Technical Memorandum

To: Poly Met Mining Inc. (PolyMet)
From: Rita Weaver, Barr Engineering Company
Subject: FTB Dam Break Analysis
Date: December 4, 2012
Project: 23/69-0862

Background

Barr conducted a dam break analysis for the north dam of the Flotation Tailings Basin (FTB) to provide information for the FTB Emergency Action Plan (EAP). The FTB dams have been designed to achieve necessary factors of safety (Geotechnical Data Package – Volume 1, [Reference (1)]), so a dam break is unlikely. The dam break analysis was completed to understand the potential extent of flood inundation between the FTB and the Embarrass River in the unlikely event of a failure at the dam. Results are incorporated in the EAP so emergency responders can plan for a worst-case scenario and be prepared to take all necessary actions should a dam break ever occur.

The FTB is located south of the Embarrass River in St. Louis County. The Trimble Creek watershed, shown in Figure 1, is the focus of the dam break analysis. Trimble Creek runs into the Embarrass River approximately 4 miles north of the FTB. The area between the FTB and the Embarrass River is sparsely populated forest.

A dam break analysis (also commonly referred to as dam breach analysis or dam failure analysis) uses a hydrologic model to determine the amount of runoff from a specified storm event and a hydraulic model to determine the route of the storm runoff and the dam break floodwave. Often the hydraulic model is run first without a dam break (only storm runoff flow is modeled) and then with a simulated dam break to determine the extent of additional inundation resulting from a break in the dam. The hydraulic model estimates the extent of flood inundation, the inundation depth, and the arrival time of a floodwave from a dam break. This memorandum describes the hydrologic and hydraulic modeling, documents the dam break assumptions, and presents a summary of the dam break model results.

Hydrologic Modeling

The HEC-HMS computer model, developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers was used to develop the hydrologic model. The HEC-HMS model uses the following mass conservation balance equation to compute the outflow volume from each subwatershed:

Outflow Volume = Runoff ± Storage – Infiltration – Evaporation + Baseflow

Evaporation and Baseflow were considered negligible compared to the volume of flow from a large storm event. Storage for the FTB was calculated based on topographic data. Runoff and infiltration were computed using the Soil Conservation Service (SCS) dimensionless unit hydrograph method. Input parameters include sub-watershed area, lagtime (which helps define how fast runoff leaves a watershed), initial abstraction (which accounts for surface storage in depressions, puddles, etc.), SCS curve number, and percent imperviousness. Each of these input parameters are described in further detail in the following paragraphs.

Subwatershed divides were delineated in the ArcMap geographic information system (GIS) using the US Geologic Survey (USGS) quadrangle maps. The subwatersheds downstream of the FTB were subdivided in order to compute a more accurate flow hydrograph in Trimble Creek during the Probable Maximum Precipitation (PMP) event. Figure 1 shows the location of the subwatershed divides.

The time of concentration, used in calculating the lagtime, was estimated using reach lengths, slopes, and velocities in each subwatershed. Charts from the Hydrology Guide for Minnesota (Reference (2)) and the channel geometry were used to estimate runoff velocity. Lagtime was then computed as 0.6 multiplied by the time of concentration, as suggested by the SCS.

The SCS curve number is based on soil type and the land cover type. Soil type was taken from the Soil Survey Geographic Database (SSURGO) provided by the Natural Resource Conservation Service, and land cover type was determined from aerial photos. Composite curve numbers calculated for each subwatershed ranged from 72 to 74. Initial abstraction was calculated using an empirical relationship developed by the SCS, which is based on a watershed's curve number.

The hydrologic model computed runoff from the 72-hour Probable Maximum Precipitation (PMP) storm event. This event was chosen for the analysis because it results in the most significant downstream inundation, allowing estimation of worst-case flooding in Trimble Creek. The total amount of precipitation for the 72-hour PMP event was assumed to be 32.2-inches for the 10-square mile watershed, based on the Hydrometeorological Report number 51(HMR 51), *Probable Maximum Precipitation Estimates, United States East of the 105th Meridian*. This precipitation was distributed according to the Huff's Fourth Quartile distribution, as described in the *Rainfall Frequency Atlas of the Midwest*. The 4th quartile distribution was chosen because it more closely represents a distribution for storm events longer than 24-hours.

