Copper Mountain Mine
Tailings Dam Breach Assessment

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Executive Summary

Lynker was retained by Conservation Northwest and the Colville Confederated Tribes to develop a tailings dam breach and runout analysis for the tailings storage facility (TSF) at the Copper Mountain Mine (CMM) near Princeton, British Columbia, Canada. The goal of this analysis was to understand the potential physical impacts of a breach of the west tailings dam, under currently permitted and proposed expanded TSF scenarios.

Our analysis used the FLO-2D hydrologic and hydraulic modeling software, a physically-based model that is recommended by the Canadian Dam Association for tailings dam runout analyses, and one of the few flood modeling packages capable of simulating the non-Newtonian flows that characterize debris flows from TSF failures. It is also commonly utilized by the mining industry for similar purposes (e.g., Knight Piesold, 2014). In this study, we used publicly available data describing the physiography and hydrology of the region, and data published by CMM and their consultants describing the currently permitted and proposed TSF and other mine site characteristics, to build a model of tailings release and downstream transport. Because the mechanism, timing, and nature of any tailings dam breach is inherently uncertain (e.g., what volume of tailings material is released, and over what duration?), we used a sensitivity analysis framework to evaluate how model parameters and decisions contribute to the uncertainty in the model outputs. Using empirical datasets of past TSF breaches to guide our analysis, we explored a wide range of breach scenarios, representing release volumes between 10-70% of the stored tailings over breach durations ranging from several hours (i.e., a catastrophic failure) to days (i.e., a slow failure).

The results of our study demonstrate that a tailings dam breach of the CMM TSF at full build-out to the permitted specifications (197 m dam height, 250 Mm^3 storage volume), if a breach were to occur, could release a debris flow that would likely exceed 10 m depth and be several times greater than the largest flood ever recorded in the town of Princeton, BC. Our simulations estimate that the leading edge of the debris flow would arrive in Princeton in just over an hour, with life-threatening peak flows cresting between 1.5 and 5.5 hours, depending on the failure mechanism and erosion rate of the dam. A near-instantaneous catastrophic failure releasing 40% of the TSF (as estimated from Rico et al., 2008 and others) could see peak discharge rates along our study cross sections of more than 25,000 cubic meters per second (CMS) at hour 1.5 in Princeton; 6,500 CMS at hour 7.6 in Hedley; 5,300 CMS at hour 13.2 in Keremeos; and 3,100 CMS at hour 24.6 at the US-Canada Border. It is highly likely that impacts from this debris flow would continue beyond the US-Canada border and into the Okanogan River up to its confluence with the Columbia River near Brewster, Washington. Total inundated area is estimated to be 147 km^2 (90 km^2 in BC; 57 km^2 in Washington) along 250 km of river. The severe and life-threatening downstream impacts of a breach of the permitted TSF would only be compounded by a similar failure of the proposed expanded TSF (260 m dam height, 450 Mm^3 storage volume), which if built would be the world's second largest facility (Global Tailings Portal, 2021).

1. Introduction and Background

Lynker was retained by Conservation Northwest and the Colville Confederated Tribes to develop a tailings dam breach and runout analysis for the tailings storage facility (TSF) at the Copper Mountain Mine (CMM) near Princeton, British Columbia, Canada, in response to the mine's proposed New Ingerbelle expansion project. This report summarizes available information on the currently permitted and proposed expansion of the CMM TSF, places this tailings facility into context relative to other TSFs and TSF failures around the world, and provides an overview of the physical model we developed to simulate downstream impacts if the TSF were to fail. This report does not render opinions regarding the probability of a dam failure at the CMM TSF. Rather, we focus on simulating the potential downstream physical impacts of such a failure under a range of plausible tailings release scenarios.

In order to understand what a hypothetical breach of the CMM TSF and the resultant downstream physical impacts would look like, we created a series of model parameterizations using the software package FLO-2D to evaluate the sensitivity of the outputs to various sets of model inputs. This sensitivity analysis is useful in understanding the range of outcomes that could possibly occur based on historical failures around the world, given inherent uncertainties in breach parameters. This systematic investigation, where we change one variable at a time and keep others constant, is a means of bridging the uncertainty gaps that exist. Through this approach, we can determine which parameters have the most/least effect on the downstream impacts, which increases the overall confidence in our risk assessment.

Figure 1-1. Aerial view of the Copper Mountain Mine tailings storage facility, with west and east dams above the Similkameen and Wolfe Creek drainages, respectively.

Figure 1-2. Image of the CMM TSF west dam looking west from the crest of the dam toward the Similkameen River valley.

This report is organized as follows: Section 2 summarizes the physical characteristics of the CMM TSF, including an overview of how the dam height, tailings volume and other parameters relate to other tailings dams and historical dam failures around the world. Section 3 describes our FLO-2D model setup, and the sensitivity analyses we conducted to evaluate how model results respond to variations in parameters that are uncertain and/or unknown. Section 4 summarizes our model results, including an overview of how the tailings runout differs for failure scenarios under the currently permitted TSF and the proposed expansion of the TSF. Finally, Section 5 provides a discussion of these results in context of the physical downstream impacts to communities in British Columbia and Washington State.

2. Copper Mountain Mine TSF

This section summarizes the parameters used for the tailings dam failure modeling. It includes both physical properties of the dam and of the modeled release (e.g., size of the impoundment, volume of the breach) as well as prescribed characteristics of the nature of the release (e.g., the release flow rate through time) and estimates of the physical properties that describe how the tailings might flow.

2.1. TSF Properties/Specifications

The CMM TSF fills a roughly east-west trending valley approximately 15 km south of Princeton, BC (Figure 1-1). The TSF is dammed on both the east and west sides of the valley, with dam heights of 152m meters (KCB, 2020). As of 2022, the TSF currently holds an estimated 150 million cubic-meters (Mm^3) of tailings; current permits held by CMM allow for expansion up to 250 Mm^3 with a final designed western dam height of 197 m. The proposed New Ingerbelle project and TSF expansion would increase the storage volume to a total of 450 Mm^3, behind a western tailings dam with a designed height of 260 m. At this full buildout, the western tailings dam would be the second largest in the world, just 5 m lower than Linga tailings dam in Peru (GRID-Arendahl, 2021). We focused our analysis on a hypothetical failure of the western tailings dam, in both its current and expanded state, primarily because of the risk of the western dam to the community of Princeton, but also because a failure at this dam would impact more stream miles on the Similkameen River as compared to a failure of the eastern tailings dam. Table 2-1 summarizes the physical specifications of the CMM TSF at the west dam, as described in various reports from AMEC and Klohn Crippen Berger (AMEC, 2013; KCB, 2020).

Table 2-1. Summary of the dam specifications for the CMM mining storage facilities

Buildout Scenario	Dam Height (m)	Elevation (m)	Surface Area (km^2)	Volume Capacity (Mm^3)	Freeboard (m)
Current Buildout	152	952	1.65	150	2
Permitted	197	997	n/a	250	2
Expanded	260	1060	2.39	450	2

British Columbia has been fortunate in that there have been relatively few significant tailings dam failures in modern mining history. The most significant event was the Mt. Polley Mine TSF dam failure in 2014, which released an estimated 23.6 Mm^3 of tailings. Because the Mt. Polley tailings dam was only a few kilometers upstream of Lake Quesnel, a large glacial lake, the tailings runout and inundated area were physically constrained. Nonetheless, this event created substantial damage to the small creek draining into Lake Quesnel, with estimated cleanup costs on the order of $70 million (Imperial Metals, 2022). Figure 2-1 shows the comparative volume (left) and dam height (right) of the Mt. Polley TSF (grey), permitted CMM TSF (blue), and proposed expansion of the CMM TSF (orange).

