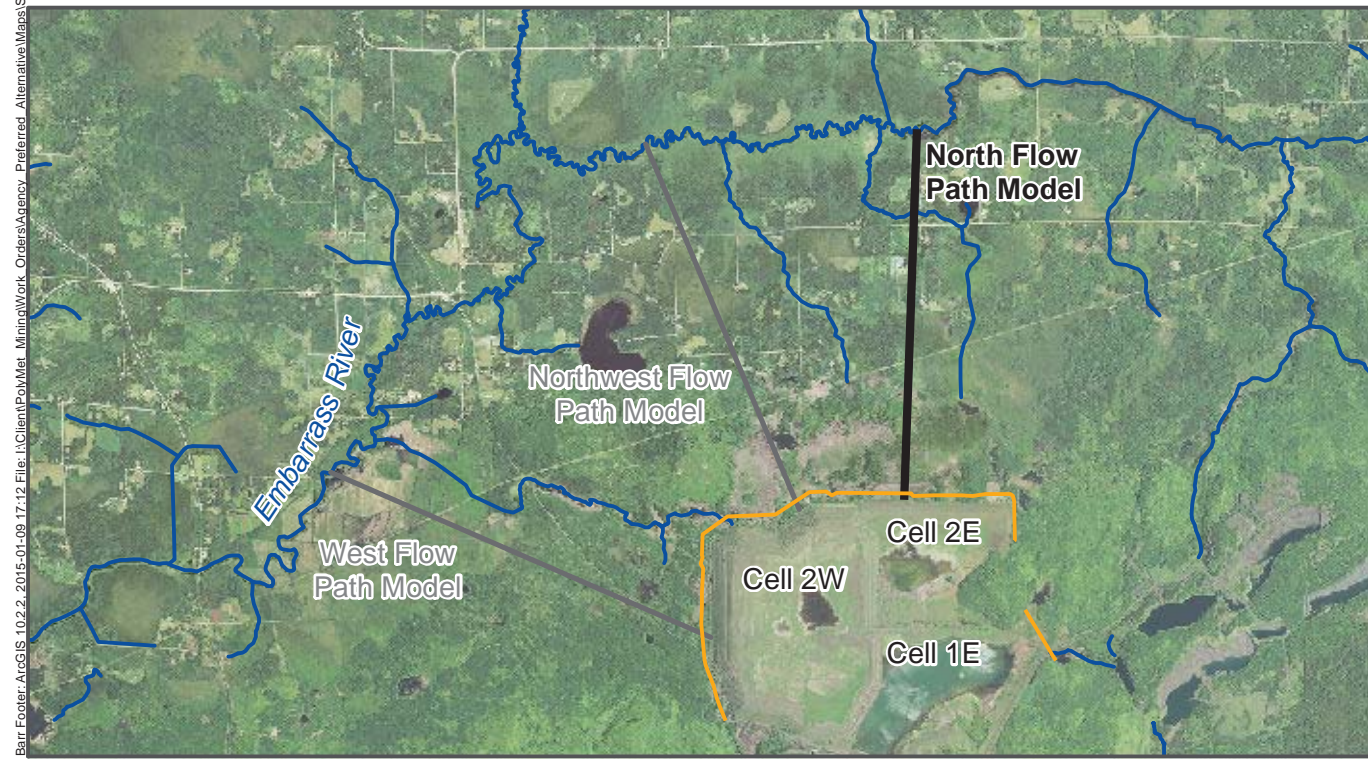
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Large Figures

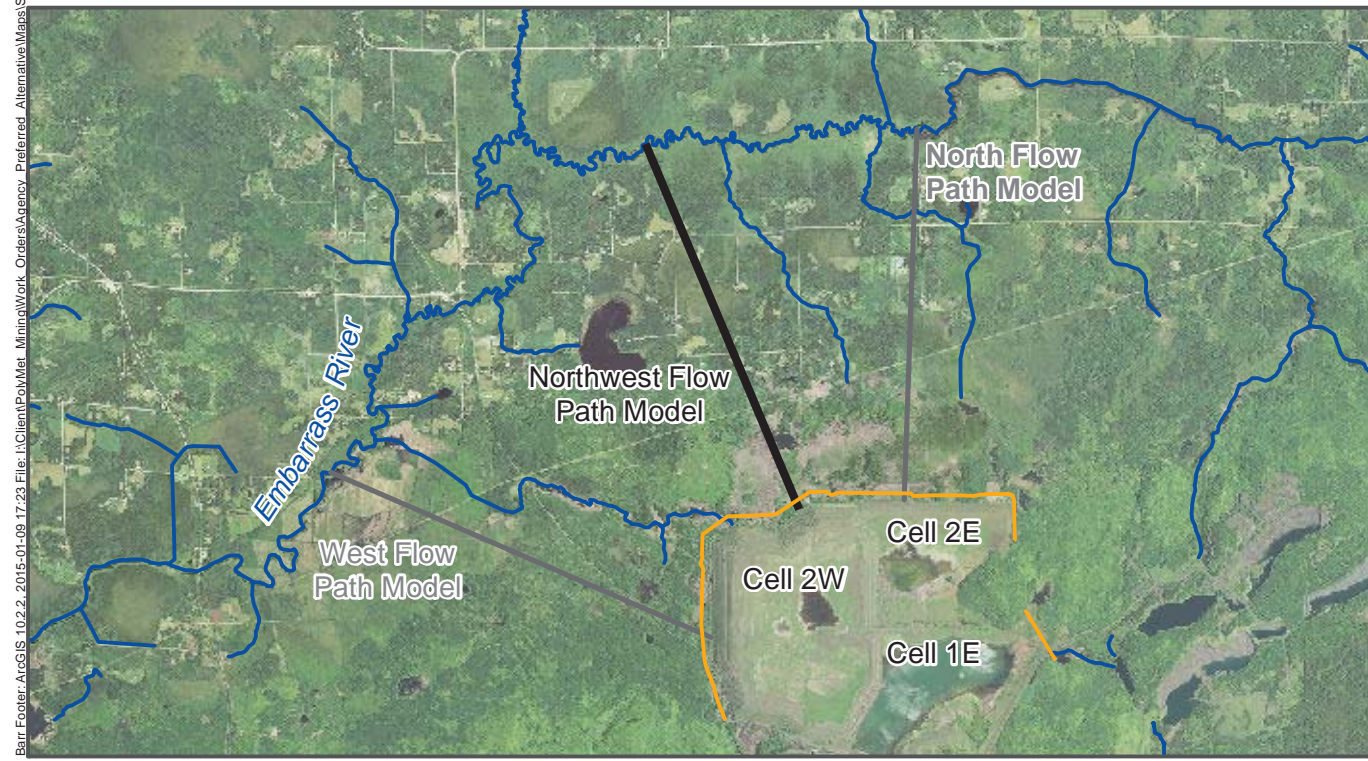
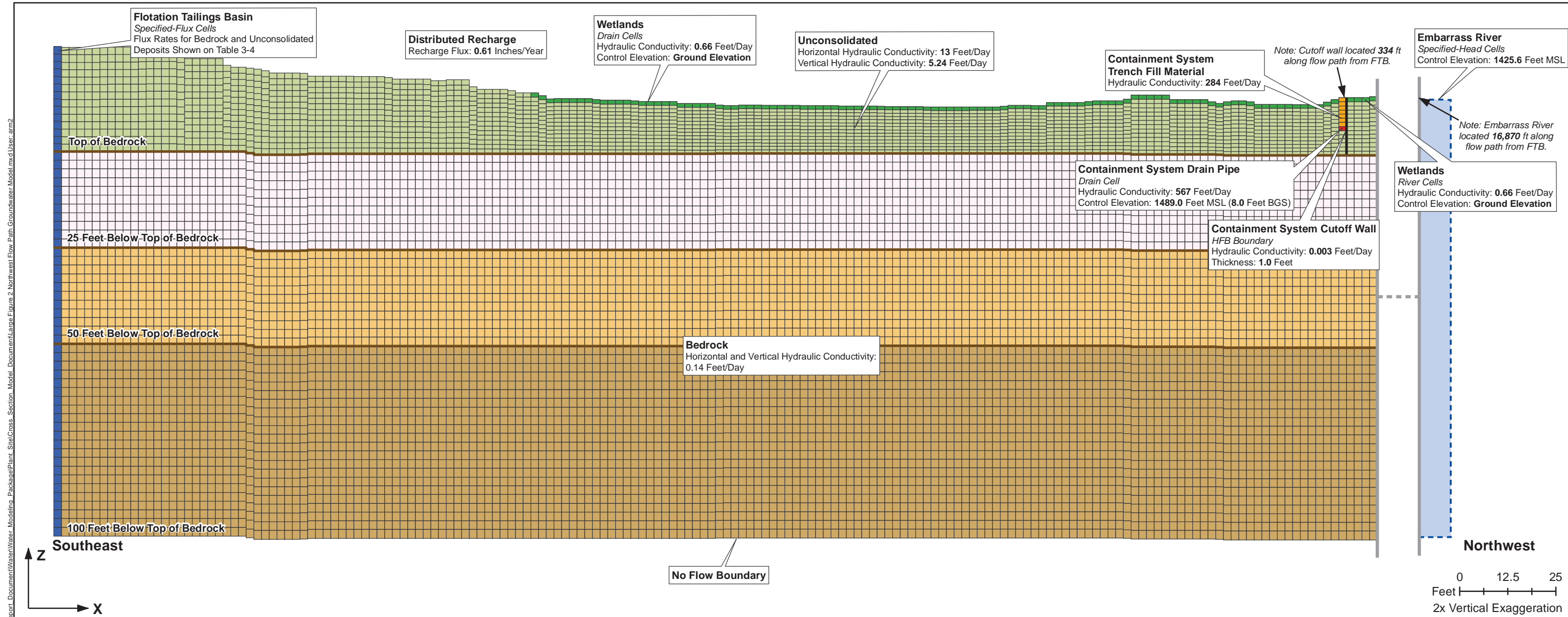


