# Preliminary Dam Breach Inundation Analysis for the Copperwood Project

by
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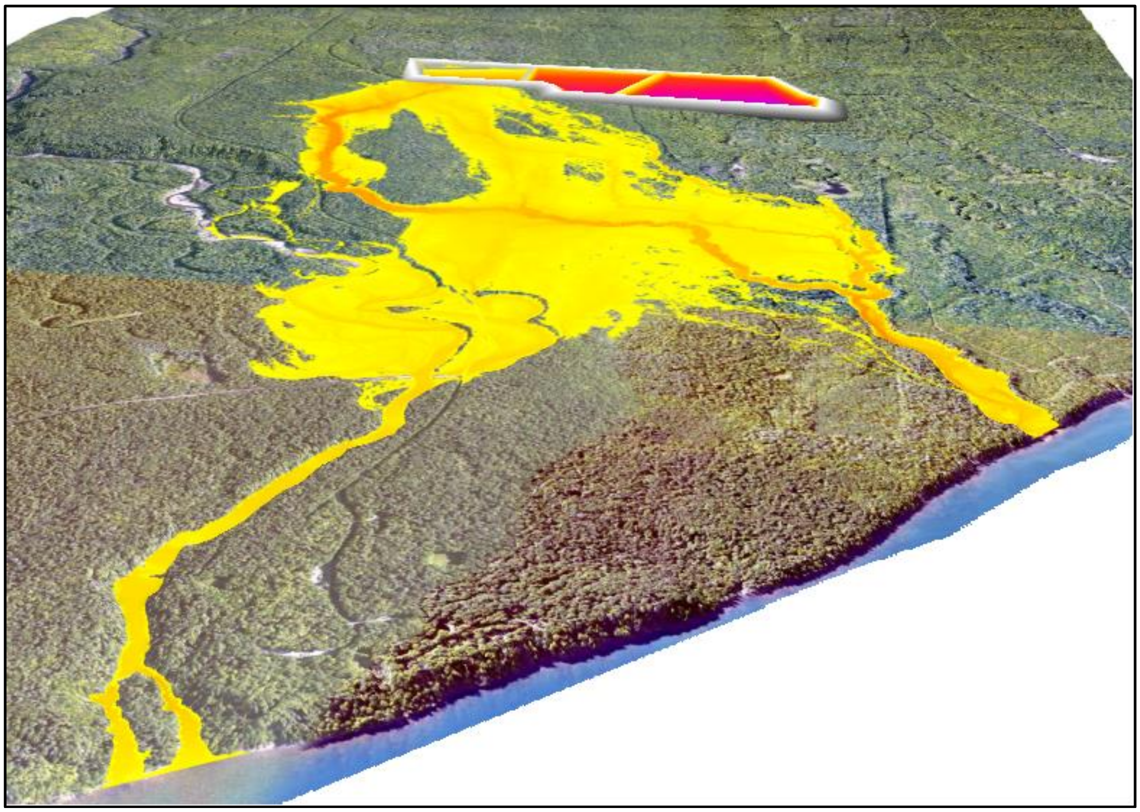

# Contents

# Summary

The Copperwood Project has proposed a tailings mine waste dam in the 1842 Ojibwe Ceded Territory. The tailings dam and basin is upstream of Anishnaabeg Gichigami (Lake Superior) and near the Porcupine Mountains Wilderness State Park and the Wild and Scenic Presque Isle River. No public analysis of the potential consequences of a possible dam failure existed, so we analyzed the effects of dam failure in HEC-RAS. We used the geometry of the basin as proposed, available data on project tailings characteristics, and the downstream topography and land cover to conduct the analysis. We found that modeled failures could release tailings that reach Anishnaabeg Gichigami in less than an hour, that could contaminate the Presque Isle River in less than 1.5 hours, and that could affect the underground mine entrance and other mine infrastructure. Tailings flowed into parts of the Porcupine Mountains Wilderness in all but the western modeled dam breaches. The tailings flood could reach up to 14 m high in parts of the flooded areas. These results suggest unacceptable consequences for downstream lands and waters, including Anishnaabeg Gichigami and the Presque Isle River, and for mine safety. This analysis does not evaluate the probability of dam breach. Further dam safety and waterway impact analyses should be conducted with final dam design specifics.

## Introduction

Mine tailings dam failures have continued to occur around the world with devastating consequences for the environment and human lives. Dam breach analysis can characterize the potential consequences of a dam failure and improve understanding of the hazard. Such assessments can identify areas downstream of dams that are vulnerable to flooding from tailings and dam projects that demonstrate unacceptable hazards.

The Copperwood Project is a proposed copper-silver mining project in a sensitive area in the 1842 Ojibwe Ceded Territory in the Upper Peninsula of Michigan. The project is adjacent to Anishnaabeg Gichigami (Lake Superior) and the Porcupine Mountains Wilderness State Park. The streams downstream of the tailings dams are all Outstanding International Resource Waters and the Presque Isle River is also an Outstanding State Resource Water and National Wild and Scenic River. Those designations entail protection from degradation of water quality. At least two of the streams have populations of redside dace (*Clinostomus elongatus*), a state endangered fish species.[1] The project mitigation wetlands and several planned mine facilities that could be affected by tailings are also downstream of potential tailings flows from a breach in the tailings basins. The tailings would contain copper, arsenic, mercury, selenium, and other constituents of concern[2].

Several aspects of the project suggest that a dam breach could potentially occur. Underground workings that could generate mine quakes would be located within several hundred meters of the toe of the tailings dam, and faults are present in the area to be mined. The proposed basin design includes a relatively narrow crest of 9 m and a freeboard of only 1.4 m.[3] The basin could store rain from a storm equivalent to only half of the Probable Maximum Precipitation, and that precipitation estimate does not account for increasing rainfall intensity due to climate change.[4] Differences in hydraulic conductivity in the foundation suggest the potential for uplift[5] and foundation blowout. For these reasons, dam failure appears to be possible. However, this paper does not formally evaluate the probability of dam failure.

No publicly available dam breach inundation maps exist for the proposed tailings facility. We therefore sought to develop such maps.

[1] Copperwood Project (2018) PDF pp. 7, 164.

[2] Arsenic, barium, boron, copper, mercury, selenium, silver, strontium, vanadium, TSS, TDS (G Mining Services 2023)

[3] G Mining Services (2023). Design figure PDF p. 378. Freeboard also minimum 4.5 ft, i.e. 1.4 m, in Knight Piésold (2011) PDF p. 69.

[4] Knight Piésold (2011) PDF pp. 50, 143

[5] Copperwood Project (2018) PDF p. 156.

## Methods

We conducted a preliminary dam breach inundation analysis in HEC-RAS 6.5 (USACE 2024) using two-dimensional unsteady flow routing based on the 2D unsteady diffusion wave equation set. We modeled the dam as a structure between a 2-D downstream area and a 2-D tailings basin.

For the geometry of the dam, we used available characteristics from the latest feasibility report (G Mining Services 2023). We modeled the dam with a crest width of 9 m and an elevation of 288 m. We developed a digital elevation model for the dam using the topographic lines in the design plan figure.