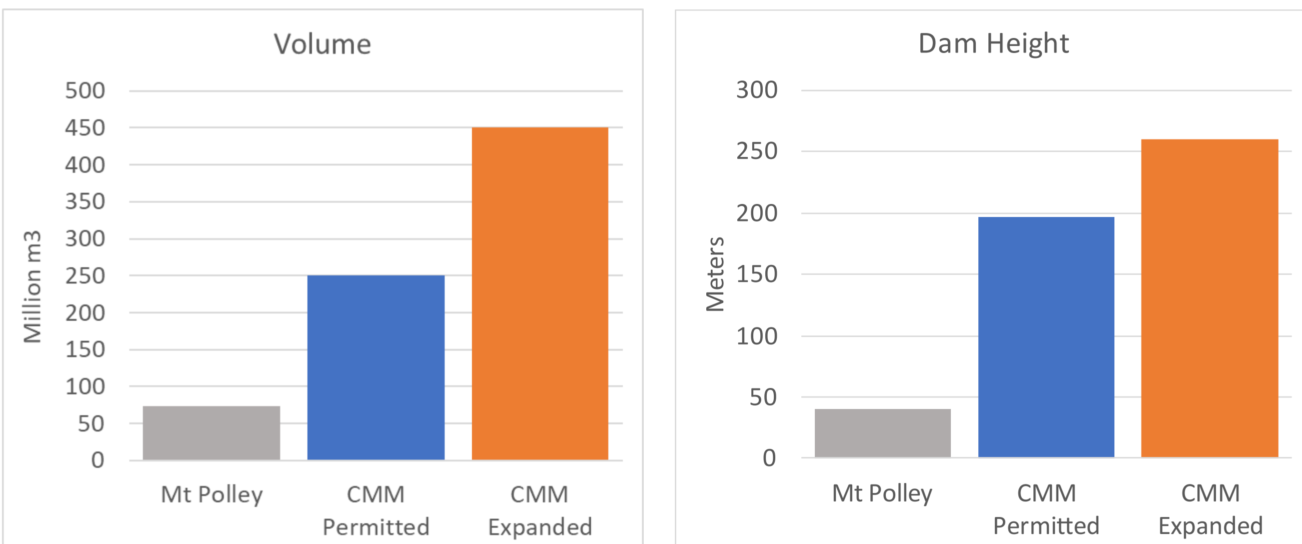

Figure 2-1. Volume (left) and height (right) comparisons between Mt. Polley (grey) and Copper Mountain Mine TSFs as it is currently permitted (blue) and under the proposed expansion (orange).

2.2. Historical Tailings Dam Failures- release volumes & runout distances

Several recent studies have compiled empirical data from tailings dam failures around the world, with a goal of understanding trends in both the magnitude of historical failures (e.g., Rico et al., 2008; Laurrari and Lall, 2018; Piciullo et al., 2022) and the frequency of these failures (Bowker and Chambers, 2017; Piciullo et al., 2022). These empirical studies provide some context for the expected impacts of a CMM TSF failure, if it were to occur. Figure 2-2 summarizes data from Piciullo et al. (2022), a recently published report that examines the functional relationship between released volume and characteristics of the dam such as dam height, storage volume, and dam factor (height and volume). The Piciullo et al. (2022) study expands on the database published by Laurrari and Lall (2018) and outlines the estimated tailings volumes released from 71 historical TSF breach events, including Mt. Polley (see inset). While we include model scenarios informed by the April 2022 study by Piciullo et al. (2022), the release of the Piciullo et al. (2022) publication came after our model simulations were complete; thus our study framework is centered around the more widely established relationships of Rico et al. (2008) and

Laurrari and Lall (2018). For reference, we also include modeling results in the appendix from the Piciullo et al., (2022) equation.

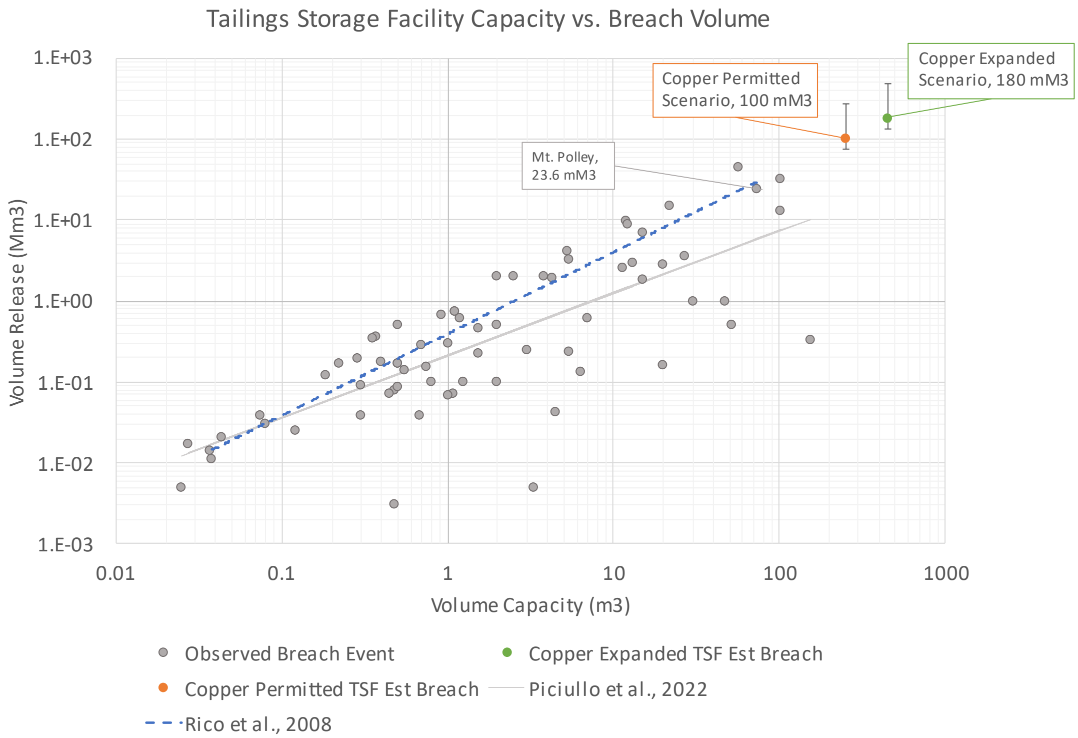

Figure 2-2. Comparison of tailings storage facility capacity and observed release volumes for historical breach events. Calculated release volume scenarios used in this study (orange and green points) are derived from the Rico et al., (2008) regression line, since Piciullo et al. (2022) was published concurrent with our modeling efforts.

To calculate an initial estimate of TSF breach release volume, we used the empirically derived equation from Rico et al. (2008) that examined the relationship between the total tailings impoundment volume and the total released tailings volume from historical failures:

$$V_f = 0.354V_t^{1.008} \qquad \text{(Eqn. 1)}$$

The regression equation (Eqn. 1) describes the relationship between V_f, the total breach release volume, and V_t, the impoundment, or storage capacity, as the sole predictor. Depending on the size of the impoundment, this equation implies that the expected tailings release volume from a TSF failure is approximately 35-45% of the total tailings impoundment volume.