Note: North Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals shown.



Large Figure 1
 NORTH FLOW PATH
 GROUNDWATER MODEL
 NorthMet Project
 Poly Met Mining, Inc.
 Hoyt Lakes, MN

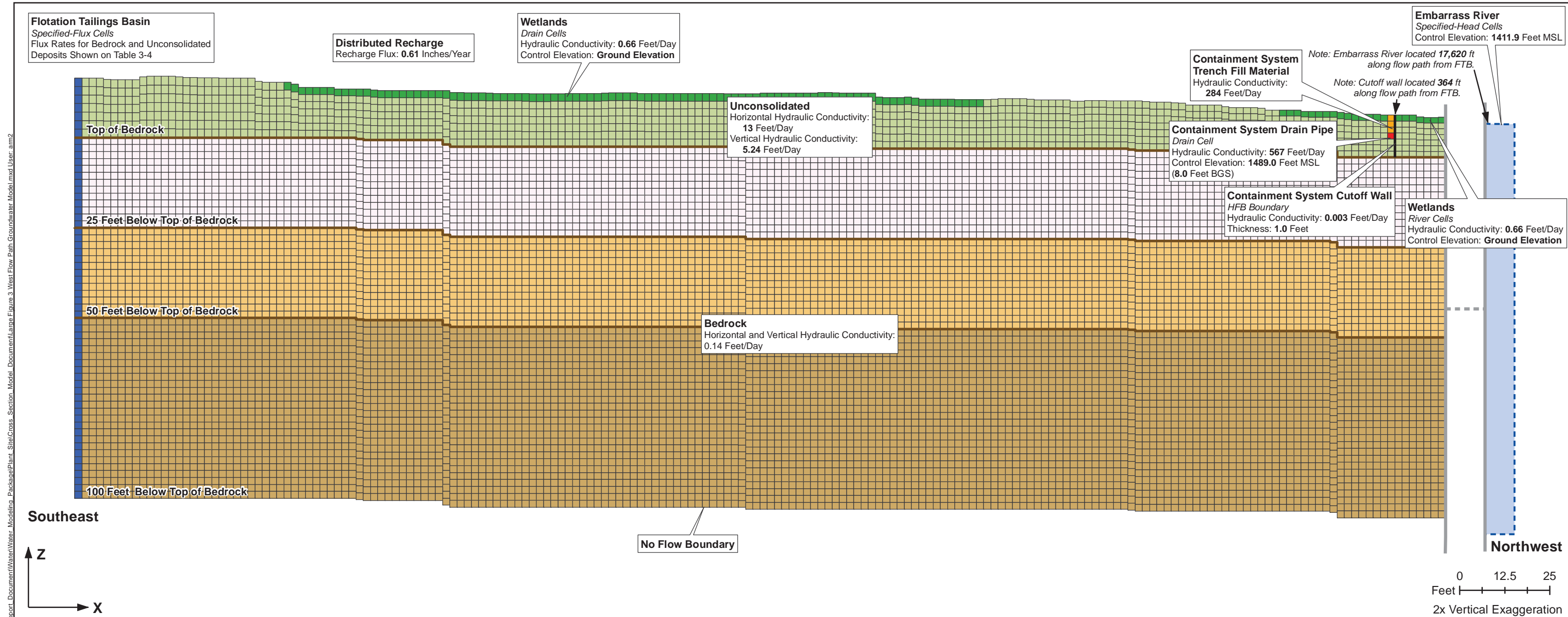
Barr Footer: ArcGIS 10.2.2, 2015-01-09 17:12 File: I:\Client\Polymet_MinnaWork_Orders\Agency_Prefered_Alternative\MapSupport_Document\Water\Water_Modeling_Package\Plant_Site\Cross Section_Model_Document\Large Figure 1 North Flow Path Groundwater Model.mxd User: am2