We modeled the tailings as a non-Newtonian, Bingham fluid and modeled the breach cause as over-topping. Over-topping could occur from excessive water in the basin or as part of an associated problem with a dam, such as a foundation blow-out or slope failure from erosion or blasting vibrations. For the geometry of the breach, we used the HEC-RAS breach parameter calculator with the Von Thunn & Gillette (1990) method (Appendix 1). We assessed breaches in each of the three cells in the basin. We produced models for two different locations in the western cell to reflect the identification of critical sections in that cell[6] and the possible inundation of mine infrastructure. We also modeled two locations in the eastern cell in order to assess consequences for the Presque Isle River. For the terrain, we used 2017 Lidar data and variable terrain roughness based on land cover for the downstream area (Appendix 1). We also assessed the influence on results of using some alternative values for tailings rheological properties, breach geometry, and terrain roughness (Appendix 1).

We ran sunny-day analyses that did not include storm water flow in the streams and rivers, and we did not model flow of tailings within Anishnaabeg Gichigami.

We assumed that interior dams separating the cells would not fail. Those dams, however, are planned to be lower than the perimeter dam and the planned tailings elevation. We therefore assumed that tailings above those interior dams could flow to a downstream cell with a breach.

[6] Knight Piésold (2011) Pdf Pp. 53, 92.

## Results

In all principal dam breach models, tailings reached Anishnaabeg Gichigami (Lake Superior) in less than 1 hr after dam failure began (from beginning of breach; Figs. 1-6). Tailings from the western breaches reached the Lake the quickest (in 21-23 min; Fig. 6). Volume of tailings that had entered Anishnaabeg Gichigami 5 hrs after the breach ranged from 4.6 $Mm^3$ to 8.6 $Mm^3$ and was greatest for the western breaches (Fig. 7).

Dam breach inundation map results showed that most of the watersheds downstream of the breaches would be vulnerable to flooding with tailings (Figs. 1-5). Between two and four major stream channels could be filled with tailings (Figs. 1-5). For failures of the eastern cell of the facility, tailings could flow into the Presque Isle River (Figs. 4-5). Our models indicated that tailings could reach the Presque Isle in 49-74 min, depending on the location of the breach in that eastern cell. Surface area in the watersheds inundated with tailings ranged from 2.6 to 4.2 $Mm^2$ and was greatest for eastern and central breaches (Fig. 8). Maximum depth of flooding was 10-14 m and depth was greatest for the most western breach (Fig. 9). Three of the breaches modeled flooded the project mitigation wetlands with up to 2-4 m of tailings (Figs 2-4). In all models except the most western breach, tailings flowed into the Porcupine Mountains Wilderness State Park (Figs. 2-5).

Several mine structures were in the path of tailings released in the modeled breaches, particularly for the westernmost breach. The middle cell breach could flood the base of the mine’s south exhaust structure to a depth of 0.4 m and first reach it after only 14 min (Fig. 3). The most western breach could reach the mine’s sewage lagoons in 13 min, the boxcut portal in 20 min, the north exhaust in 25 min, and the air intake in 34 min (Fig. 1). Maximum depths at those sites were 1.2 m at the sewage lagoons, 2.0 m at the boxcut portal, 1.9 m at the north exhaust, and 2.2 m at the air intake.

Results for models with variations in parameters mostly did not differ greatly from results of the primary models (Appendix 1). More viscous tailings yielded results that were similar to the primary models except that more tailings remained on the landscape after 5hrs (Appendix 1). The most influential parameters were breach size and terrain roughness. Tailings in models with relatively shallow breaches took longer to reach the Lake, and resulted in lower volumes, depths, and surface area of tailings released (Appendix 1). The tailings in the main models with variable roughness reached Anishnaabeg Gichigami slower than a model with a fixed Manning’s $n$ of 0.06 (Appendix 1).

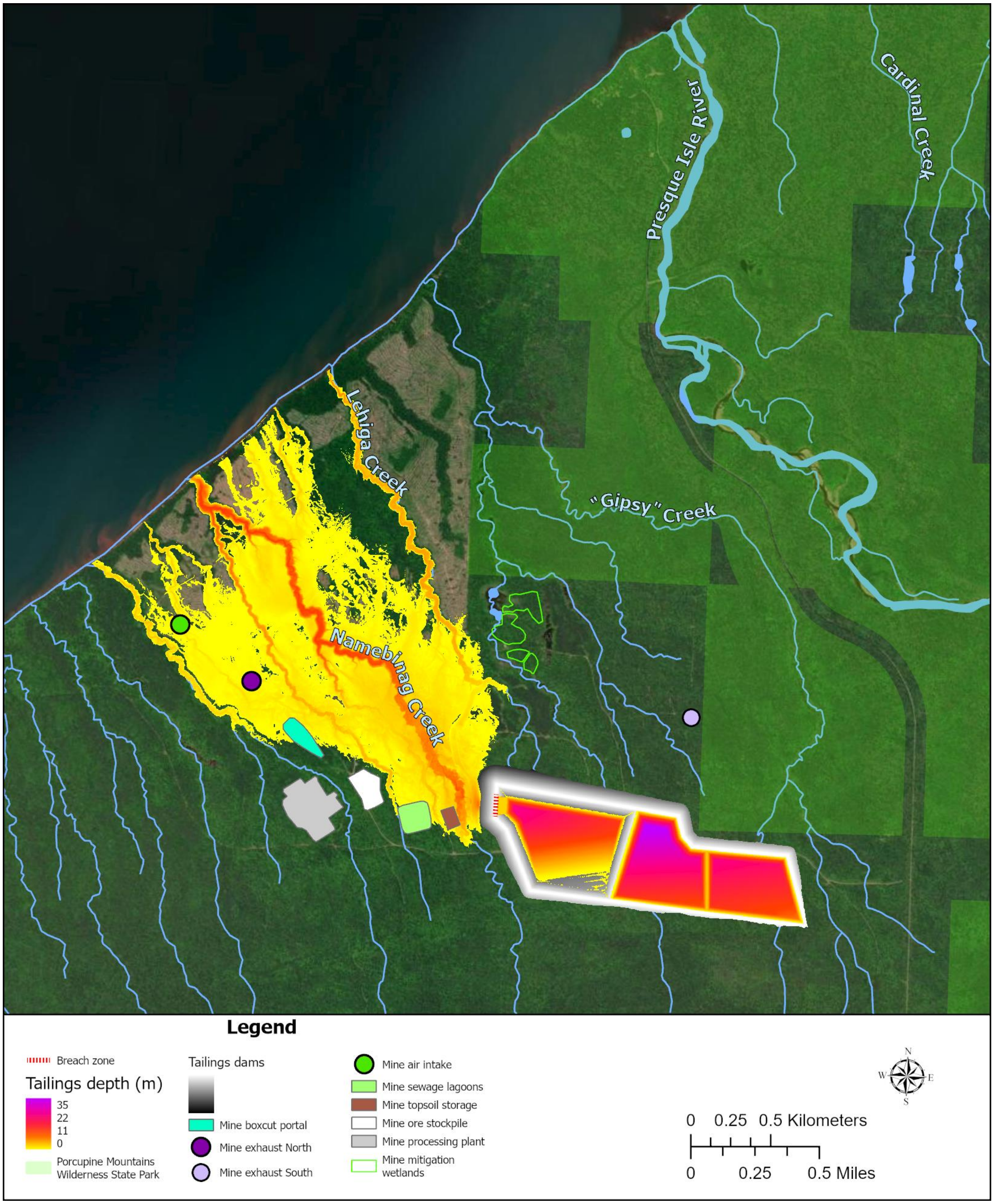


Fig. 1. Potential dam inundation map for failure of the west dam of the west cell of the proposed Copperwood tailings facility. Downstream tailings depths represent the maximum depth in the 5 hours after breach, and tailings basin depths represent the depth 5 hours after breach. We did not model tailings flows in Anishnaabeg Gichigami.