For a storage capacity of 250-450 Mm^3, this equation estimates a breach volume of approximately 40% of the impoundment capacity, although critically, neither Rico et al. (2008) nor the updated Piciullo et al. (2022) include historical breach data for TSFs of this magnitude, with most data points at least an order of magnitude smaller than the CMM TSF (Figure 2-2). As discussed in Section 3, this 40% breach volume is used as our baseline release volume throughout many of our model simulations in the sections that follow, with significant consideration for much smaller and much larger breaches. For reference, the estimated breach of the CMM TSF as currently permitted (orange) and under the proposed expansion (green), would be approximately four to seven times larger than the Mt. Polley breach.

A secondary empirical analysis of dam failure flood run-out distance from Laurrari and Lall (2018) is provided in Figure 2-3. This analysis quantifies the downstream extent of tailings release distance from historical tailings dam failures:

$$D_{max} = 1.4388x^{0.563} \qquad \text{(Eqn. 2)}$$

Equation 2 shows the observed tailings runout distance as a function of the "Dam Factor," which combines dam height and total storage volume. As shown, a dam failure at either the permitted or proposed expanded CMM TSF would be larger than any of the historical dam failures in the Laurrari and Lall (2018) database. Additionally, the trendline through the Laurrari and Lall (2018) data suggests that a failure, if it were to occur, would likely create a tailings runout extending well beyond the US-Canada border, approximately 115 km downstream from the TSF facility. As described in our Model Results Section, our physical model of a tailings runout produces results consistent with this empirically-based projection.

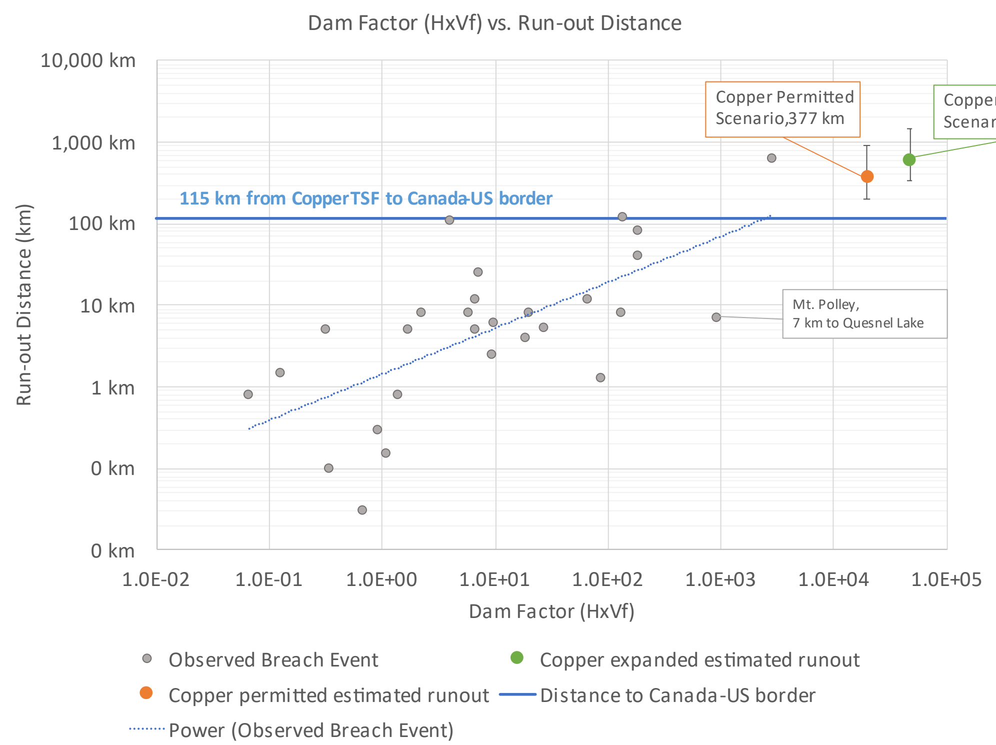

Figure 2-3. Comparison of dam factor and observed breach run-out distance for historical breach events (historical breach data obtained from Larrauri & Lall, 2018) and the estimated Copper TSF run-out distance. Blue horizontal line shows distance to US-Canada border for reference. Note that the Mount Polley runout distance was terminated by a downstream lake.

3. FLO-2D Model Setup

We built our TSF failure and transport model using the FLO-2D software package, a two-dimensional flood routing model that can simulate the types of non-Newtonian flows created by mud flows, debris flows, and other sediment laden flows such as outflows from tailings ponds (FLO-2D, 2021). FLO-2D is commonly used by mining companies and their consultants to simulate tailings dam failures (e.g., Knight Piesold, 2014), and is one of the models recommended by the Canadian Dam Association (CDA) for dam breach and runout modeling (CDA, 2021). It is also a FEMA approved hydrologic/hydraulic model. This section describes the model setup, our approach to developing breach scenarios and hydrographs, and the range of parameters we explored in our model sensitivity analyses.

3.1. Model Domain

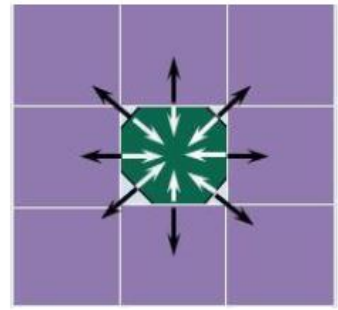
Figure 3-1: A representation of FLO-2D grid elements and flow direction vectors (FLO-2D, 2021)

FLO-2D uses a network of uniform and square grid elements over a user-defined model study area to perform multi-direction flow calculations of "…discharge across each of the boundaries in the eight potential flow directions" (FLO-2D, 2021; Figure 3-1). We developed the initial model boundary by using the full extent of the best available topographic data (Section 3.2) in the Similkameen River valley and running a large dam breach scenario within this domain to estimate a reasonable maximum inundation extent. We then refined the model domain through an iterative process that reduced the model footprint by reducing superfluous grid elements, thereby maximizing computational efficiency. The result of this refinement was a default model domain that extended from the west dam of the CMM TSF down the Similkameen River valley to the US-Canada border, approximately 105 km downstream, with an area of 202.3 km^2 (Figure 3-2, red). To achieve a balance of model spatial resolution with computational resources and model run time, we used a default grid resolution of 30 m[1].

We developed two additional model domains. The first of these was a 10 m resolution model domain that extended 20 km downstream of the west dam, with an area of 31.3 km^2 (Figure 3-2, orange). We used this higher resolution domain to provide a more detailed assessment of the impacts of a hypothetical breach to the town of Princeton. The second of these was a 50 m, international model domain that extended beyond the US-Canada border to the confluence of the Okanogan River and Columbia River near Brewster, Washington, approximately 200 km downstream (A 20- Appendix 7.8). Limitations in the best available topographic data (Section 3.2) and in computational resources prevented a comprehensive sensitivity analysis of the full BC-WA model domain, though select model results from the full international model domain are included in this report due to the interest in the potential impacts of a dam failure from downstream communities in Washington.