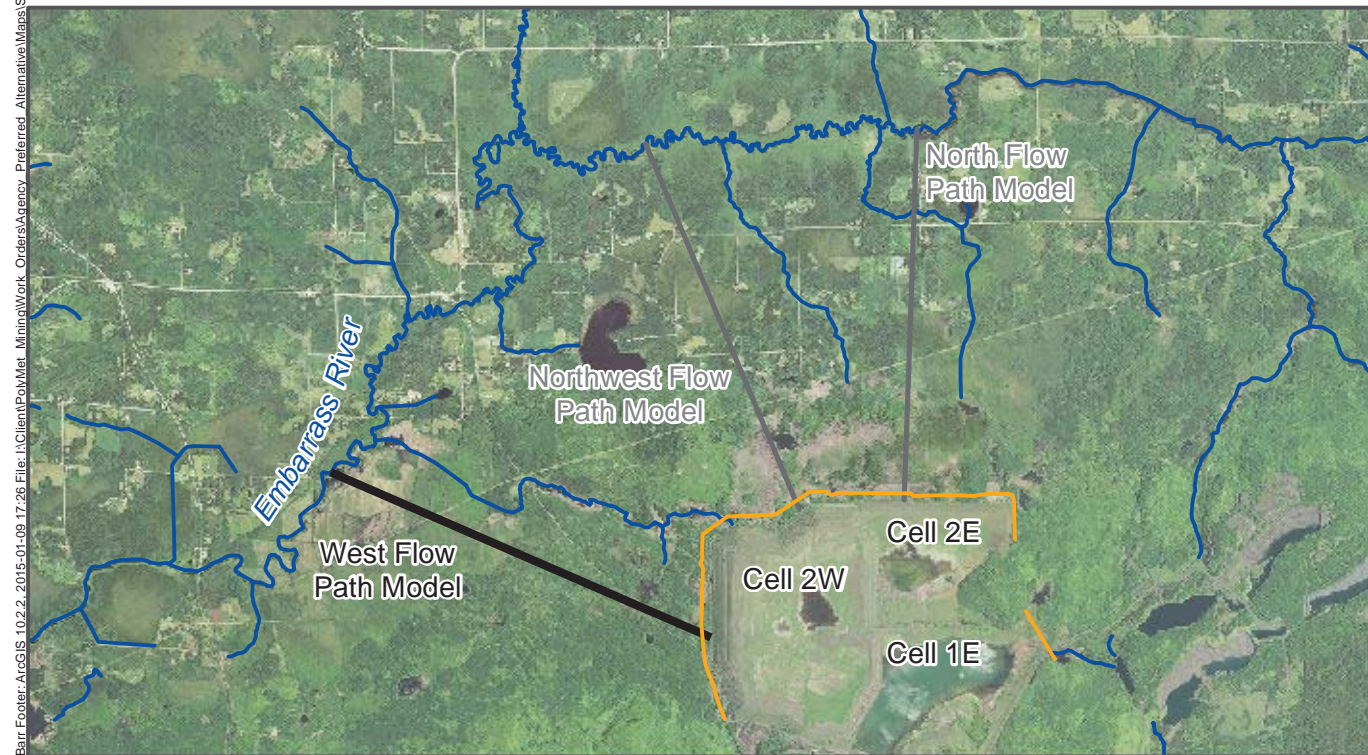
Note: Northwest Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals shown.

Large Figure 2
NORTHWEST FLOW PATH
GROUNDWATER MODEL
NorthMet Project
Poly Met Mining, Inc.
Hoyt Lakes, MN

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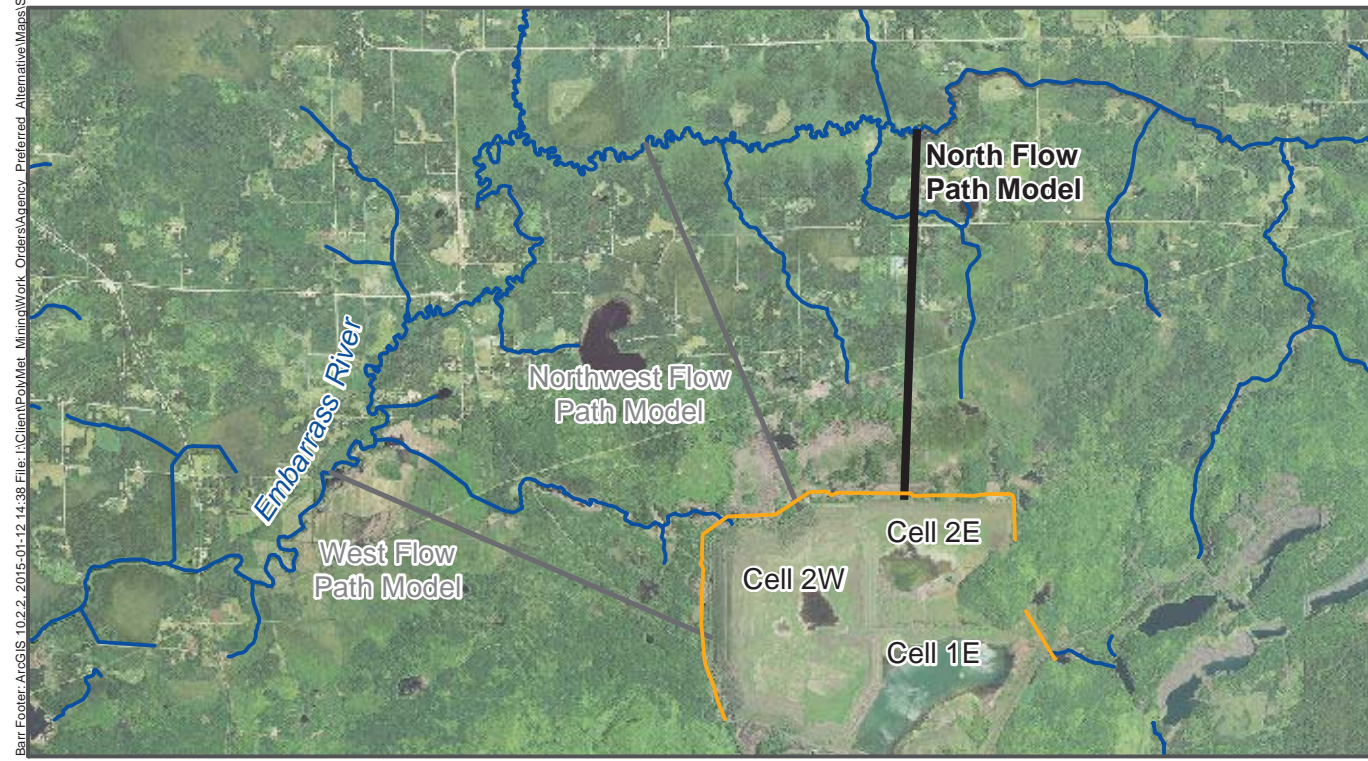
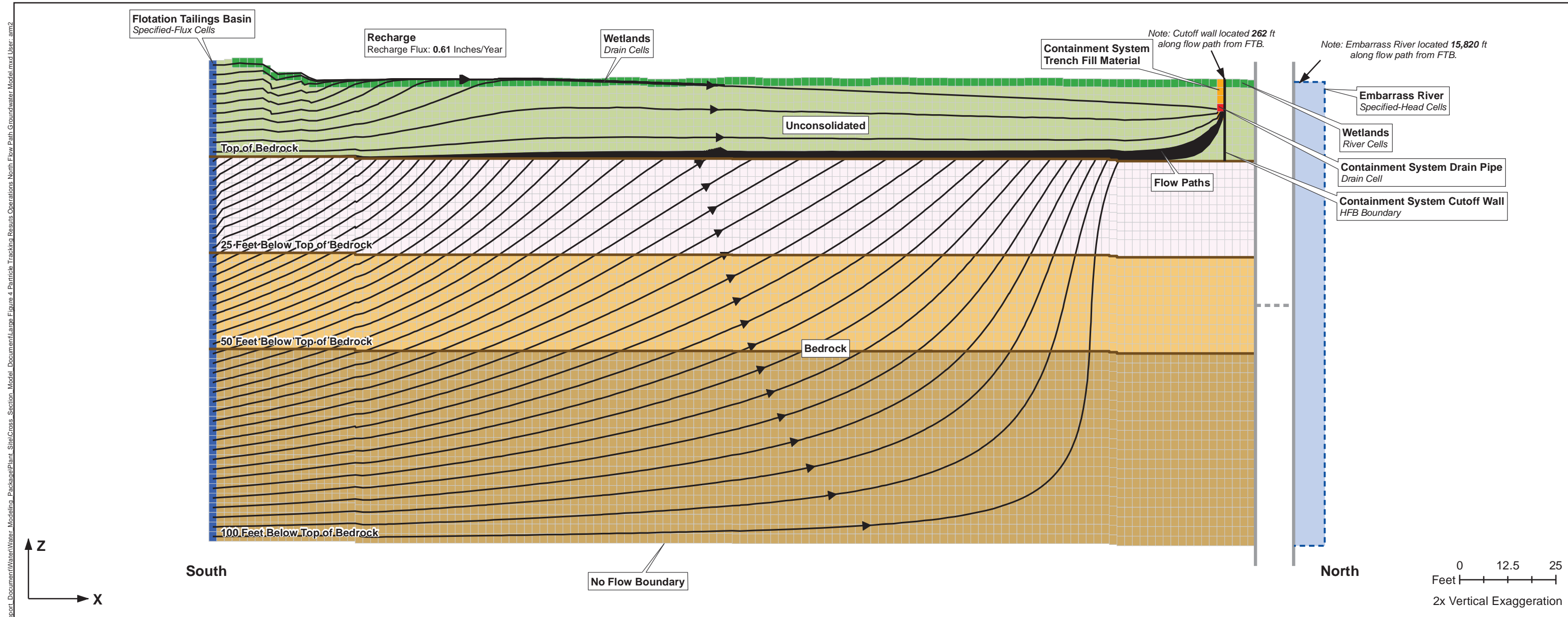