Storm runoff from the Trimble Creek watersheds was routed downstream using the Muskingham-Cunge method of channel routing in HEC-HMS. This method uses the channel length, shape, slope and Manning's n for the channel and overbanks to route the watershed downstream. Channel length, slope, and an assumed channel shape were taken from GIS. Manning's n was determined by reviewing the aerial photos of the flow paths. Manning's n was assumed to be 0.04 for the main flow path and 0.1 for the overbanks. The runoff hydrograph for Trimble Creek had a calculated peak flow rate of approximately 6,000 cfs. This hydrograph was entered into the hydraulics model to evaluate the effect of flooding on Trimble Creek during the Probable Maximum Flood (PMF).

Storm runoff to the FTB was calculated using the same method as the Trimble Creek watersheds, however the volume of runoff from the storm event was not routed downstream. Since the FTB was designed to hold runoff from the 72-hour PMP event, it was assumed that the total runoff volume from the FTB direct watershed was added to the open water in the FTB and there was no discharge downstream.

Hydraulic Modeling

The hydraulics model HEC-RAS, also developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers, was used to route the Trimble Creek runoff hydrograph from the FTB to the Embarrass River. HEC-RAS calculated the maximum water surface profile along Trimble Creek for the 72-hour Probable Maximum Flood (PMF; produced by the PMP). A 'without-failure' profile was created to show the extent of flooding during the PMF with no dam break. This profile is used to compare the flooding from the storm event with and without a dam break. For the without-failure analysis, no outflow was assumed from the FTB because the 72-hour PMP volume would be contained by the FTB.

Trimble Creek were modeled as part of this study. A total of 41 cross-sections (not including interpolated cross-sections) were used to define the geometry of the creek. Road crossings were not modeled because they would likely be inundated with or without a FTB dam failure, and have a high probability of being washed out during the PMP event.

Cross-section geometry was defined using the USGS 30-meter digital elevation models (DEMs, approximate accuracy is 10-feet). The location of cross-sections was chosen based on the location of homes and the point where the topographic data showed a defined conveyance area. Normal depth was used as the downstream boundary condition for the model because there would be no backwater effect from the Embarrass River. Manning's n values were kept consistent with the hydrologic model.

Initial runs showed that the floodwave from a dam break would cause flooding outside of the main flow channel along Trimble Creek so "breakout" paths were defined to carry flow that would not be contained in the Trimble Creek floodplain. Natural overflow geometry taken from the DEM was used to define the natural overflow to the breakout paths, and an additional 24 cross-sections were used to define the breakout paths. Flows to each breakout path were calculated by the model. Figure 2 shows the locations of the breakout paths and the location of the cross-sections included in the HEC-RAS model.

Dam Break Analysis Methodology

The topography at the proposed FTB will be formed by perimeter dams up to 200 feet high, with side slopes of approximately 4.5H:1V, and 30-foot wide benches every 20 feet vertically. The tailings basin perimeter dams consist of coarse tailings from taconite processing operations. The dam break analysis focused on the north side of the FTB, because this is the section of the dam where a break would result in the shortest warning time for potentially affected downstream properties. A breach was not considered to the east or south of the FTB because a large portion of the perimeter ties into natural ground and/or no homes are within the respective downstream flow path.

At closure, the FTB will cover approximately 1,400 acres. The final dam crest elevation will be 1732 ft. The FTB will have approximately 10 feet of freeboard and will contain flotation tailings to a depth of approximately 160 feet.

The FTB is designed as a closed system, not allowing for release of water through overflow or outlet structures during operations; however a constant discharge from the FTB was assumed to aid with model stability. All precipitation that falls within the FTB perimeter will be contained by freeboard, including the precipitation from the 72-hour PMP event. The flow into the FTB from plant operations was assumed to be negligible compared to the runoff from the storm event so it was not included in this analysis.