Throughout all model runs, we established a series of cross sections at locations of interest (Figure 3-2, green lines). In the default 30 m model domain, these cross sections included: 1) bottom of the CMM TSF west dam, 2) Princeton, BC, 3) above Wolfe Creek, 4) Hedley, BC, 5) Keremeos, BC, and 6) US-Canada Border. Additional cross sections were included in the 50 m international model domain, including: 7) below Palmer Lake, 8) above Oroville, WA, 9) Tonasket, WA, 10) Okanogan, WA, and 11) Brewster, WA (A 20- Appendix 7.8).

[1] Grid resolution refers to the size of each cell in a digital elevation model, or DEM. A 30 m grid resolution means that each value in the elevation model is an average of the actual land surface elevations on a 30 m x 30 m square. A 1 m grid resolution means that each value represents the elevation on a 1 m x 1 m square. Thus, smaller values of grid resolution provide an increasingly detailed depiction of the actual land surface.

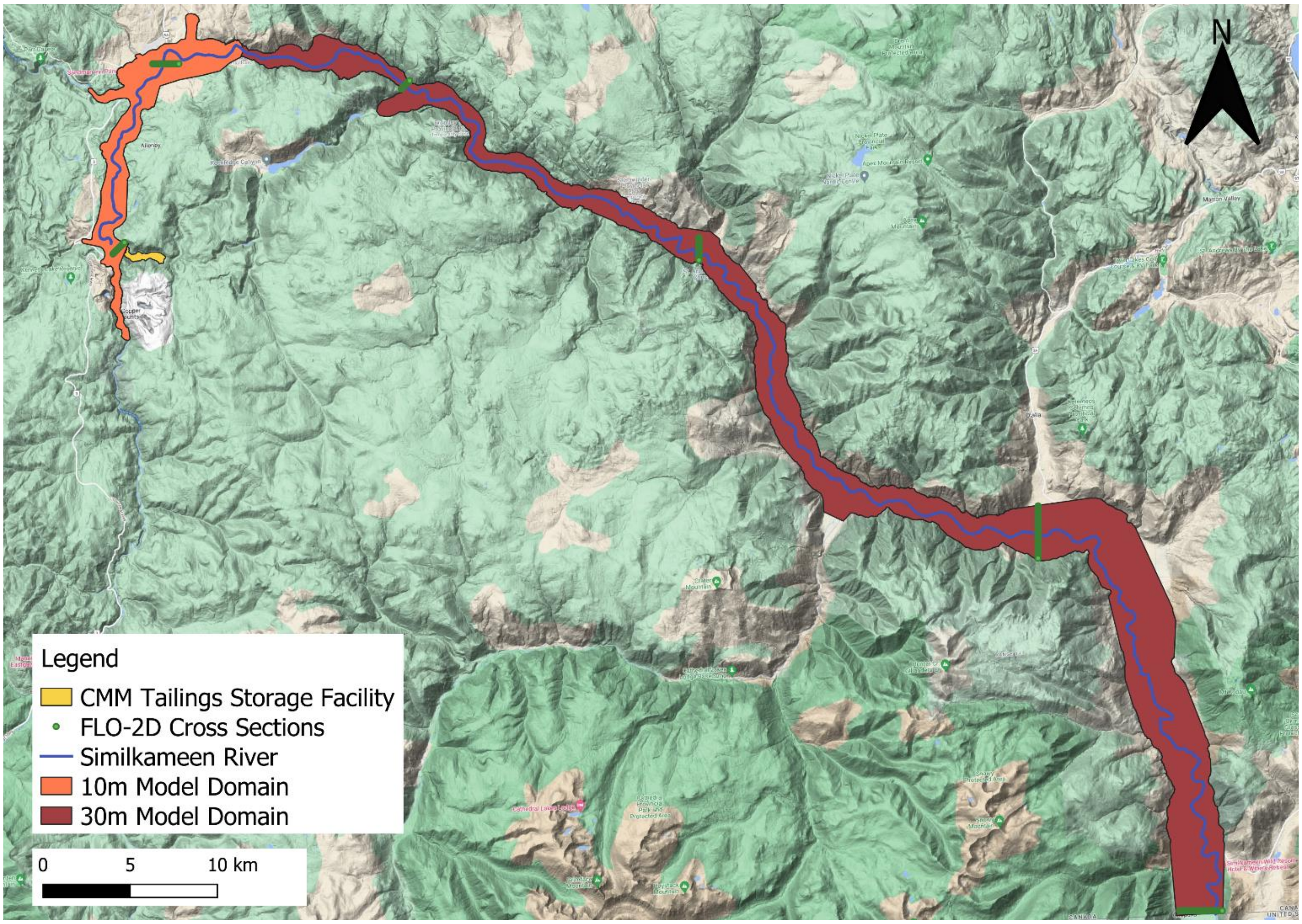

Figure 3-2: British Columbia tailings dam breach study domains, including the 10m high resolution model domain (orange) to Princeton, BC and the larger 30m default model domain (red) to the US-Canada Border, which is overlaid by the 10 m domain in the upper portion of study area. A map of the 50m, international model domain can be found in Appendix 7.8.

3.2. Topography and Hydrography

FLO-2D uses a gridded computational solver to simulate overland flow across the modeled land surface. Due to the way debris flows are routed in the model, the underlying elevation dataset in the model is a first order control on the model outputs. Generally, the best available topographic datasets are derived from lidar-based surveys, which use plane-mounted lasers to measure land surface elevation with high precision. Over the last several years, the Province of British Columbia has made significant investments in lidar data, including the large majority of the Similkameen River valley floodplain, which was flown in 2018 (Province of British Columbia, 2022). This 1-m resolution digital elevation model (DEM) served as the basis for our model simulations where these data were available.

The high-resolution DEM was available for the entirety of the Similkameen River floodplain from 7 km downstream of the west dam to the US-Canada Border. In areas where the high-resolution DEM was not available, we used a coarser, 10 m resolution DEM to fill missing topographic data. This 10 m DEM product is part of the National Hydrography Dataset Plus High Resolution (NHDPlus HR) geospatial dataset, which is a part of the U.S. Geological Survey's 3D Elevation Program (3DEP; USGS, 2017). As a tributary to the Okanogan River in Washington, the 3DEP data includes the entirety of the Similkameen River valley. Approximately 19% of the expanded study area was filled with the 10 m NHDPlus HR dataset, including the first approximately 7 km of the study domain downstream of the west dam, to the beginning of the BC lidar data extent. Other notable regions of the study domain that were missing lidar data included a section of Wolfe Lake, the northeast part of Hedley, BC (Figure 3-3), and all points in Washington. FLO-2D uses a linear interpolation to resample the underlying DEM dataset to the appropriate resolution of the model (see Appendix 7.8, Figure A 21).