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Note: West Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals indicated.

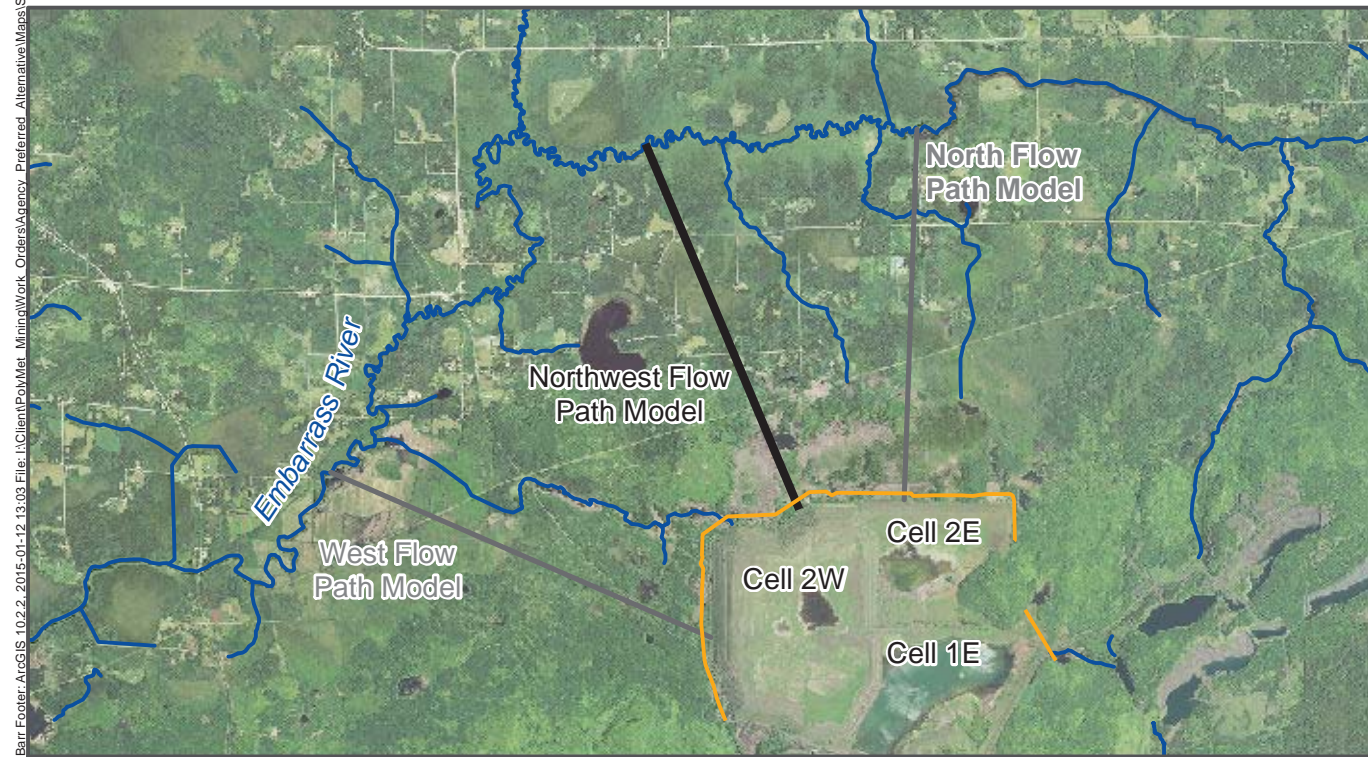
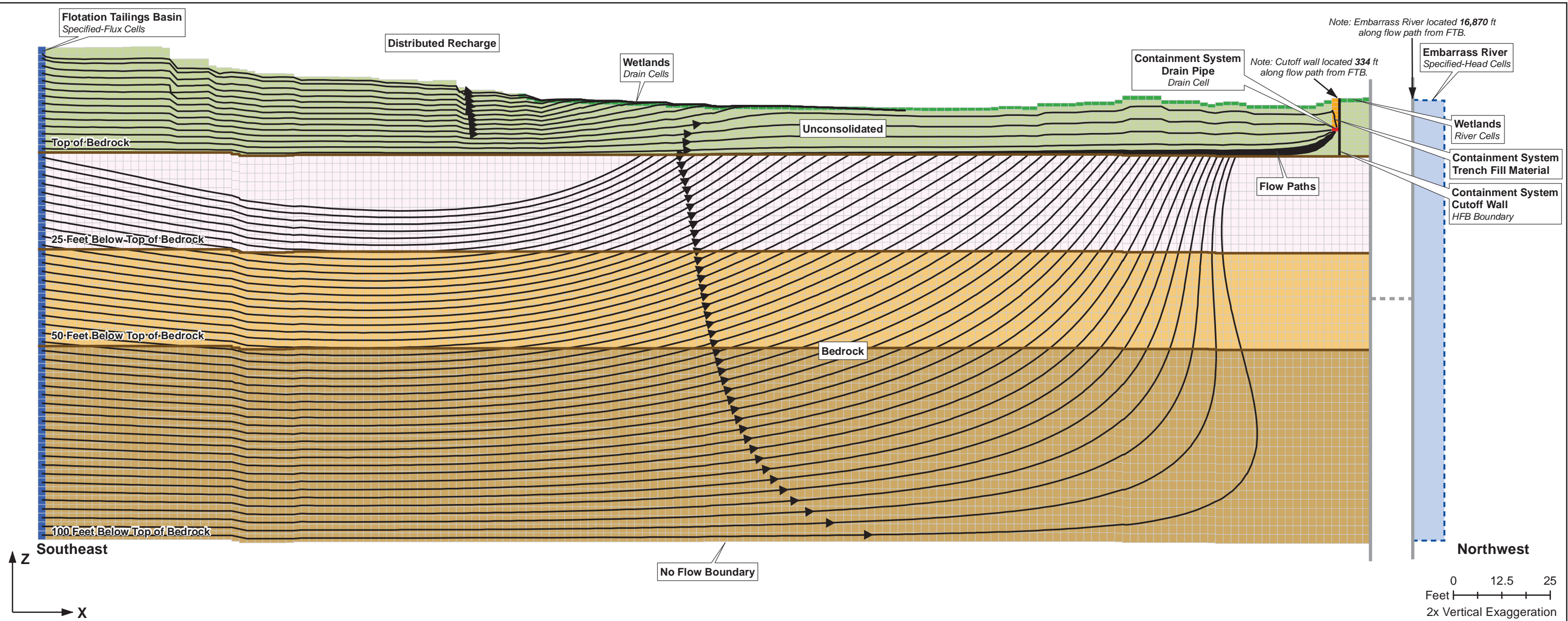
Large Figure 3
 WEST FLOW PATH
 GROUNDWATER MODEL
 NorthMet Project
 Poly Met Mining Inc.
 Hoyt Lakes, MN



Note: North Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals indicated. Particle tracking results are only shown for the simulation with 100 feet of bedrock.