Piping was selected as the cause of the dam break for this study. Piping is the process whereby seepage through the dam is of sufficient velocity to initiate erosion and downstream transport of soils from the structure of the dam. Failure resulting from overtopping the dam was not considered because the dam is designed to not be overtopped even with the volume of the 72-hour PMP event.

Dam break parameters are based on recommendations by the Federal Energy Regulatory Commission (FERC) and the Bureau of Reclamation as well as a review of the *Breaching Parameters for Earth and Rockfill Dams* (Reference (3)). The recommendations for breach parameters in Reference (3) were developed by creating empirical relationships between five breaching parameters (breach depth, breach location top width, average breach width, peak outflow rate, and failure time) and five dam and reservoir variables (dam height, reservoir shape, dam type, failure mode and dam erodibility) recorded for historical dam failures. This reference was considered for our analysis because the study's evaluation of breach parameters considered dams of heights and volumes comparable to the FTB dams. Also, this method estimated failure parameters for recorded large dam failures more accurately than other potential methods. Table 1 provides a summary of breach parameters recommended by federal agencies and the breach parameters used for this evaluation. The extensive regression and empirical equations developed in Reference (3) are not summarized here, but can be found in that document.

Table 1 Dam Break Analysis Breach Parameters

Parameter	FERC Suggested Breach Parameters	Bureau of Reclamation's Suggested Breach Parameters	Breach Parameters Used for this Study
Average Width of Breach (BR)	HD* ≤ BR ≤ 5HD	$3H_w$*	2.24HD
Horizontal Component of Breach Side Slope (Z)	0.25 ≤ Z ≤ 1	N/A	0.64H:1V
Time to Failure (hours)	0.1 ≤ TFM ≤ 1	0.011BR	3

*(HD = Height of dam, Hw = Height of water, Z = Horizontal Component of Side Slope (ZH:1V), TFM = Time to Failure (in hours), BR = Breach Width (feet)

The average breach width was assumed to be 2.24 times the height of the dam, and the breach side slopes were assumed to be 0.64H:1V. These were calculated based on the methods of Reference (3), and fall within the Bureau of Reclamation agency recommendations.

Time to failure is a sensitive parameter for dam failure analysis, and all three methods were used to calculate the time to failure and were then compared. Time to failure represents the time from onset of piping to completion of the dam break. Time to failure suggested by the Bureau of Reclamation is approximately three hours. Time to failure calculated using the methods and equations in Reference (3) is closer to four hours (note FERC's recommendation is less than an hour). The Bureau of Reclamation's recommendation was selected because it is more conservative than the time to failure computed following the methods of Reference (3). FERC's recommendation of a failure time of less than one hour seemed unrealistic based on the size of the dam and final breach configuration.

The depth of breach (from dam crest to bottom of breach) was calculated at 134 feet using the empirical equation included in Reference (3). This breach depth is nearly the entire final 160-foot depth of floatation tailings.

The most significant unknown breach parameter for a tailings basin dam is how much of the tailings would be suspended and carried downstream in the event of a dam breach. Studies have shown that in many cases only 30 percent of the volume in the basin is carried downstream, however basin dam breaks have been recorded where up to 80 percent of the volume was carried downstream. The volume of tailings released is dependent on how the basin is constructed and operated. Additional unique attributes of tailings basin dam breaks are the rate of sediment deposition downstream of the basin (i.e., how quickly do the tailings flowing from the basin redeposit outside of the basin) and flow properties of the liquefied tailings compared to water. These variables will affect the floodwave volume, flow rate, and travel time.

The complexity of dam break analysis requires many simplifications, so modeling inputs were chosen to be conservative by setting each parameter in the range that could cause more severe impacts. Assumptions include:

- One hundred percent of the Flotation Tailings above the bottom breach elevation will leave the FTB. This assumption maximizes flood volume.
- None of the Flotation Tailings will be re-deposited immediately downstream of the dam breach. This assumption maximizes flood volume.
- The dam break will occur simultaneously with the peak flow from the 72-hour PMP event in the Trimble Creek watershed. This assumption maximizes the inundation area.
- The floodwave will act as water instead of liquefied Flotation Tailings. This assumption minimizes the travel time of the flood wave.
- Structures are at the ground surface elevation shown on the 30 meter DEM, rather than elevated several feet on foundations. This assumption maximizes the number of structures affected.