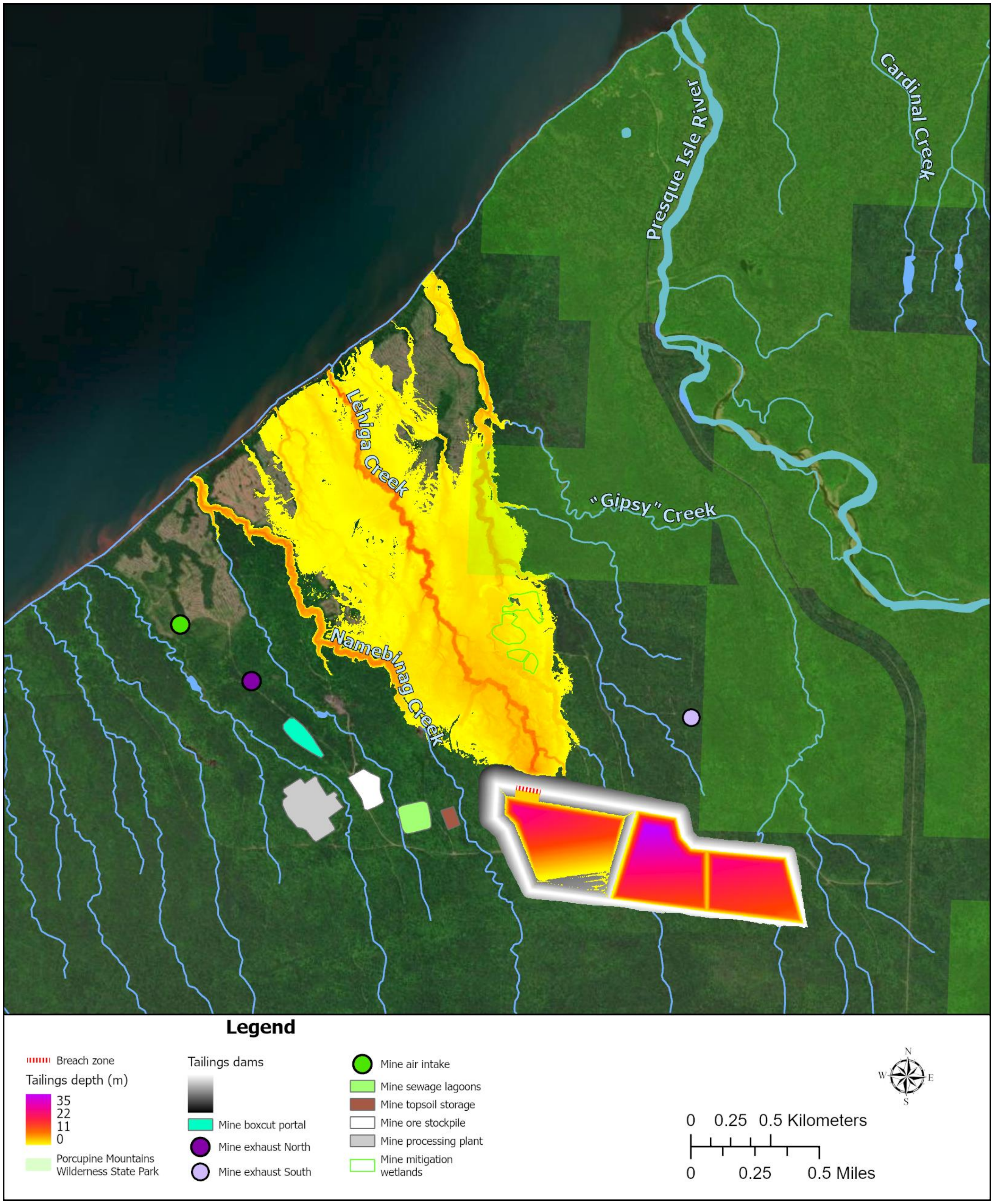


Fig. 2. Potential dam inundation map for failure of the north dam of the west cell of the proposed Copperwood tailings facility. Downstream tailings depths represent the maximum depth in the 5 hours after breach, and tailings basin depths represent the depth 5 hours after breach. We did not model tailings flows in Anishnaabeg Gichigami.

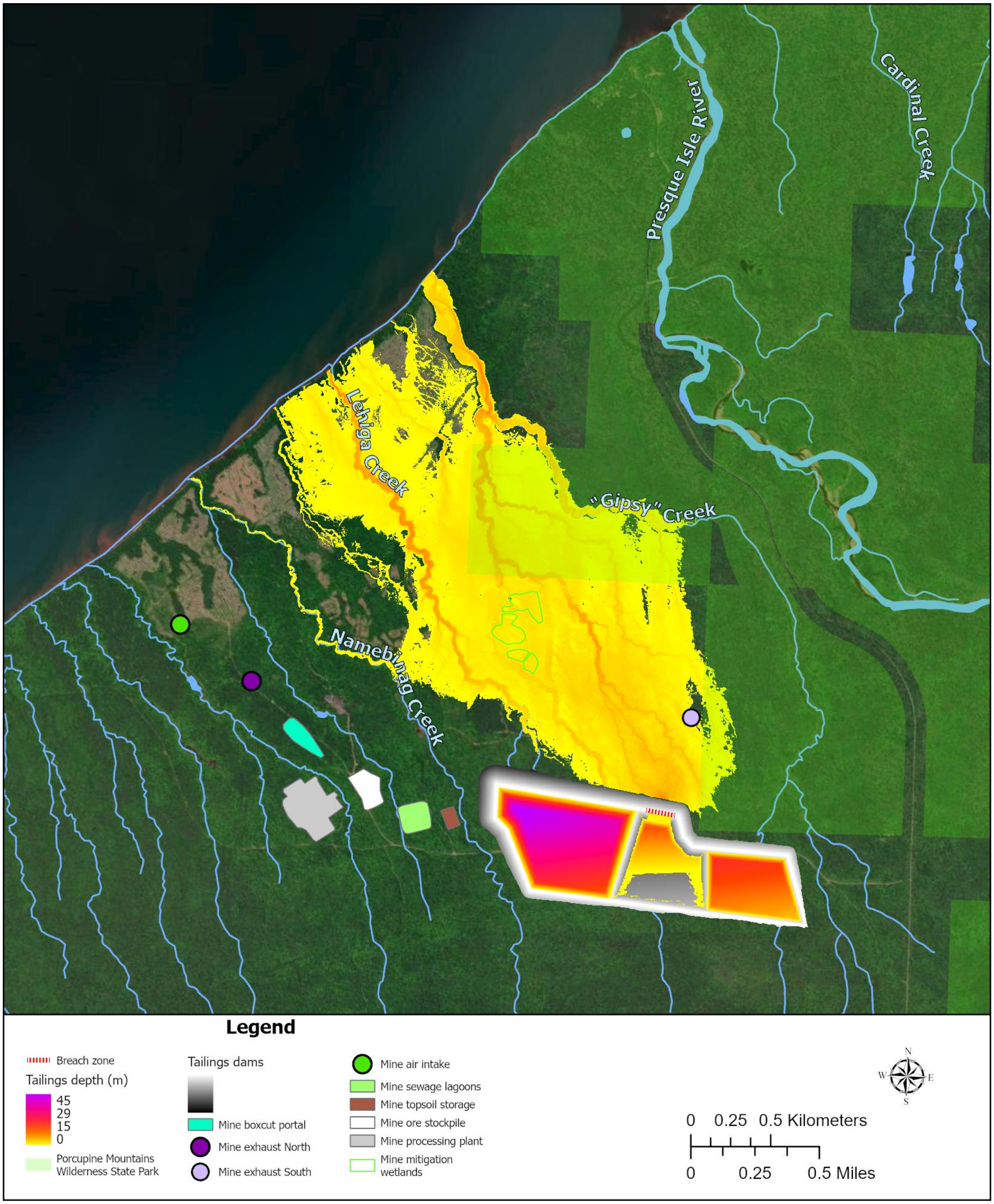


Fig. 3. Potential dam inundation map for failure of the middle cell of the proposed Copperwood tailings facility. Downstream tailings depths represent the maximum depth in the 5 hours after breach, and tailings basin depths represent the depth 5 hours after breach. We did not model tailings flows in Anishnaabeg Gichigami.