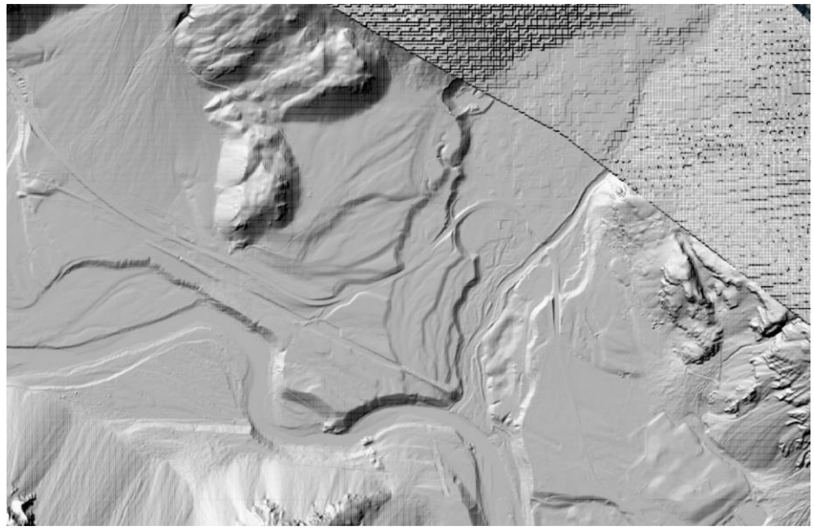

Figure 3-3: Hillshade rendering of the DEM data showing the transition between the high-resolution lidar DEM (1 m) in the Similkameen River floodplain and the coarser NHDPlus-HR DEM (10 m) in Hedley, BC.

Because the lidar-derived 1 m DEM was not available in Washington, we instead used a minimally post-processed version of the 10 m NHDPlus HR DEM for all simulations within the 50 m international model domain[2]. The USGS's 3DEP strives to compile the best-available elevation data to produce a nationally contiguous (including much of Canada) DEM that meets high standards of accuracy and resolution. Despite being the best-available DEM for the 50 m model domain, it was apparent that significant deficiencies and artifacts exist within the dataset. For example, upon our analysis of the hill shade rendering of the DEM, it was evident that the underlying raw elevation data was markedly different in Canada and in the US. An elevation profile traced along the approximate axis of the Similkameen River from Canada into the US showed a rise in elevation from approximately 350 m to nearly 360 m (Figure 3-4), with no physical explanation for such a rise. This artifact is likely the result of stitching together two elevation datasets and presented significant issues for all modeling downstream of the border. Investigation into possible solutions for rectifying this artifact revealed no scientifically justifiable solution within the scope of this task order.

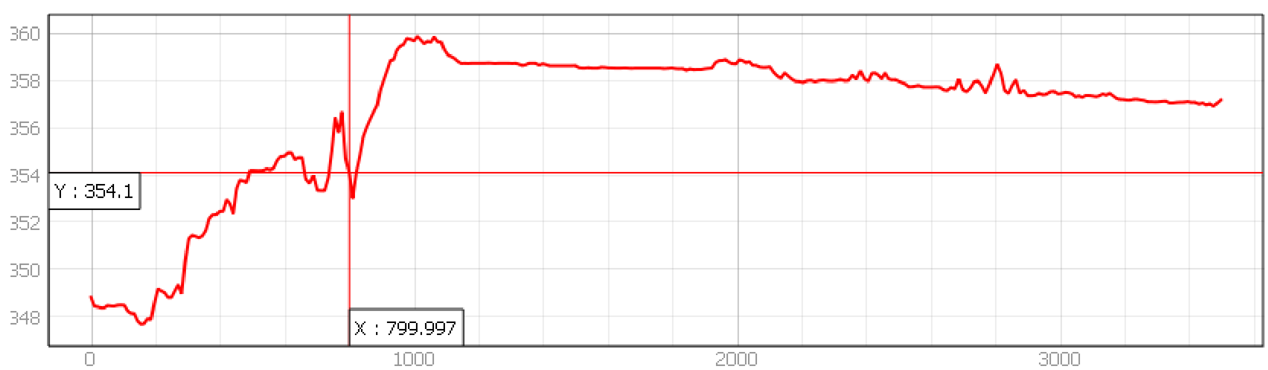

Figure 3-4: Elevation profile (m) of the 10m NHDPlus HR DEM from upstream to downstream along the axis of the Similkameen River across the US-Canada Border. The crosshairs are located at the US-Canada Border.

[2] Because of the many lakes in the Washington study area, we used rasterized bathymetry contour data (WA DOE, 1995) to post-process the NHDPlus HR DEM to represent lake bathymetry in the model. FLO-2D then filled these lakes to a user-provided lake surface elevation.

3.3. Surface Roughness

Open channel and overland debris flow is governed not only by topography, but also by the roughness of the land surface, as described by the empirically derived Manning's Equation. Estimates of surface roughness and the associated roughness coefficients (i.e., Manning's n-values) are typically inferred from land use datasets derived from satellite imagery. In this study, we extracted land use classes from the 2015 North American Land Change Monitoring System (NALCMS) dataset, a 30 m gridded product that identifies 19 land use classes from satellite observations spanning the US, Canada, and Mexico (NALCMS, 2020). While standardized reference tables are typically used to estimate Manning's n-values, FLO-2D prescribes higher n-values since "Steady, uniform flow (Manning's [equation]) n-values are not equivalent to unsteady, non-uniform grid element n-values in a discretized flood routing model" (FLO-2D, 2021b). Land cover within the model domain included needleleaf forests, broadleaf deciduous forests, mixed forests, shrublands, grasslands, croplands, barren lands, urban areas, and open water (Table 3-1). Manning's n-values presented in Table 3-1 and used in our modeling are adapted by FLO-2D from the U.S. Army Corps of Engineers HEC-1 manuals. Additional model scenarios used in the sensitivity analysis of this study perturbed the Manning's n-values in Table 3-1 by values 50% higher and lower, and assessed these changes on model behavior.

Table 3-1: Land use classifications from NALCMS 2015 dataset and associated FLO-2D Manning's n-values

NALCMS 2015 Land Class	NALCMS ID #	FLO2-D Manning's n-value
Temperate or sub-polar needleleaf forest	1	0.3
Temperate or sub-polar broadleaf deciduous forest	5	0.3
Mixed forest	6	0.3
Temperate or sub-polar shrubland	8	0.25
Temperate or sub-polar grassland	10	0.15
Cropland	15	0.15
Barren lands	16	0.15
Urban	17	0.04
Water	18	0.04

3.4. Tailings Characteristics

Mudflow simulations in FLO-2D are characterized as a non-Newtonian fluid. Fluid motion for non-Newtonian fluids is controlled by the fluid stresses that dominate in clear water flows, as well as by the interactions among fine-grained sediment particles within the fluid. As a result, the equations of motion for these fluids are a function of the sediment concentration, the maximum value and distribution of which is parameterized within the model. The sediment concentration-dependent parameters describing the fluid properties of the tailings within the model are the yield stress, τ_y, and the Bingham viscosity, K_B or η; together, these are known as Bingham parameters. Empirically derived equations of these fluid properties can be expressed as exponential functions of the sediment concentration, with two parameters, α and β, defining the shape of the curve relationship.

Field-based measurements of the yield stress and Bingham viscosity of the tailings materials requires a cone penetrometer test (CPT). Because data from such geotechnical analyses from the CMM TSF are unavailable or do not exist, we instead explored a wide range of experimentally derived values of yield stress and Bingham viscosity. After personal communications with Dr. Jim O'Brien of FLO-2D, we selected a wide range of α and β values from Table 4 of the FLO-2D *Simulating Mudflow Guidelines* documentation (FLO-2D, 2020) that would produce a reasonable approximation of yield stress and Bingham viscosity values while also evaluating a sufficiently large range of values in our sensitivity analyses. We allowed resistance parameters for laminar flow to be dynamically calculated by the model, while specific gravity values were pulled from the 2020 Klohn Crippen Berger mine expansion design report (KCB, 2020).