These conservative assumptions likely result in over estimation of inundation area, flood depth, and number of structures affected and underestimate floodwave travel time Extensive additional analysis would be necessary to realistically estimate the percentage of flotation tailings left in the FTB, to evaluate flotation tailings deposition after the breach and to better understand flow properties of the liquefied flotation tailings. Such analysis is not warranted given the objective of this dam break analysis, which is to serve as an aid in development of the facility Emergency Action Plan. In other words, in the unlikely event of a dam break at the FTB, response actions developed on the basis of this dam break analysis are expected to be conservative. The actual extent of inundation and risk to residents and infrastructure can reasonably be anticipated to be lower than suggested by this analysis.

Dam Break Analysis Results

This study shows that a dam break could increase flood elevations approximately 15 feet at the upstream end of Trimble Creek (near the FTB) and approximately 9 feet at the downstream end of Trimble Creek (at the Embarrass River). Average flow velocities range from 10 feet-per-second (fps) to 25 fps in the main channel, but are reduced to 2 fps to 10 fps along the overbanks. Note again that these velocities are based on use of physical properties of water in the model; actual flow velocities for more viscous liquefied flotation tailings may be lower than these values.

Figure 3 shows the estimated inundation areas along Trimble Creek for the 72-hour PMP event, and the estimated inundation area along the creek and overflow paths for dam breach floodwave. The breach inundation area does not include flows from the 72-hour PMP event, because modeling found that storm runoff in the Trimble Creek watershed contributed only 1% of the total flow during a dam break event. The time to peak elevation is also noted on Figure 3 at several locations along the downstream flow paths to show estimated travel times of the floodwave.

This conservative dam break analysis indicates that there are 34 properties along Trimble Creek or the breakout paths that could potentially be affected by a FTB dam break. One of these properties would be inundated in the event of a 72-hour PMP event without a dam break. Because of the conservative assumptions made for this dam break analysis, it is likely that many of these homes would remain outside of the actual area of inundation.