Large Figure 4
 PARTICLE TRACKING RESULTS, OPERATIONS
 NORTH FLOW PATH GROUNDWATER MODEL
 NorthMet Project
 Poly Met Mining, Inc.
 Hoyt Lakes, MN

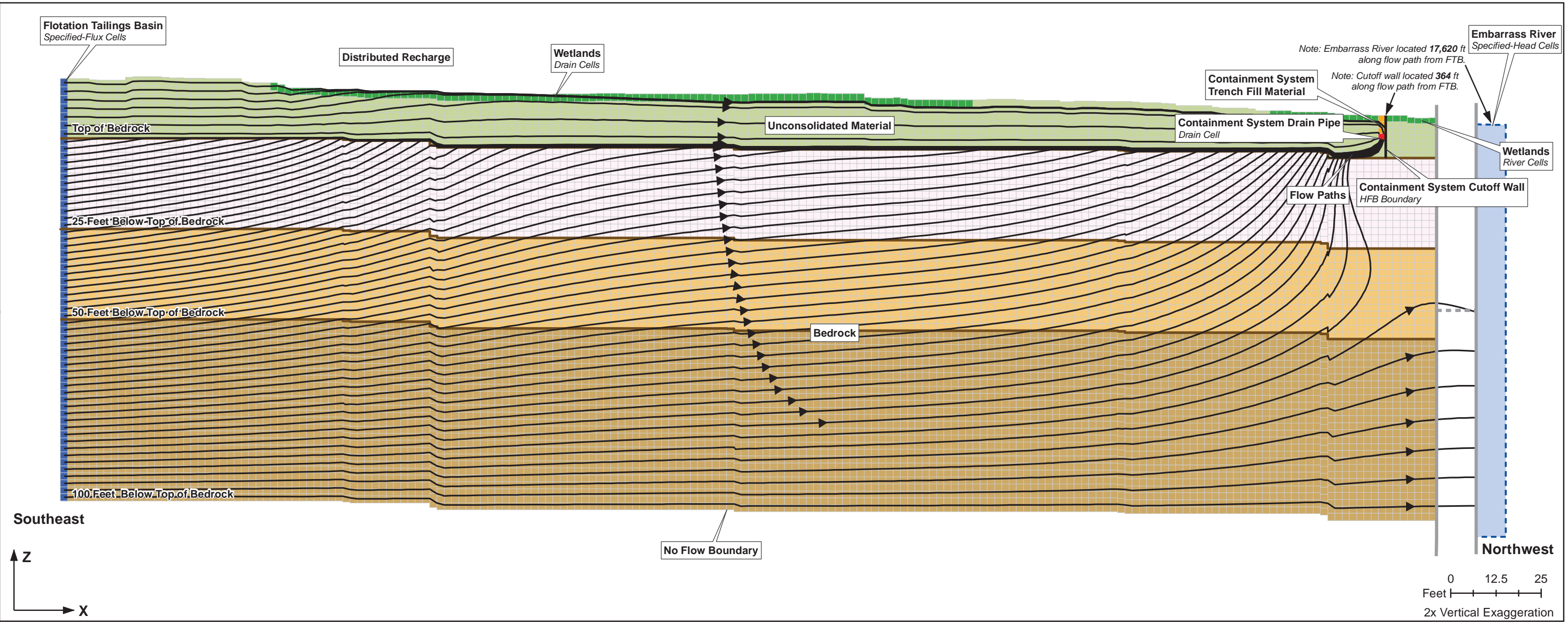
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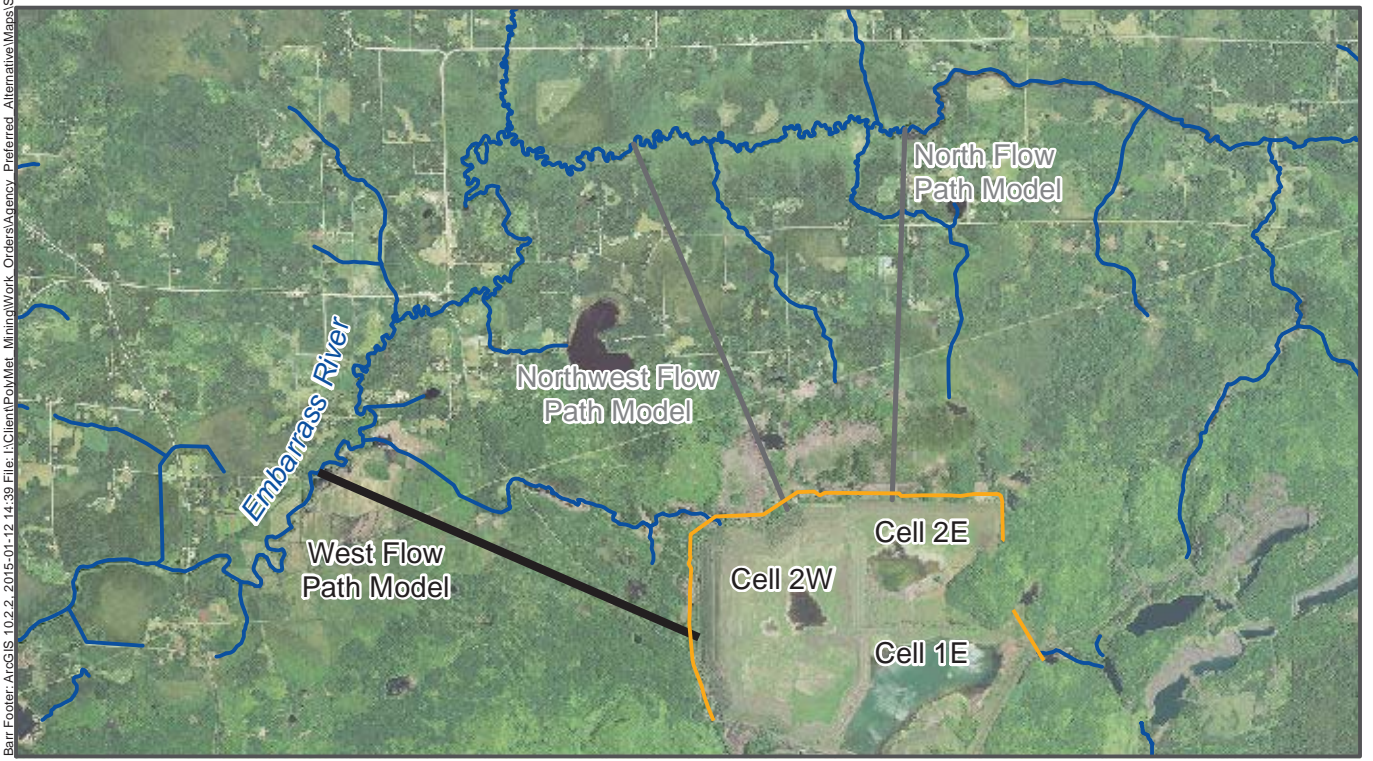
Note: Northwest Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals indicated. Particle tracking results are only shown for the simulation with 100 feet of bedrock.