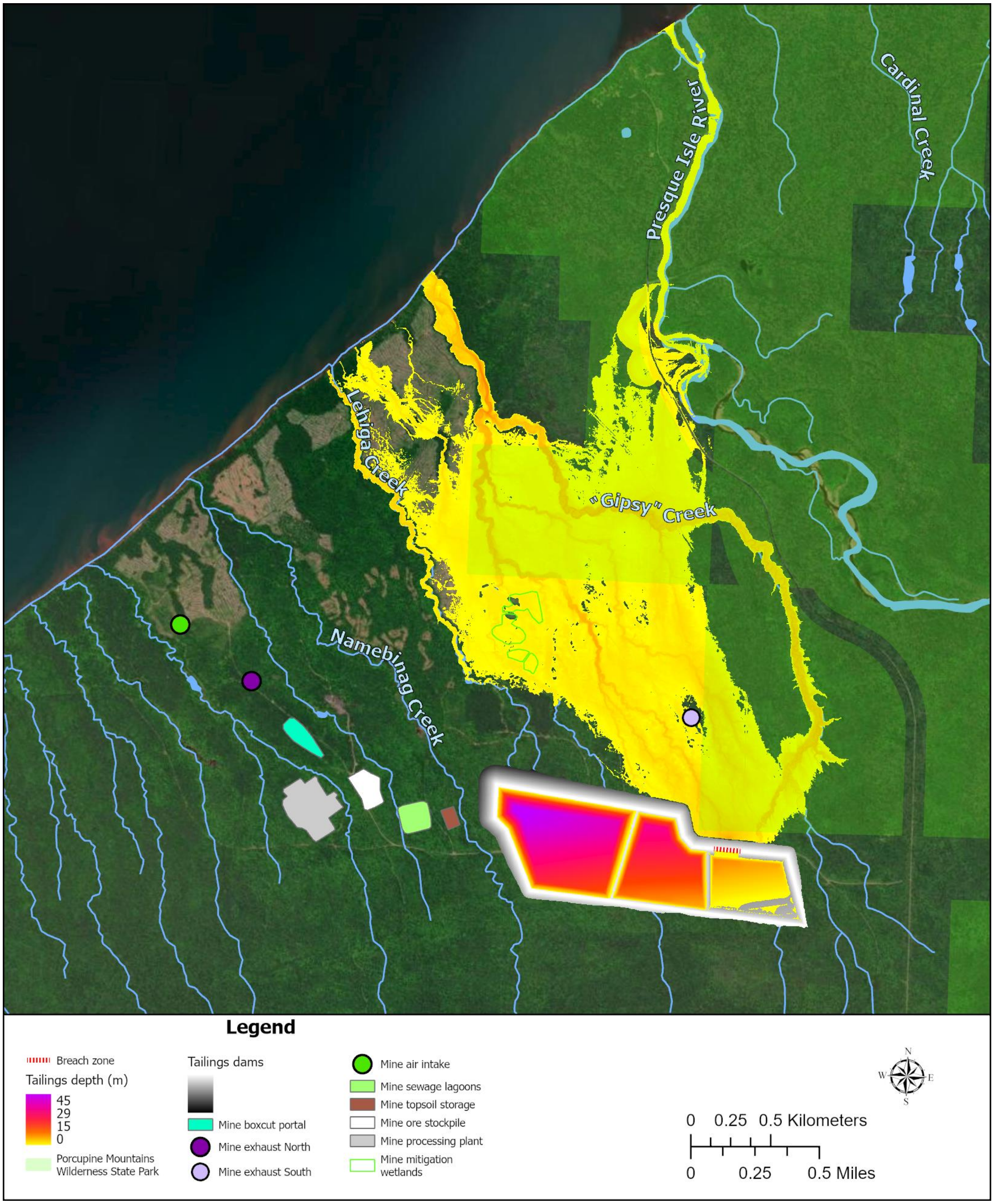


Fig. 4. Potential dam inundation map for failure of the west end of the north dam of the eastern cell of the proposed Copperwood tailings facility. Downstream tailings depths represent the maximum depth in the 5 hours after breach, and tailings basin depths represent the depth 5 hours after breach. We did not model tailings flows in Anishnaabeg Gichigami.