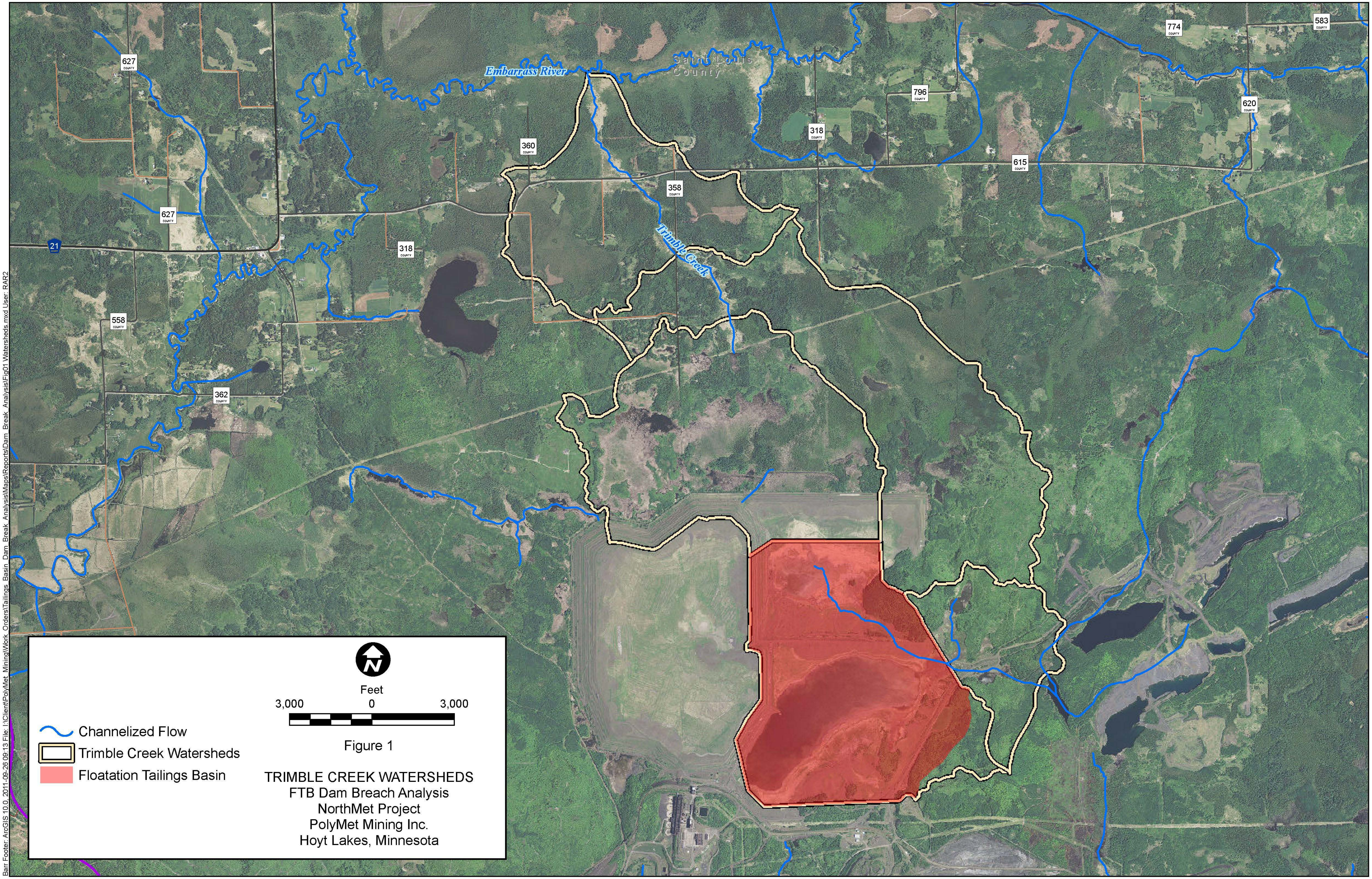
References

1. **Poly Met Mining Inc.** NorthMet Project Geotechnical Data Package Vol 1 - Flotation Tailings Basin (v3). November 2012.

2. **Soil Conservation Service (SCS).** Hydrology Guide for Minnesota. St. Paul, Minnesota : s.n., 1977.

3. **Xu, Y. and Zhang, L.** Breaching Parameters for Earth and Rockfill Dams. *J. Geotech Geoenviron. Eng.* 2009, Vol. 135, 12, pp. 1957-1970.

Figures


Embarrass River
Saint Louis County
Trimble Creek
627
360
358
318
796
774
583
620
615
21
558
362
Feet
3,000
0
3,000
Channelized Flow
Trimble Creek Watersheds
Floatation Tailings Basin
Figure 1
TRIMBLE CREEK WATERSHEDS
FTB Dam Breach Analysis
NorthMet Project
PolyMet Mining Inc.
Hoyt Lakes, Minnesota