Large Figure 5
 PARTICLE TRACKING RESULTS, OPERATIONS
 NORTHWEST FLOW PATH GROUNDWATER MODEL
 NorthMet Project
 Poly Met Mining, Inc.
 Hoyt Lakes, MN

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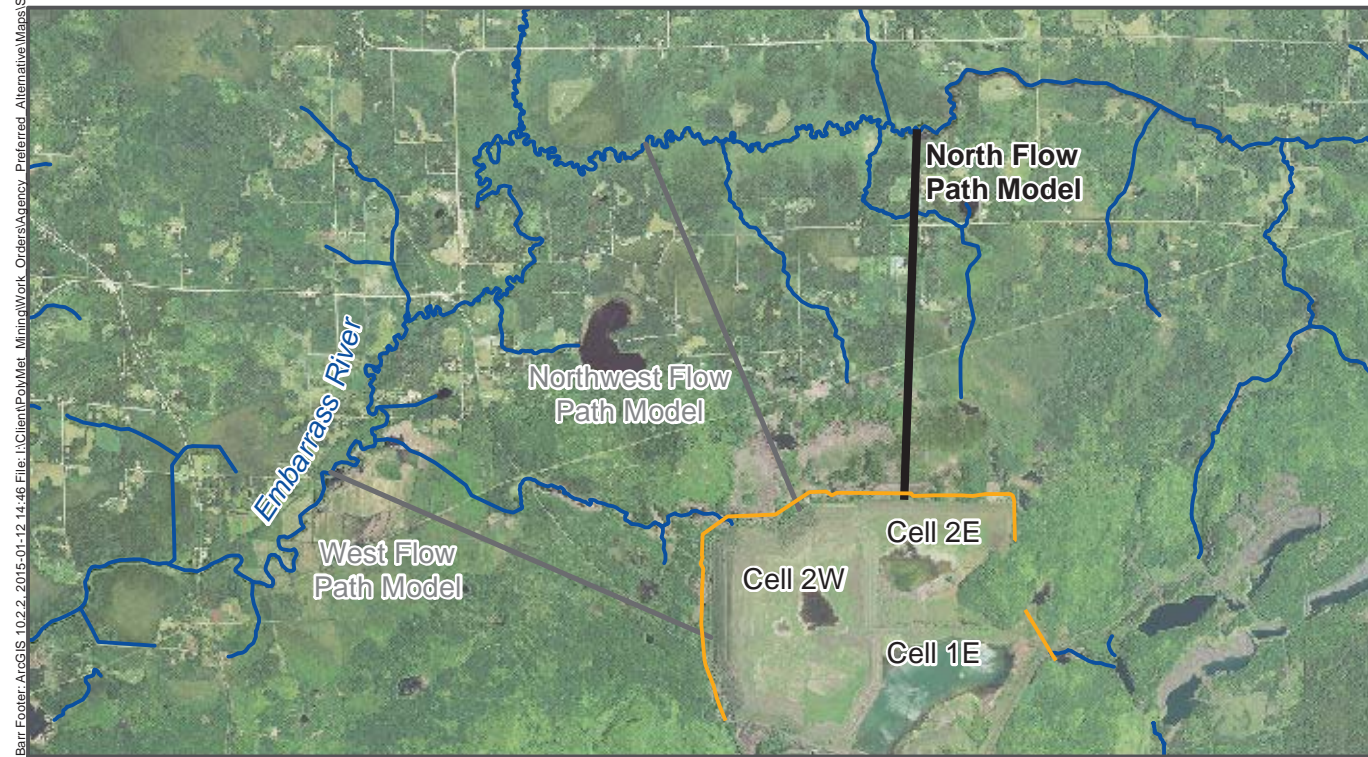
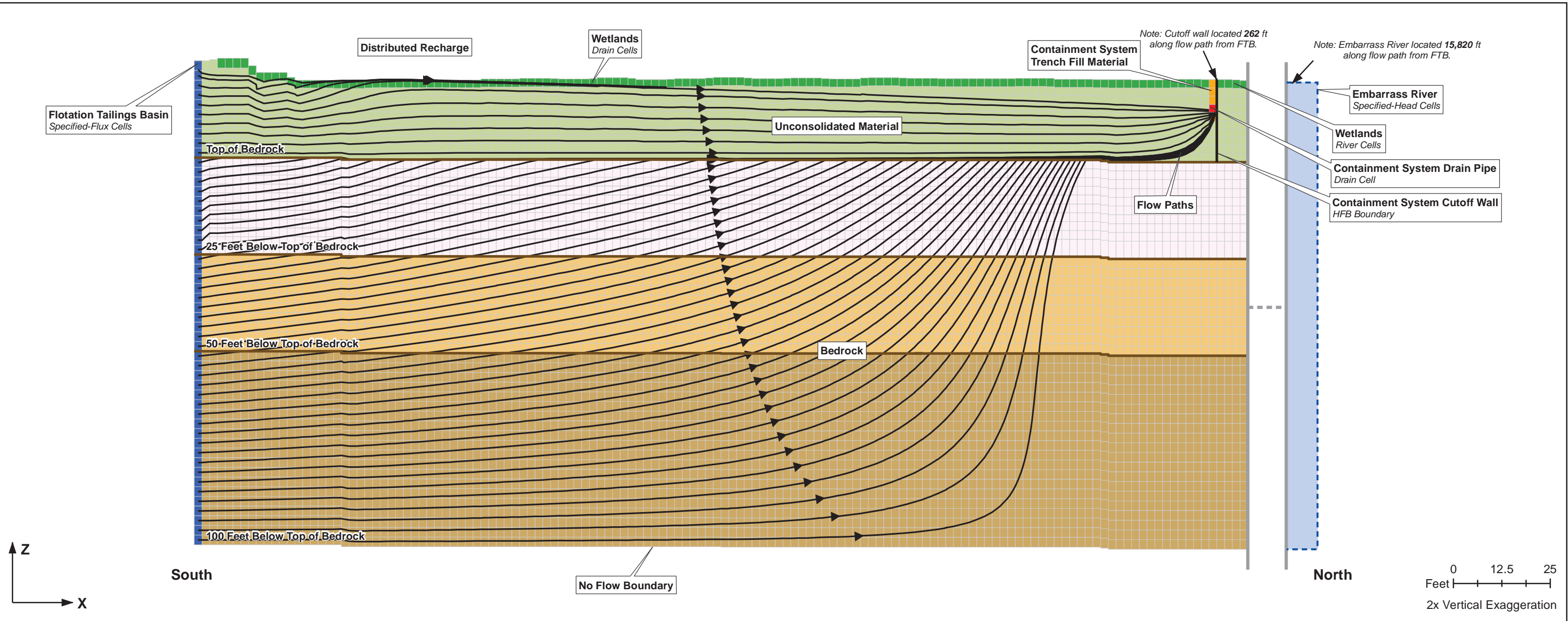


Note: West Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals indicated. Particle tracking results are only shown for the simulation with 100 feet of bedrock.