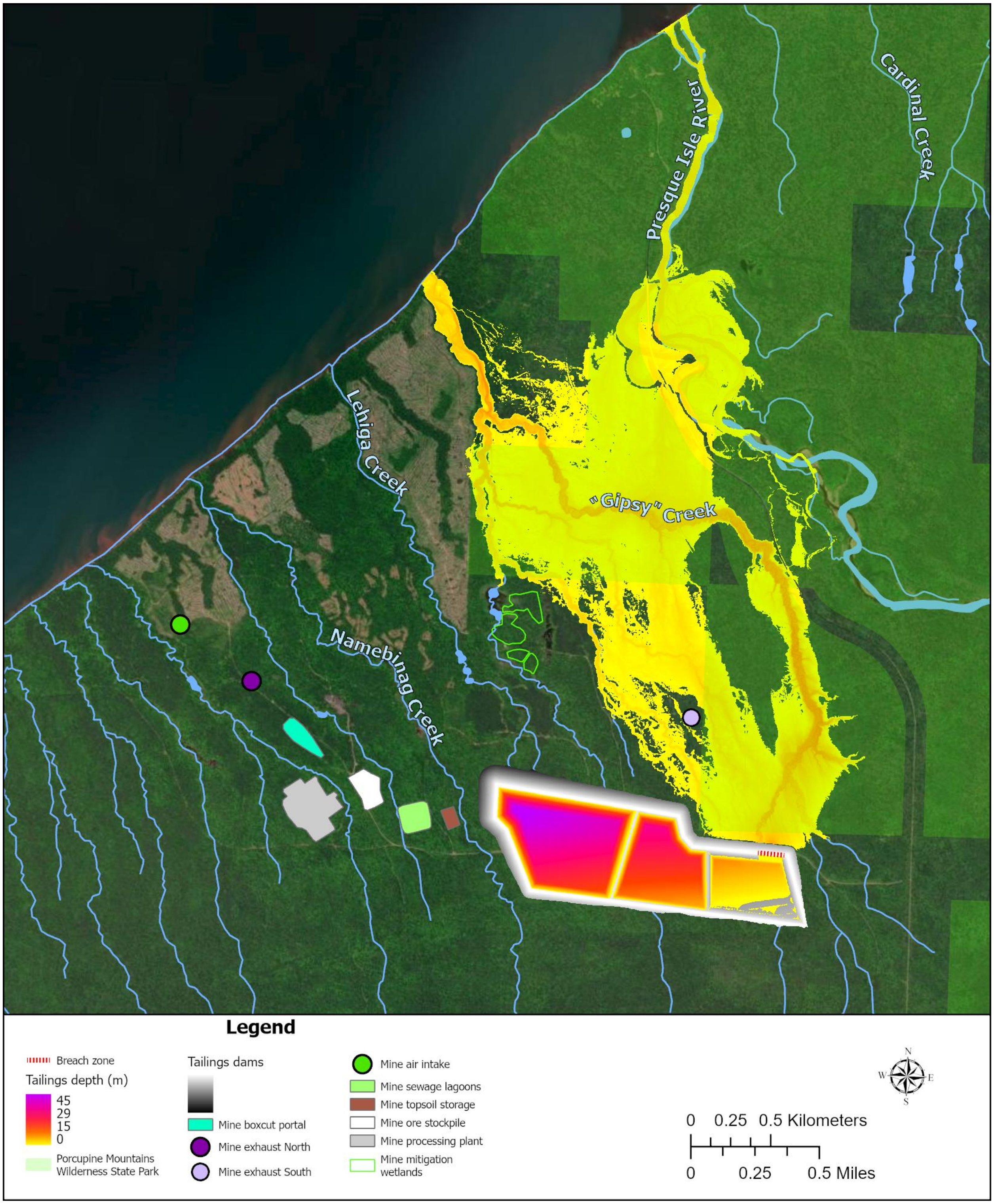


Fig. 5. Potential dam inundation map for failure of the east end of the north dam of the eastern cell of the proposed Copperwood tailings facility. Downstream tailings depths represent the maximum depth in the 5 hours after breach, and tailings basin depths represent the depth 5 hours after breach. We did not model tailings flows in Anishnaabeg Gichigami.

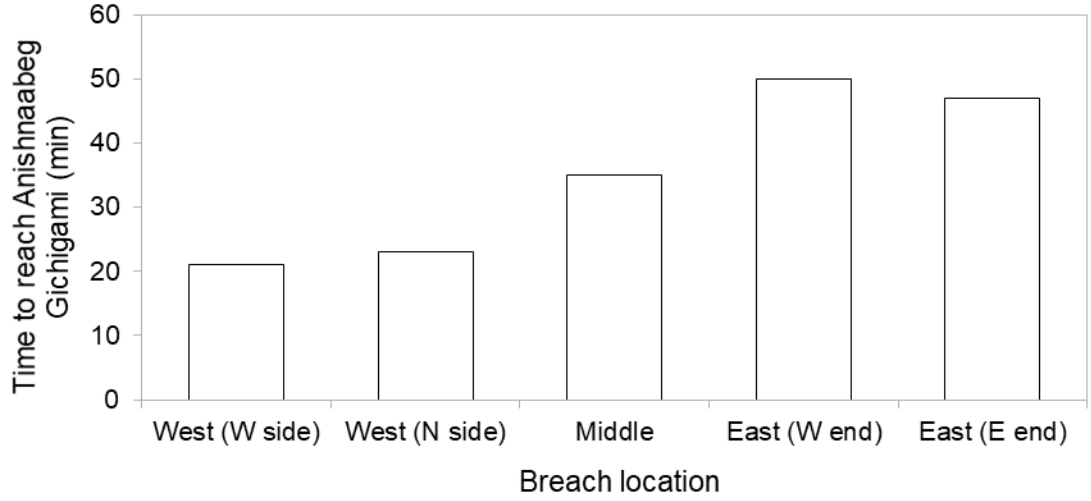


Fig. 6. Tailings flood arrival time to Anishnaabeg Gichigami for five breach locations assessed. Results represent time since beginning of breach formation.


Fig. 7. Volume of tailings entering Anishnaabeg Gichigami 5 hrs after dam breach for five breach locations assessed.

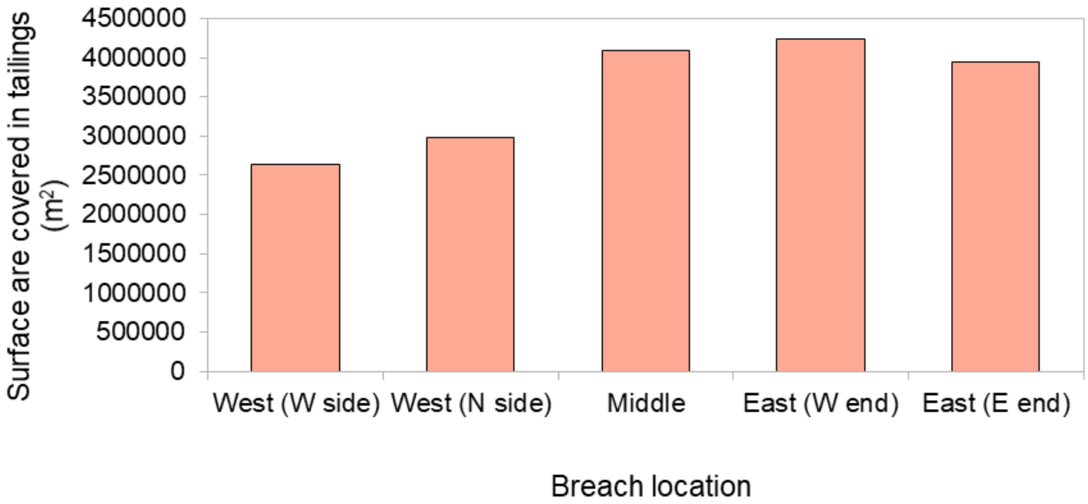


Fig. 8. Surface area (2-D) covered in released tailings in zones downstream of tailings after dam breach for five breach locations assessed.


Fig. 9. Maximum depth of tailings in zones downstream of dam breaches for five breach locations assessed.

## Discussion

This assessment has provided preliminary inundation maps of the consequences of dam failure at the proposed Copperwood tailings storage facility. Potential consequences include the rapid contamination of Anishnaabeg Gichigami, the Presque Isle River, and multiple streams with tailings. International Outstanding Water streams and watersheds – including the Wild and Scenic Presque Isle River and other parts of the Porcupine Mountains Wilderness State Park -- could be filled with tailings flows. A breach on the western side of the tailings basins could cause a failure of the mine's planned sewage pond basins and add partially-treated sewage to the contamination flowing downstream.

A dam breach at this tailings facility also represents a hazard to human safety. The flood wave could harm any workers or others on the surface downstream of a breach, but potentially also those in the underground mine. Our models indicate that tailings flows could reach the mine portal and exhaust and intake vents. Given that deadly disasters have occurred at other tailings dams when tailings have flooded underground mines (e.g. Mufilira Mine in Zambia, in ICOLD 2001), this is of concern. Best practice recommendations are to not site tailings facilities upstream or above underground mines or mine infrastructure (e.g., ANCOLD 2012, Boswell & Sobkowicz 2015).

A failure of these dams could result in consequences that differ from our modeled results. We relied on the rheological properties of the bulk tailings modeled as a Bingham fluid to determine how much of the tailings would exit a breach. In reality, the initial supernatant pond waters would flow as a Newtonian fluid like water, and the fines or slimes below the supernatant pond would flow as a Bingham or similar fluid and might not all leave a breach. Breach size might also differ from our models. We modeled a breach extending up to 25 m below the dam crest on the west and central cells based on an average breach depth of three copper tailings dam failures, but the dam is approximately 38 m tall at its highest and so a breach could be shallower or deeper. A dam could also fail more rapidly, and catastrophically, than what we modeled. We also assumed that the interior dams would withstand the forces exerted on them when one side was emptied and tailings flowed over the top of the interior dams, which are lower than the perimeter dam. In reality, those processes could very well lead to the failure of one or both interior dams and to the release of larger volumes of tailings from the facility. Larger releases because of a larger breach or failure of the internal dams would likely result in more tailings entering Anishnaabeg Gichigami and deeper, more extensive spread of the tailings flow downstream of the breach.