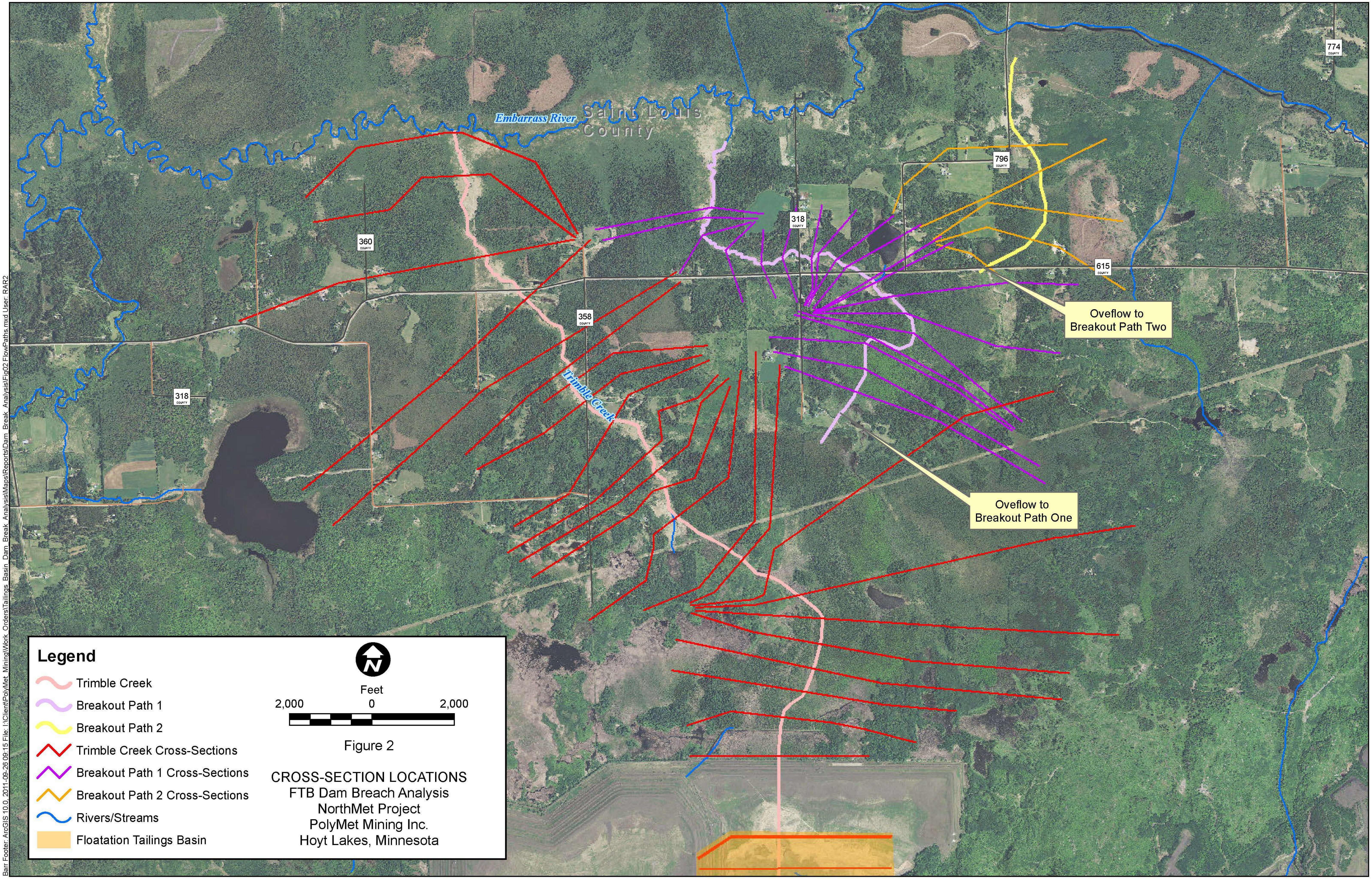
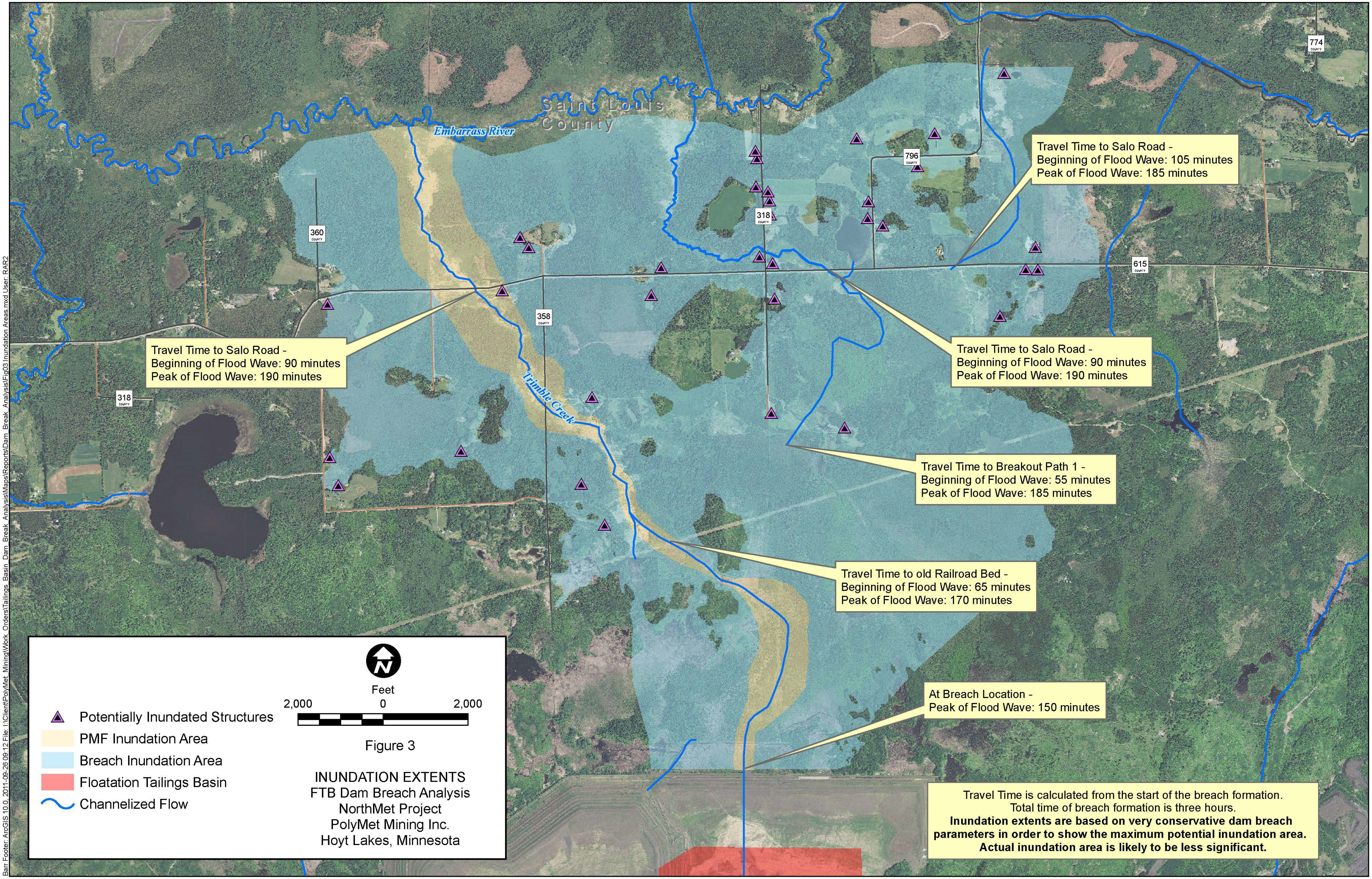