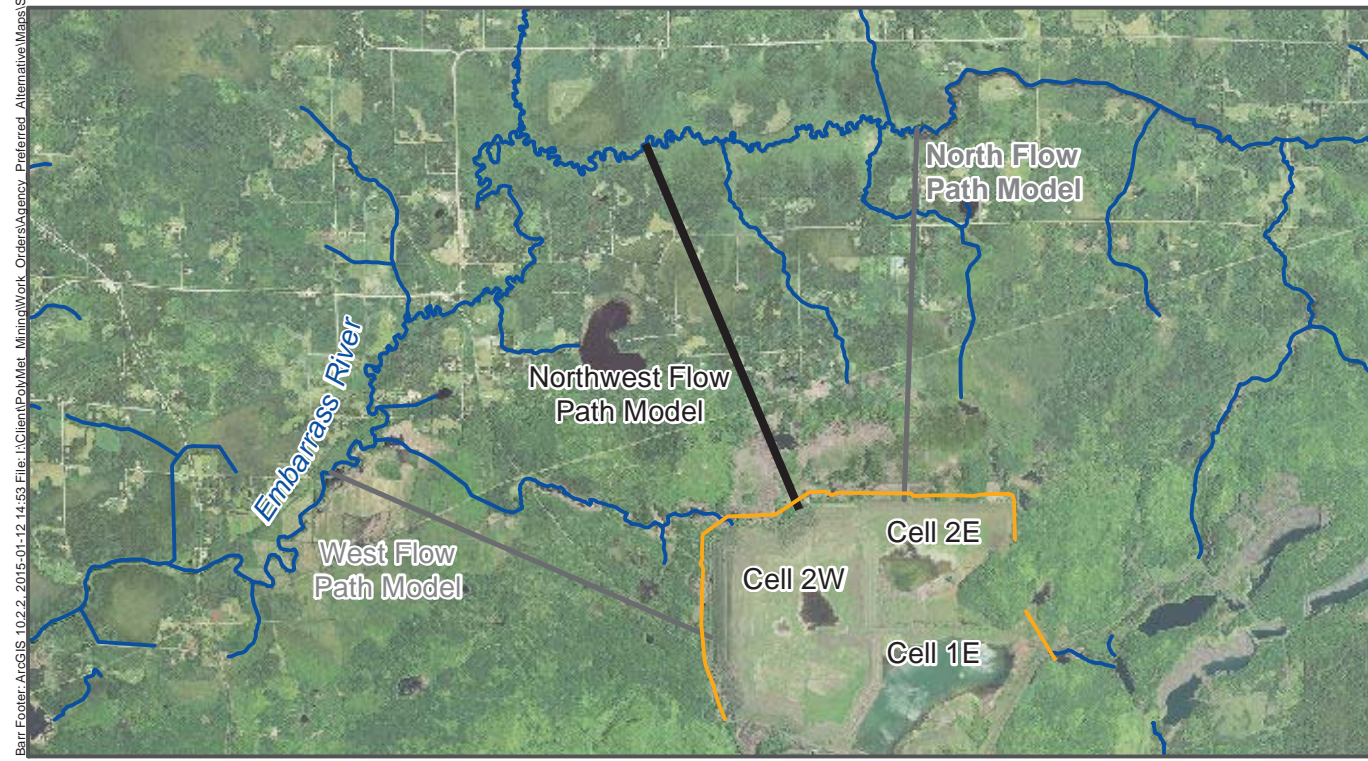
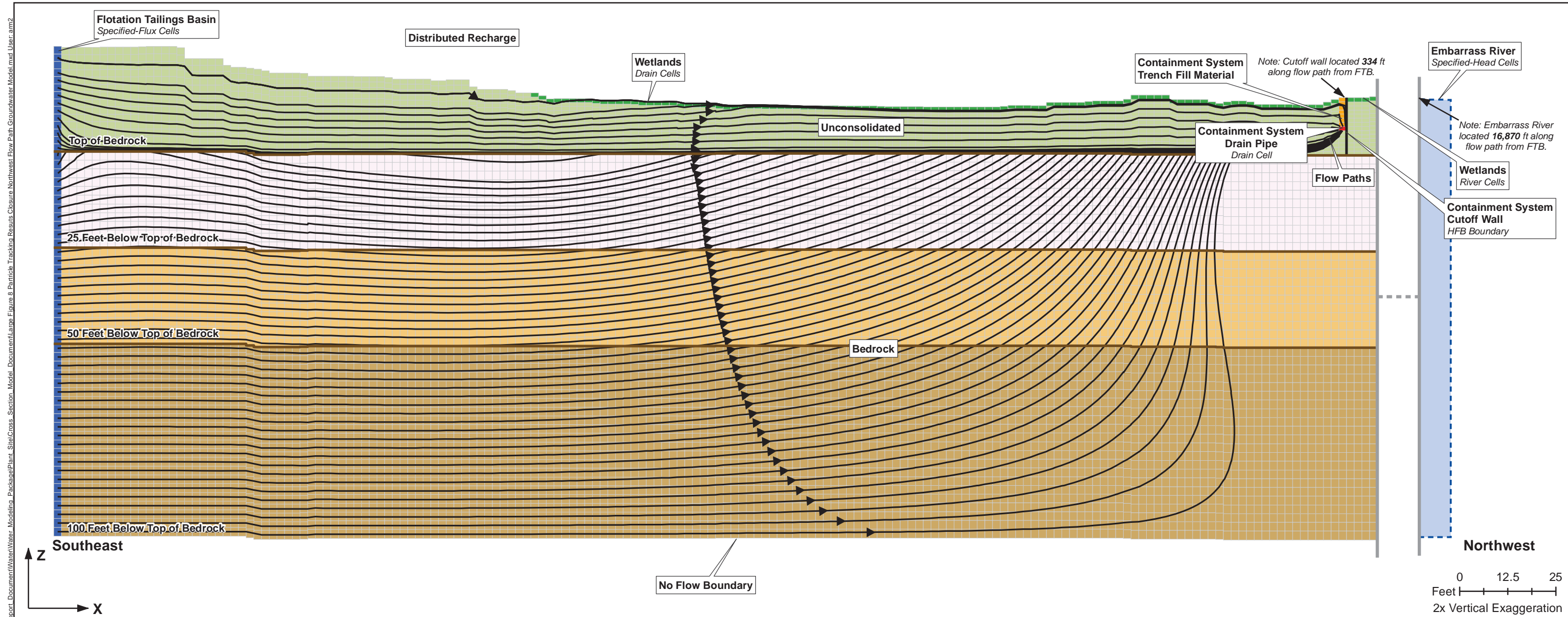
Large Figure 6
 PARTICLE TRACKING RESULTS, OPERATIONS
 WEST FLOW PATH GROUNDWATER MODEL
 NorthMet Project
 Poly Met Mining Inc.
 Hoyt Lakes, MN

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Note: North Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals indicated. Particle tracking results are only shown for the simulation with 100 feet of bedrock.