Table 3-2: Mudflow parameters, from Table 4 of the FLO-2D Simulating Mudflow Guidelines (FLO-2D, 2020)

Parameter	Sensitivity Test 1 (low values of τ_y & η)	Sensitivity Test 2 (moderate values of τ_y & η)	Sensitivity Test 3 (high values of τ_y & η)
Viscosity (η)	**Coefficient**: 0.000495 **Exponent**: 27.1	**Coefficient**: 0.000201 **Exponent**: 33.1	**Coefficient**: 0.000602 **Exponent**: 33.1
Yield Stress (τ_y)	**Coefficient**: 0.0383 **Exponent**: 19.6	**Coefficient**: 0.291 **Exponent**: 14.3	**Coefficient**: 0.00172 **Exponent**: 29.5
Specific Gravity	2.83		
Laminar Flow Resistance	Dynamically Calculated by FLO-2D		

3.5. Dam Breach Scenarios

The dam breach inflow hydrograph determines the rate of the tailings release, and the peak discharge from the facility during the breach. To develop these breach inflow input files for the FLO-2D model, we used the Tailings Dam Tool, developed by O'Brien (2015) and embedded within the FLO-2D modeling framework. This tool generates both a bulked flow hydrograph and a sediment concentration time series for a prescribed breach volume, duration, and shape. Because of the sensitivity of the breach simulation to the inflow hydrograph, we evaluated a wide range of parameters, following guidance from the Canadian Dam Associations Tailings Dam Breach Bulletin (CDA, 2021), the FLO-2D Documentation (FLO-2D, 2021b), and personal communications with both Dr. Jim O'Brien (2022) and Dr. Steven Emerman (2022).

As discussed in Section 2, we used empirical relationships derived from historical dam failure data to guide our evaluation of the plausible range of breach volumes, as summarized in Figure . These empirical relationships from Rico et al. (2008) and Piciullo et al. (2022) characterize release volumes from more than 70 tailings dam failures around the world, as a function of the TSF capacity. We used this relationship to develop our scenarios of tailings release volume. Specifically, our default tailings release volume was set to match the central trendline of the Rico et al. (2008) relationship, or approximately 40% of the total tailings impoundment volume[3]. We used lower and upper bounds of 10% and 70% of the total tailings volume to evaluate changes in the inundated area and runout distances due to smaller and larger volume releases, reflecting the spread in the empirical data and simulating a wide range of plausible release scenarios.

There are many variables that would likely affect the duration of a dam breach, the shape of the resulting breach hydrograph, the maximum sediment concentration of the debris flow, and the evolution of the sediment concentration through time as the breach wave progresses and propagates downstream. Some of these variables include the mechanism of failure (e.g., a slow overtopping of the dam vs. catastrophic liquefaction of the tailings and dam), but also the construction of the dam (e.g., upstream vs. downstream construction techniques), which would likely affect the rate of failure. To reflect a reasonable range of possible failure mechanisms, we explored eight different release volumes (10-70% of storage capacity, in increments of 10%, plus a scenario from the Piciullo et al., 2022 regression), six different release durations (3-96 hours), three different breach hydrograph

[3] The release volume percentages represent the water component of the debris flow as a percent of the total storage capacity. Bulked flow volumes (i.e., both sediment and water) are a function of the water component of the release volume, plus the sediment component, which is a function of the maximum sediment concentration and sediment concentration distribution parameterizations.

shapes (flashy to more gradual), two different sediment concentration curves (variable through time to constant), and six different maximum sediment concentrations (30-55% by volume). This full range of model discharge scenarios is summarized in Tables 3-3 and 3-4 for the permitted and the expanded dam, respectively.

The "default" model breach parameters, which are described in the most detail in the results sections of this report, included a 40% breach volume, a 12-hour breach duration, default FLO-2D breach hydrographs and sediment concentration curves (Figure 3-5), and a maximum sediment concentration of 35%.

Table 3-3 Summary of all breach discharge scenarios for input to FLO-2D for the permitted CMM TSF (250 Mm³ storage)

Model Scenario Permitted TSF	Breach Volume (million m³)	Breach Volume (% of Dam Capacity)	Breach Duration (hours)	Max Sediment Concentration (%)	Discharge Water Volume (million m³)	Discharge Sediment Volume (million m³)
Variable Breach Volume[4]						
10% Breach	31.5	10	12	35	25	6.5
20% Breach	62.9	20	12	35	50	12.9
30% Breach	94.4	30	12	35	75	19.4
40% Breach	125.9	40	12	35	100	25.9
50% Breach	157.3	50	12	35	125	32.3
60% Breach	188.8	60	12	35	150	38.8
70% Breach	220.3	70	12	35	175	45.3
Piciullo et al. (2022)	18.8	22	12	35	15	3.8
Variable Breach Hydrograph Duration ("Breach Duration")[5]						
3 hours	125.9	40	3	35	100	25.9
6 hours	125.9	40	6	35	100	25.9
12 hours	125.9	40	12	35	100	25.9
24 hours	125.9	40	24	35	100	25.9
48 hours	125.9	40	48	35	100	25.9
96 hours	125.9	40	96	35	100	25.9
Maximum Sediment Concentration (by volume)[6]						
30	125.9	40	12	30	100	25.9
35	125.9	40	12	35	100	25.9
40	125.9	40	12	40	100	25.9
45	125.9	40	12	45	100	25.9
50	125.9	40	12	50	100	25.9
55	125.9	40	12	55	100	25.9
Variable Hydrograph and Sediment Concentration Distribution Scenarios[7]						
Hydrograph #3	125.9	40	12	35	100	25.9
Hydrograph #4	125.9	40	12	35	100	25.9
Sediment #3`	125.9	40	12	35	100	25.9

Table 3-4: Summary of all breach discharge scenarios for input to FLO-2D for the expanded CMM TSF (450 Mm³ total storage)

Model Scenario Permitted TSF	Breach Volume (million m³)	Breach Volume (% of Dam Capacity)	Breach Duration (hours)	Max Sediment Concentration (%)	Discharge Water Volume (million m³)	Discharge Sediment Volume (million m³)
Variable Breach Volume[4]						
10% Breach	56.6	10	12	35	45	11.6
20% Breach	113.3	20	12	35	90	23.3
30% Breach	169.9	30	12	35	135	34.9
40% Breach	226.6	40	12	35	180	46.6
50% Breach	283.2	50	12	35	225	58.2
60% Breach	339.9	60	12	35	270	69.9
70% Breach	396.5	70	12	35	315	81.5
Piciullo et al. (2022)	29.7	22	12	35	23.6	6.1
Variable Breach Hydrograph Duration ("Breach Duration")[5]						
3 hours	226.6	40	3	35	180	46.6
6 hours	226.6	40	6	35	180	46.6
12 hours	226.6	40	12	35	180	46.6
24 hours	226.6	40	24	35	180	46.6
48 hours	226.6	40	48	35	180	46.6
96 hours	226.6	40	96	35	180	46.6
Maximum Sediment Concentration (by volume)[6]						
30	226.6	40	12	30	180	46.6
40	226.6	40	12	40	180	46.6
45	226.6	40	12	45	180	46.6
50	226.6	40	12	50	180	46.6
55	226.6	40	12	55	180	46.6
Variable Hydrograph and Sediment Concentration Distribution Scenarios[7]						
Hydrograph #3	226.6	40	12	35	180	46.6
Hydrograph #4	226.6	40	12	35	180	46.6
Sediment #3`	226.6	40	12	35	180	46.6

[4] The 10-70% breach volumes are approximately centered on the empirical dam breach relationship from Rico et al. (2008), which estimates a breach volume equal to approximately 40% of the storage capacity of a tailings dam. An updated analysis from April of 2022 (Piciullo et al., 2022) consider both dam height and storage, which predicts a release volume of approximately 22%.