Future work should refine these analyses based on final dam designs and additional sensitivity analysis. The assessment should also include inundation mapping during probable maximum precipitation events. Dam failure during storm flooding could lead to greater volumes of fluid released from the tailings basins, but the tailings would not represent all of the overall downstream flooding. Studies could also model flow of tailings in Anishnaabeg Gichigami to better understand the potential impacts on the Lake. Other work should use dam design and site characteristics to assess the likelihood of failure of the dams, which was not the focus of this analysis.

The implications for management include that the current dam project presents serious potential consequences for downstream waters, including Anishnaabeg Gichigami and the Presque Isle River, and for mine safety. The project proponent previously rejected disposing of tailings in the underground workings after mining. Underground disposal of tailings in the mine would reduce the hazard from a tailings dam breach.

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# Appendix 1

*Methods details*

We estimated tailings rheological properties based on Copperwood project documents[7] and Fitton and Setton (2012) (Table A1).

*Table A1. Tailings rheological Bingham properties used.*

| Tailings characteristic | Value used | Min. and max. considered |
|---|---|---|
| Volumetric concentration, Cv (%)[a] | 43 | 32, 50 |
| Yield stress T (Pa) [b] | 8.5 | 8.5, 20 |
| Dynamic viscosity, μ (Pa-s) [b] | 0.03 | 0.03, 36 |

[a] Information considered:
In 2011, White Pine samples were reportedly 45-50% solids[8]
In 2018, the project reported Copperwood test tailings were 21-50% solids[9]
In 2023, the project reported Copperwood tailings to be 32.4% solids.[10]
[b] Information considered:
Fitton & Setton (2012) copper site 1, with the closest match to test Copperwood tailings particle size distribution and Atterberg limits from Copperwood Project (2018), had Yield stress of 8.5 Pa and dynamic viscosity of 0.03 Pa-s.
Fitton & Setton (2012) copper site 13, with a relatively close match to test Copperwood tailings particle size and Atterberg limits from Copperwood Project (2018), had Yield stress of 19 Pa and dynamic viscosity of 36 Pa-s.

For dam breach characteristics, we used parameters from the HEC-RAS parameter calculator using the Von Thunn & Gillette (1990) method (Table A2). For the breach height, we used 25 m as an average of copper tailings dam failure depths from Adria *et al*. (2023; mean of Aznalcollar, Mt. Polley, and Tonglüshan North breaches).

*Table A2. Dam breach characteristics*

| Breach characteristic | Value used, west cell | Value used, center cell | Value used, east cell |
|---|---|---|---|
| Breach height (m) | 25 | 25 | 18 |
| Breach bottom width (m) | 88 | 88 | 49 |
| Breach side slopes | 0.5 (1H:2V) | 0.5 (1H:2V) | 0.5 (1H:2V) |
| Formation time (min) | 43 | 43 | 34 |

[7] Copperwood Project (2018) PDF pp. 29, 73, 138.
[8] Knight Piésold (2011) Appendices. PDF pp 782-783, 791, 851
[9] Copperwood Project (2018). PDF pp. 10, 29, 138. Some results represented settled tailings without including the supernatant pond.
[10] G Mining Services (2023). PDF pp. 382.

For assigning terrain roughness in the downstream 2-D flow area, we supplemented a 2021 National Land Cover Dataset raster with stream channels digitized from 2017 Lidar. We assigned Manning's *n* roughness values based on values reported for area streams from stream mitigation activities (0.04 as mid-range; Barr 2023) and the mid-range value of recommended values from HEC-RAS documentation (Table A3). For the tailings basin 2-D flow area, we used a constant Manning's *n* value of 0.03. That value was within the range of barren land recommended values.

*Table A3. Values used Manning's* n *for terrain roughness*

| Land cover type | Manning's *n* used |
|---|---|
| Deciduous Forest | 0.15 |
| Mixed Forest | 0.14 |
| Developed, open space | 0.04 |
| Developed, low intensity | 0.09 |
| Developed, medium intensity | 0.12 |
| Evergreen forest | 0.12 |
| Woody Wetlands | 0.098 |
| Barren Land (Rock/Sand/Clay) | 0.026 |
| Emergent Herbaceous Wetlands | 0.068 |
| Grassland/Herbaceous | 0.038 |
| Shrub/Scrub | 0.12 |
| Developed High Intensity | 0.16 |
| Pasture/Hay | 0.038 |
| Open Water | 0.04 |

We developed the downstream grid based on 1-m Lidar data terrain re-sampled to 2 m, and a 10 m HEC-RAS grid cell size. The Lidar data were from 2017 from the Ottawa National Forest and did not include bathymetry. We added in the stream re-route dug around the west side of the basin[11].

*Sensitivity analysis results*

[11] Barr. 2023. Copperwood Mine TDF Area Stream Mitigation, Gogebic County, Michigan. Plan design maps. 2227100700_2227100700_TDF Area Stream Mitigation_02-10-23_red.pdf.

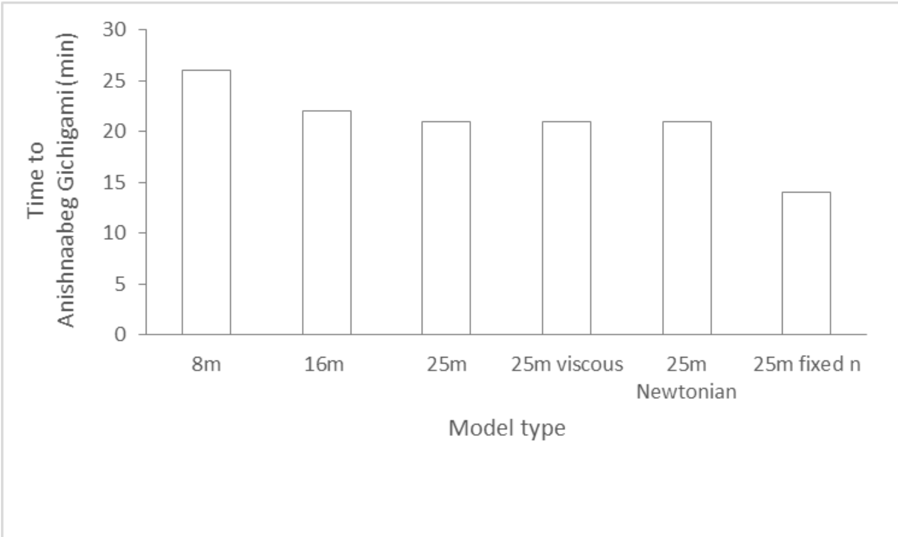


Fig. A1. Variation in time of arrival of tailings to Anishnaabeg Gichigami for a breach of the western side of the western tailings basin cell. Modeling used breach, rheological, and landscape roughness characteristics from Tables A1-3 unless indicated otherwise (model names include breach depth; viscous = maximum values from Table A1; Newtonian = Newtonian not Bingham fluid; fixed *n* = constant roughness of 0.03). Results represent time since beginning of breach formation.