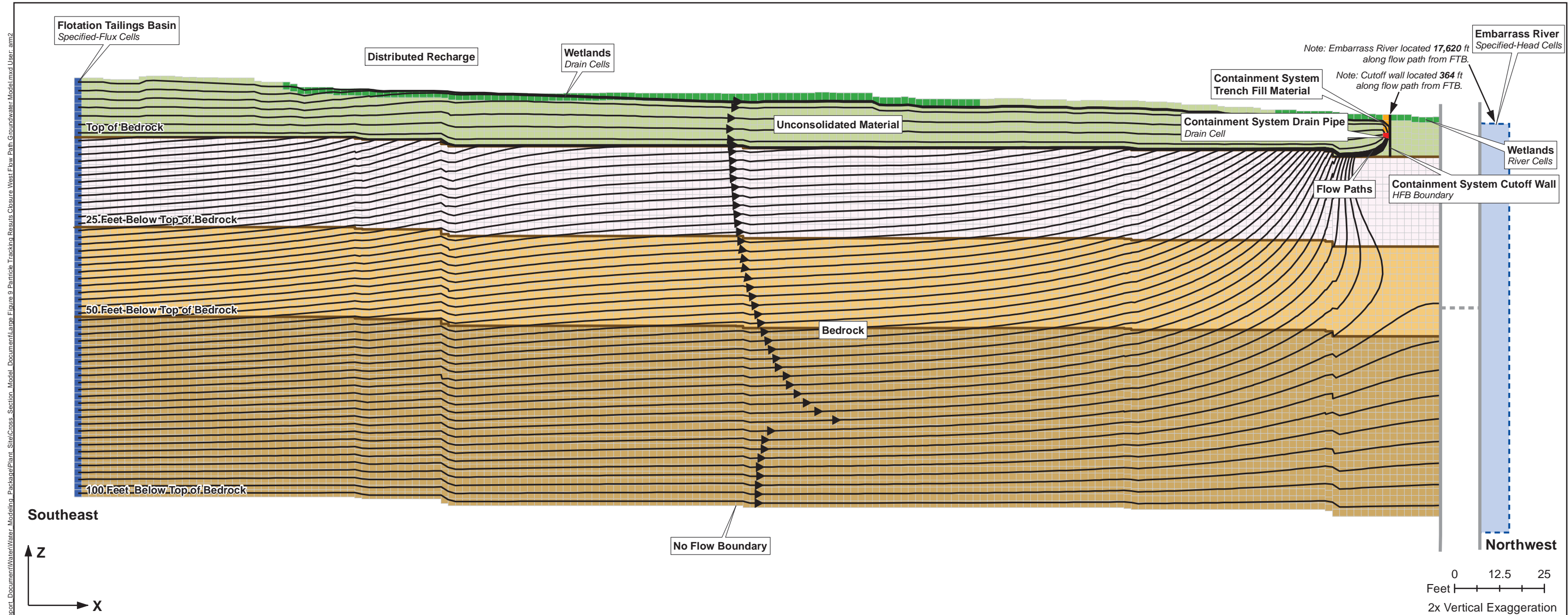
Large Figure 7
 PARTICLE TRACKING RESULTS, CLOSURE
 NORTH FLOW PATH GROUNDWATER MODEL
 NorthMet Project
 Poly Met Mining, Inc.
 Hoyt Lakes, MN



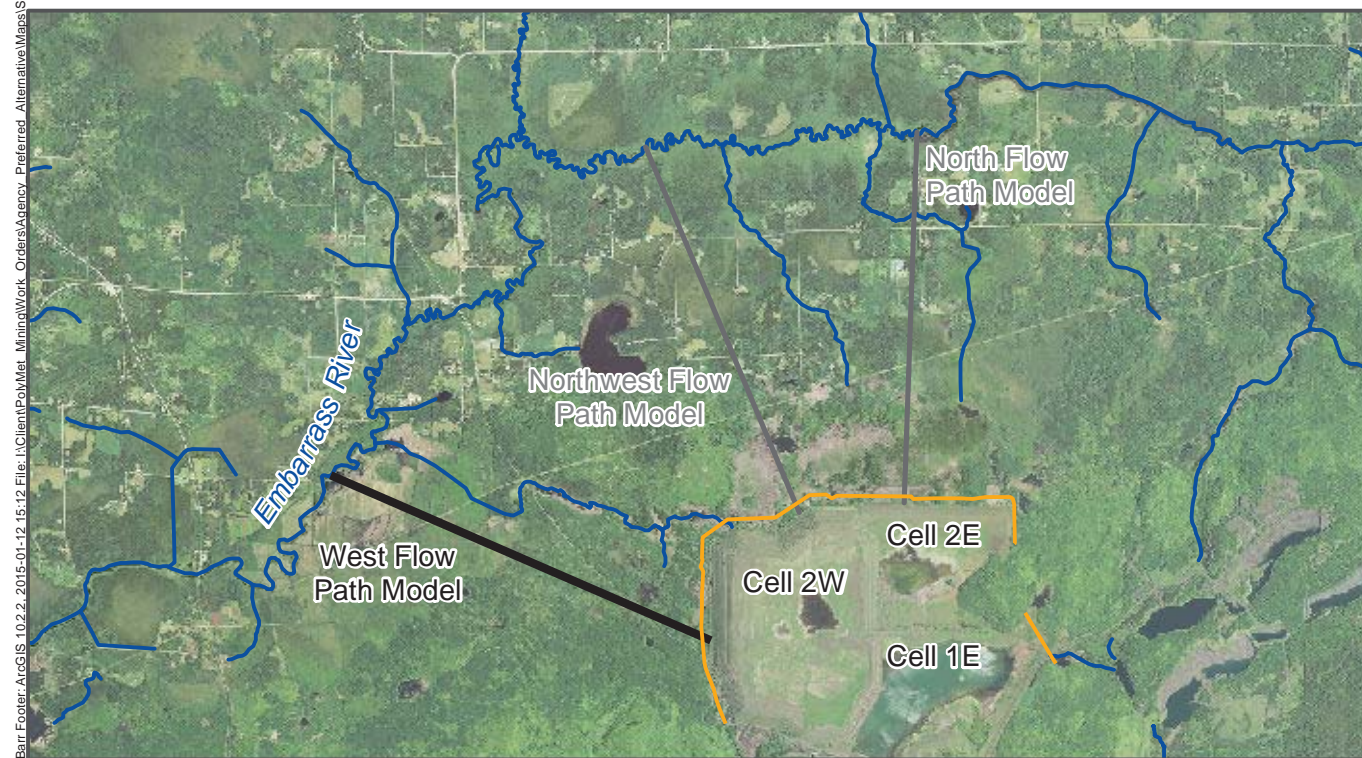
Note: Northwest Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals indicated. Particle tracking results are only shown for the simulation with 100 feet of bedrock.

Large Figure 8
 PARTICLE TRACKING RESULTS, CLOSURE
 NORTHWEST FLOW PATH GROUNDWATER MODEL
 NorthMet Project
 Poly Met Mining, Inc.
 Hoyt Lakes, MN

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Note: West Flow Path Models included the top 25, 50, or 100 feet of bedrock. The total depth shown represents 100 feet of bedrock with the 25- and 50-foot depth intervals shown. Particle tracking results are only shown for the simulation with 100 feet of bedrock.



Large Figure 9
 PARTICLE TRACKING RESULTS, CLOSURE
 WEST FLOW PATH GROUNDWATER MODEL
 NorthMet Project
 Poly Met Mining Inc.
 Hoyt Lakes, MN

Barr Footer: ArcGIS 10.2.2, 2015-01-12 15:12 File: I:\Client\PolyMet_MineralWork_Orders\Agency_Prefered_Alternative\MapSupport_Document\WaterWater_Modeling_Package\Plant_Site\Cross Section_Model_Document\Large Figure 9 Particle Tracking Results Closure West Flow Path Groundwater Model.mxd User: am2