[5] The breach hydrograph duration is the length of time that the simulated breach is inputting bulked sediment into the model domain, where a shorter duration represents a faster, more catastrophic failure.

[6] Depending on the capacity of the supernatant tailings pond at the time of the breach, and the saturation content of the tailings, maximum sediment concentrations (by volume) can range from 30% (mud flood) to 55% (mud flow to landslide).

[7] FLO-2D's Tailings Dam Tool prescribes a range of hydrograph and sediment concentration distribution scenarios. See Appendix 7.3 for additional figures.

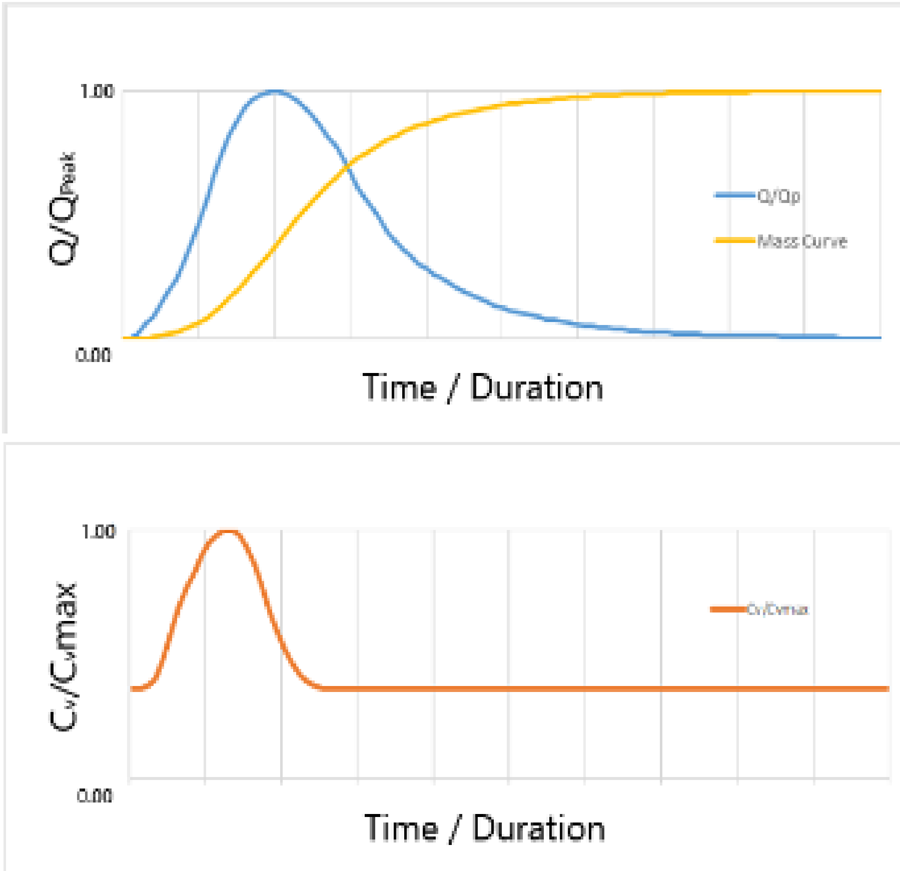

Figure 3-5. FLO-2D default breach hydrograph (top) and sediment concentration curves (bottom).

3.6. FLO-2D Runtime Settings

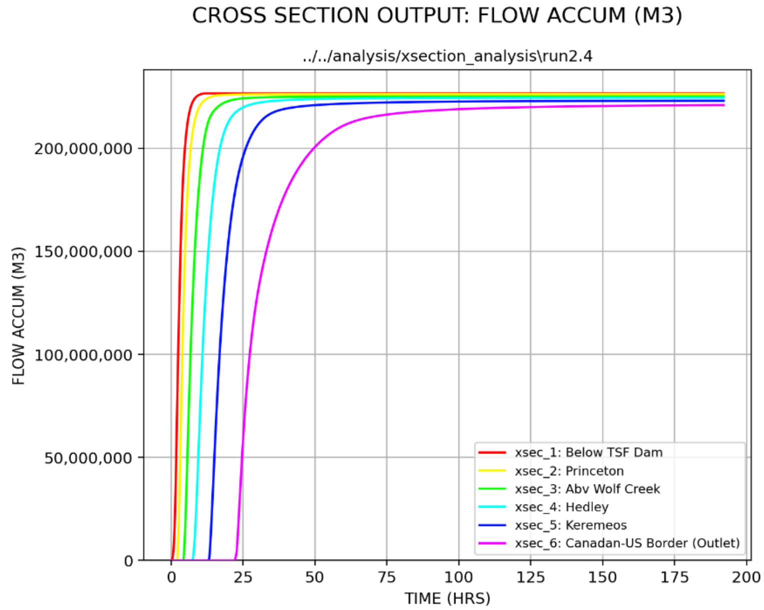

Figure 3-6: Accumulated flow at six cross sections for the 12-hour, 40% breach scenario of the expanded TSF in the 30 m model

We used an analysis of the discharge hydrographs and flow accumulation throughout the model domain to constrain a reasonable model runtime after which the model reached a steady state. For example, by looking at the accumulated flow at the outlet of the 30 m model domain (US-Canada Border, pink line, Figure 3-6) in the 40% breach scenario of the expanded TSF, we can see that by hour 125, nearly all of the flow that passes across the border has exited the model domain. To accommodate larger breach scenarios, a standardized run time of 192 hours (8 days) was used for the default 30 m model domain. The simulations for the smaller 10 m model domain (CMM TSF to downstream of Princeton) were only run for 72 hours (3 days) while simulations for the 50 m international model domain (CMM TSF to Brewster, WA) were run for 480 hours (20 days). Model outputs from each simulation were evaluated to ensure the model maintained mass balance and numerical stability throughout. Across the BC simulations, we set the model timesteps to 0.1 hours, while for the international model domain we set the model timesteps to 1.0 hours.

4. Model Results

We ran model simulations for 31 different parameter sets for each dam size, for a total of 62 total scenarios. Of these 62 scenarios, the large majority (52 scenarios, or 84%) were run within the default 30 m model domain, which had the best available DEM data and also covers the area most likely to be severely impacted by a dam breach at the CMM due to proximity to the TSF. Six model scenarios were run at the higher model resolution from the TSF to Princeton, while four model scenarios were run at the coarser model resolution, across the US-Canada border to the confluence of the Columbia River.