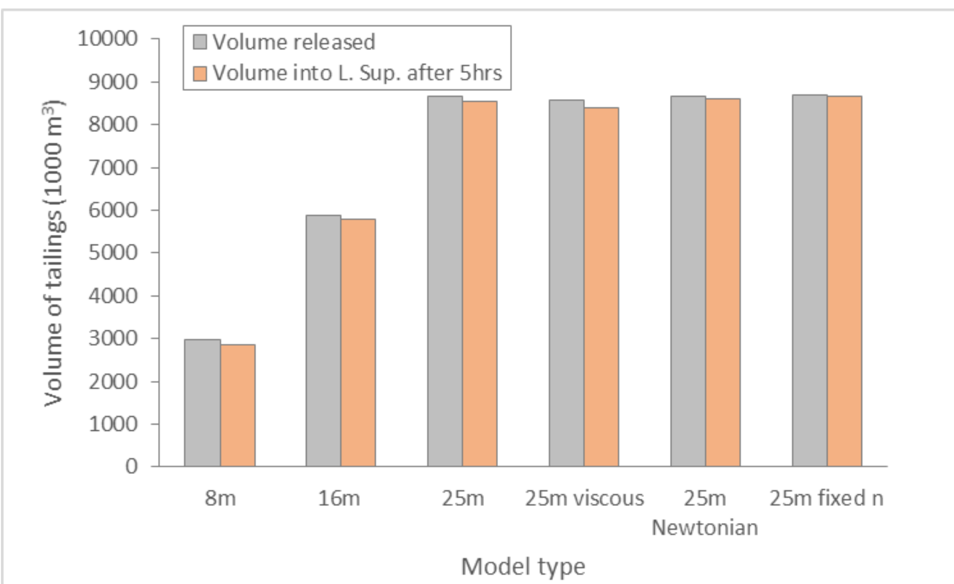


Fig. A2. Variation in volume released from breach and volume entering Anishnaabeg Gichigami after 5 hrs for a breach of the western side of the western tailings basin cell. Modeling used breach, rheological, and landscape roughness characteristics from Tables A1-3 unless indicated otherwise (model names include breach depth; viscous = maximum values from Table A1; Newtonian = Newtonian not Bingham fluid; fixed *n* = constant roughness of 0.03).

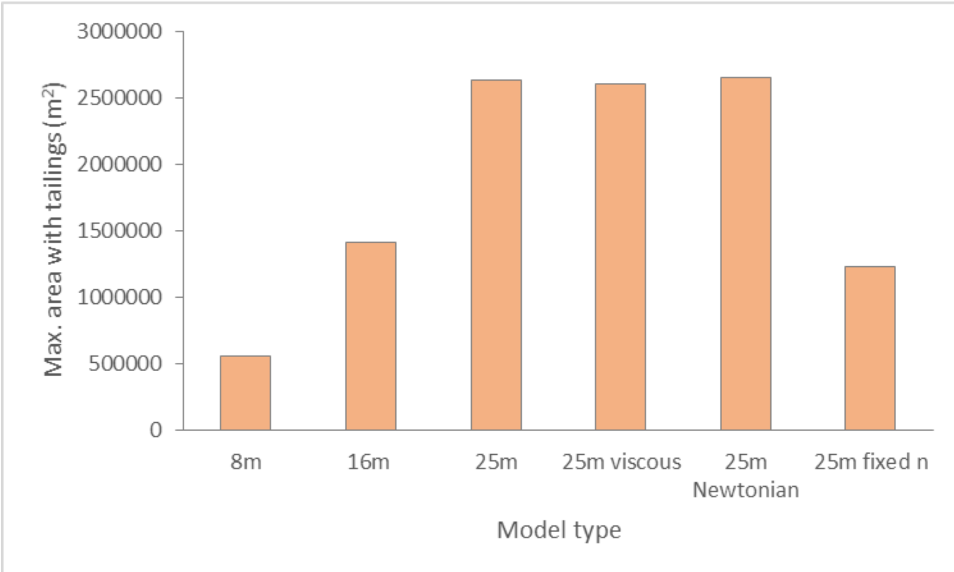


Fig. A3. Variation in maximum surface area with tailings for a breach of the western side of the western tailings basin cell. Modeling used breach, rheological, and landscape roughness characteristics from Tables A1-3 unless indicated otherwise (model names include breach depth; viscous = maximum values from Table A1; Newtonian = Newtonian not Bingham fluid; fixed *n* = constant roughness of 0.03).

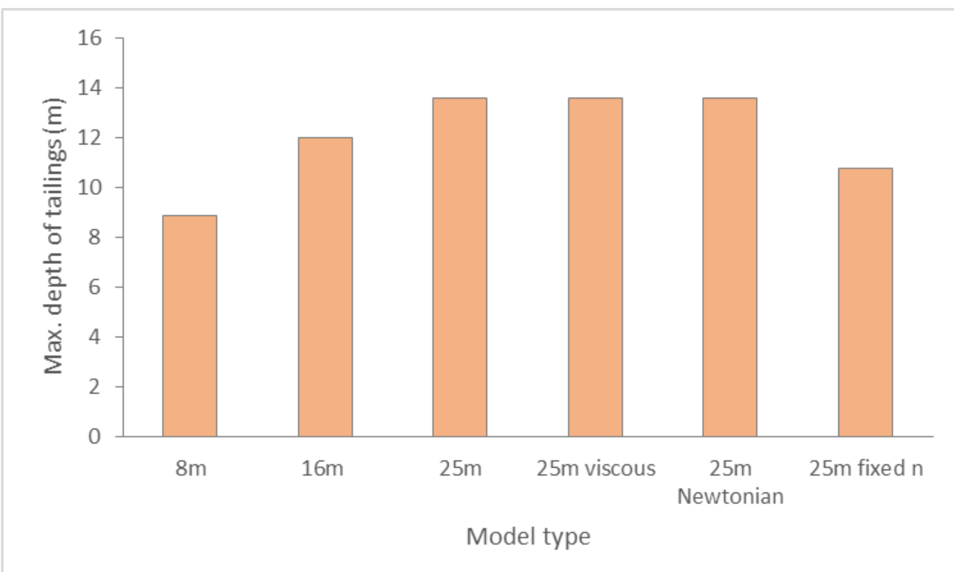


Fig. A4. Variation in maximum depth of tailings for a breach of the western side of the western tailings basin cell. Modeling used breach, rheological, and landscape roughness characteristics from Tables A1-3 unless indicated otherwise (model names include breach depth; viscous = maximum values from Table A1; Newtonian = Newtonian not Bingham fluid; fixed *n* = constant roughness of 0.03).

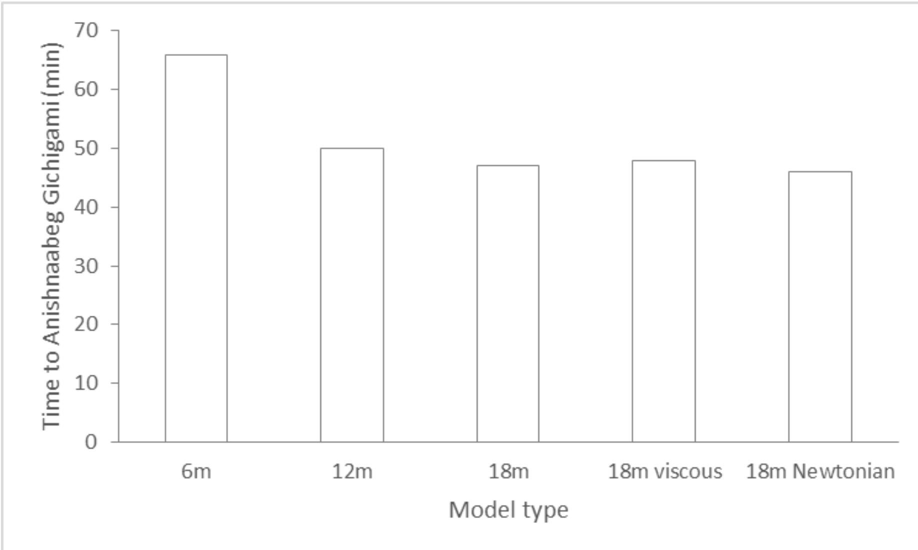


Fig. A5. Variation in time of arrival of tailings to Anishnaabeg Gichigami for a breach of the eastern end of the north side of the eastern tailings basin cell. Modeling used breach, rheological, and landscape roughness characteristics from Tables A1-3 unless indicated otherwise (model names include breach depth; viscous = maximum values from Table A1; Newtonian = Newtonian not Bingham fluid).