Figure 2

CROSS-SECTION LOCATIONS
FTB Dam Breach Analysis
NorthMet Project
PolyMet Mining Inc.
Hoyt Lakes, Minnesota



Saint Louis County
Embarrass River
Trimble Creek
360
358
318
796
615
774
Travel Time to Salo Road -
Beginning of Flood Wave: 105 minutes
Peak of Flood Wave: 185 minutes
Travel Time to Salo Road -
Beginning of Flood Wave: 90 minutes
Peak of Flood Wave: 190 minutes
Travel Time to Salo Road -
Beginning of Flood Wave: 90 minutes
Peak of Flood Wave: 190 minutes
Travel Time to Breakout Path 1 -
Beginning of Flood Wave: 55 minutes
Peak of Flood Wave: 185 minutes
Travel Time to old Railroad Bed -
Beginning of Flood Wave: 65 minutes
Peak of Flood Wave: 170 minutes
At Breach Location -
Peak of Flood Wave: 150 minutes
Potentially Inundated Structures
PMF Inundation Area
Breach Inundation Area
Floatation Tailings Basin
Channelized Flow
N
Feet
2,000 0 2,000
Figure 3
INUNDATION EXTENTS
FTB Dam Breach Analysis
NorthMet Project
PolyMet Mining Inc.
Hoyt Lakes, Minnesota
Travel Time is calculated from the start of the breach formation.
Total time of breach formation is three hours.
Inundation extents are based on very conservative dam breach parameters in order to show the maximum potential inundation area.
Actual inundation area is likely to be less significant.