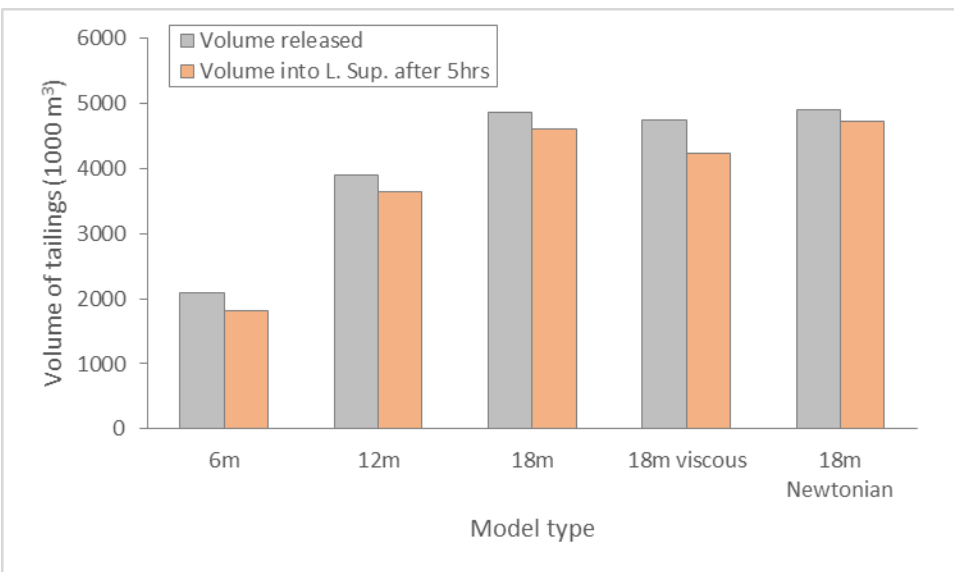


Fig. A6. Variation in volume released from breach and volume entering Anishnaabeg Gichigami after 5 hrs for a breach of the eastern end of the north side of the eastern tailings basin cell. Modeling used breach, rheological, and landscape roughness characteristics from Tables A1-3 unless indicated otherwise (model names include breach depth; viscous = maximum values from Table A1; Newtonian = Newtonian not Bingham fluid).

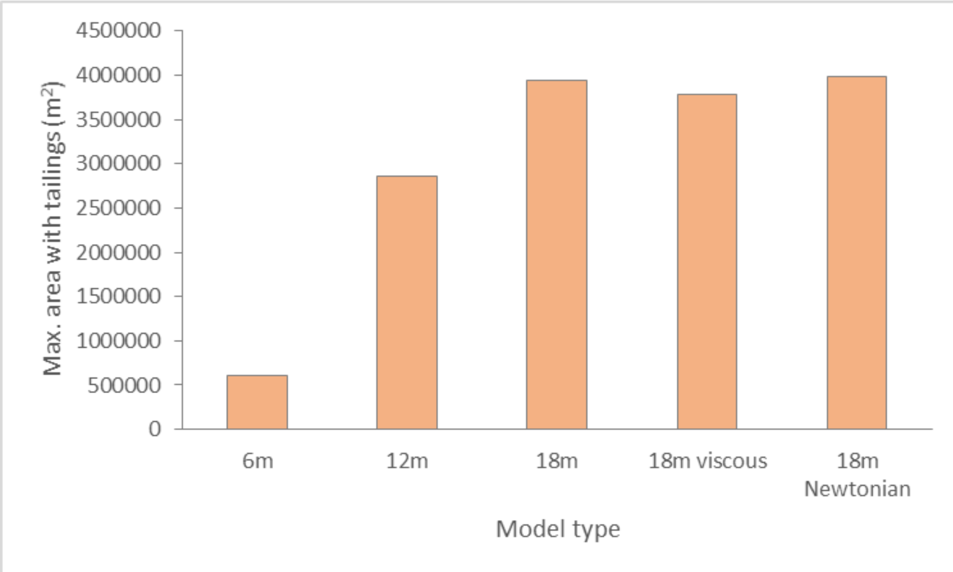


Fig. A7. Variation in maximum surface area with tailings for a breach of the eastern end of the north side of the eastern tailings basin cell. Modeling used breach, rheological, and landscape roughness characteristics from Tables A1-3 unless indicated otherwise (model names include breach depth; viscous = maximum values from Table A1; Newtonian = Newtonian not Bingham fluid).

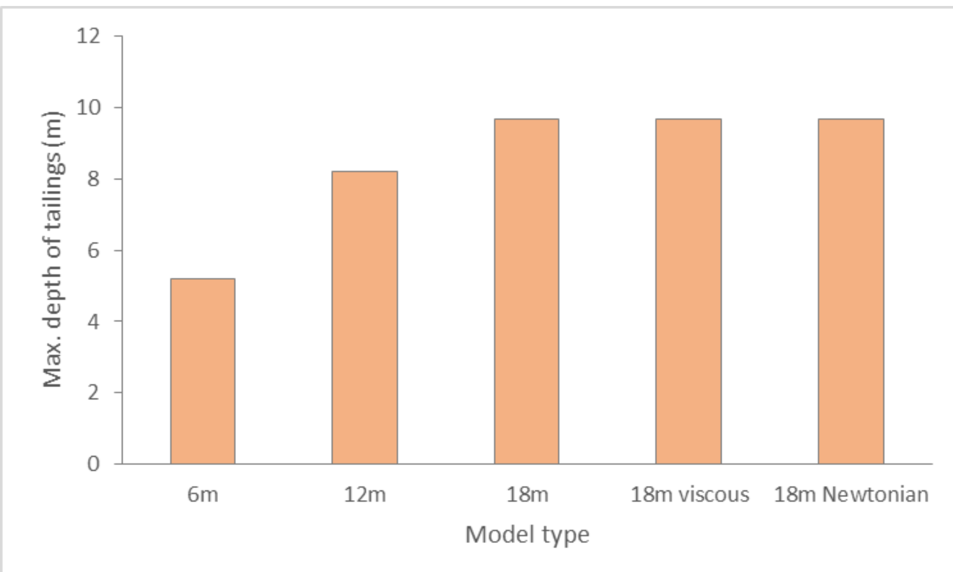


Fig. A8. Variation in maximum depth of tailings for a breach of the eastern end of the north side of the eastern tailings basin cell. Modeling used breach, rheological, and landscape roughness characteristics from Tables A1-3 unless indicated otherwise (model names include breach depth; viscous = maximum values from Table A1; Newtonian = Newtonian not Bingham fluid).

*Appendix references*

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