Evaluating model results over a wide range of parameter space allowed us to bracket the range of uncertainty in our assumptions and to classify model sensitivity to individual parameters. We determined the parameter sensitivities by varying individual model parameters one at a time and comparing the model outputs between the high and low end of each parameter, for each sensitivity test (Table 4-1). Among the scenarios we evaluated, the volume of the tailings dam breach was the most significant factor in determining both the spatial extent of the breach outflow (i.e., inundation area) and average maximum depth of the flow across the model domain. For example, in the simulations of a breach of the currently permitted dam, the 10% breach scenario inundated 74.3 km^2 while the 70% breach scenario inundated 96.6 km^2, or approximately 30% more area (Figure 4-1). Average maximum depth[8] across the entire domain were 0.95 m and 4.3 m, respectively. In comparison, the results were virtually insensitive to varying the sediment concentration distribution of the breach hydrograph or the location of the dam breach, with differences in inundation area on the order of 1% or less. Because of the constrained geography of the Similkameen River valley, average maximum depth was a more sensitive objective function than inundated area when evaluating parameter sensitivity. In other words, large changes in model parameters resulted in large changes in average maximum flow depth, but rather similar inundated areas, because of the topographically steep valley walls constraining the flow extent around the river floodplain.

In the following sections, we present highlights of model results for both dam scenarios under our “default” 40% breach, showing inundation area, flow depths, and hydrographs. A detailed summary of our model sensitivity analysis is provided in the appendix.

[8] Average maximum depth is a measure of the spatial mean of the maximum flow depth across all grid cells (Figure 4-1) in a given model domain.

Table 4-1: FLO-2D model sensitivity test results for the permitted CMM TSF[9].

Sensitivity Test	Min values	Max values	% Diff. of Inundated Area (between max/min)	% Diff. in Avg. Max Depth (between min/max)	Parameter Sensitivity
Breach Volume	10%	70%	23.2%	127.6%	High
Breach Duration	3 hour	96 hour	13.7%	58.3%	High
Max Sediment Concentration	30%	55%	11.9%	66.8%	High
Hydrograph Scenario	Flashy, quick recession	Slow and steady	6.6%	36.5%	Moderate
Manning's n	50% lower	50% higher	3.4%	18.2%	Moderate
Viscosity + Yield Stress	Low viscosity/yield stress	High viscosity/yield stress	2.5%	15.3%	Moderate/Low
Sediment Concentration	Variable through time	Constant	1.3%	4.4%	Low
Breach Location	Bottom of Dam	Top of Dam	0.9%	0%	Low/Insensitive

[9] Please refer to the Appendix for a thorough review of the sensitivity analyses conducted for each type of parameter.

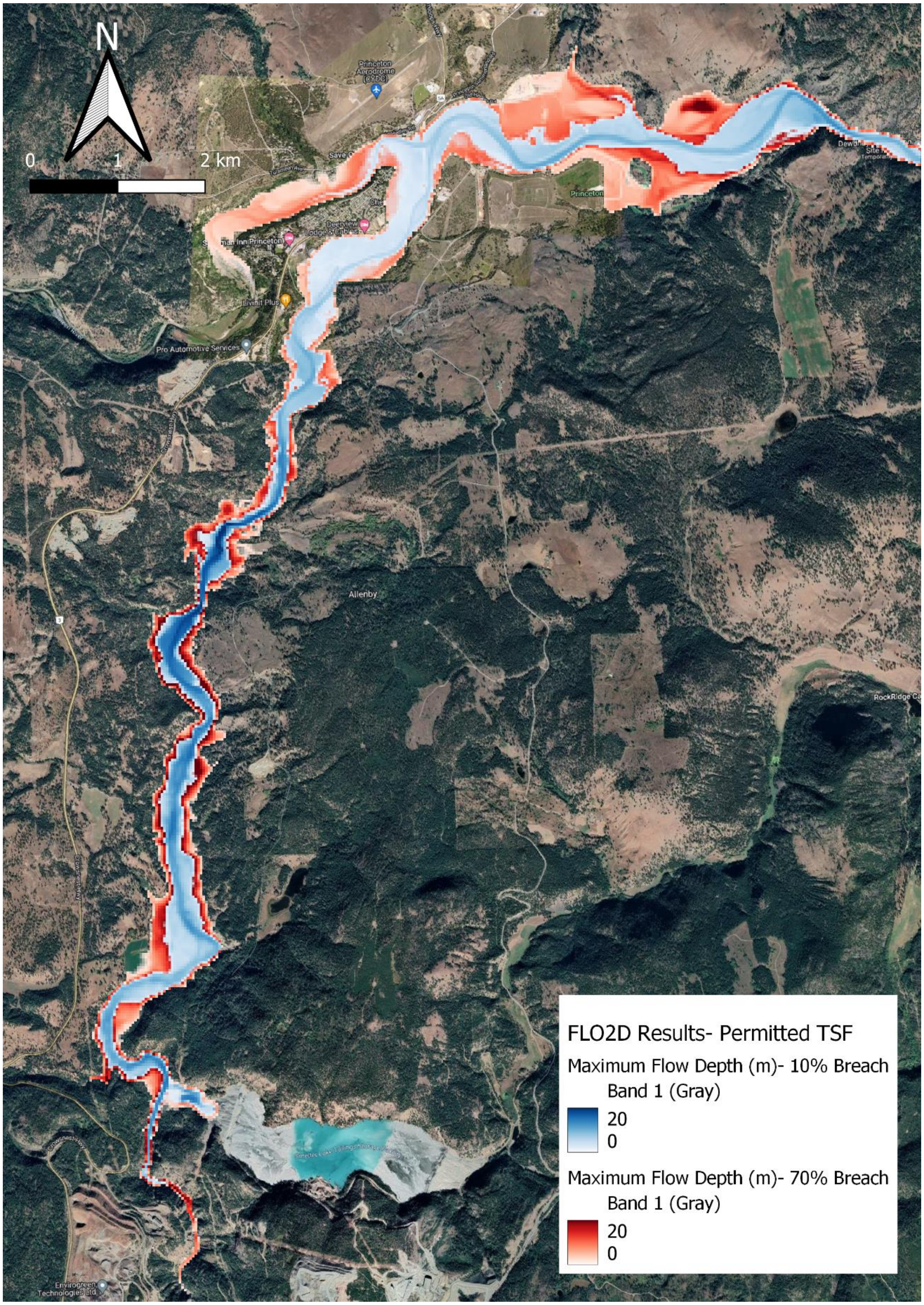

Figure 4-1: Overlay of maximum flow depth (m) of the 10% and 70% breach volume scenarios for the permitted CMM TSF.

4.1. Breach Analysis Results: Permitted TSF Volume

Model results for the 40% breach scenario with default parameter values suggest complete inundation of the Similkameen River valley floodplain (Figure 4-2) from the west tailings dam of CMM to Lake Palmer, Washington (Figure 4-3), with average depths in British Columbia of 2.9 m and maximum depths of 34.3 m. The model indicates that the greatest flood depths, flow velocities, and impact forces (calculated from depth, flow velocity, and debris flow density) would be closest to the dam and in topographically constrained points along the river channel, while the broader floodplains near Princeton and Keremeos allowed the debris flow to spread out and slow down, reducing the overall scale of potential damage to property and infrastructure. The total area of inundation under the default breach scenario is approximately 90 km^2 in British Columbia, with an additional 57 km^2 in Washington state[10]. Maximum flood depth maps such as Figure 4-2 (flow entering from bottom left and exiting top right) illustrate this behavior of the debris flow, where darker red colors correspond to greater flow depths in constrained portions of the river channel. Extensive backflow up the Tulameen River to the west can also be observed in the flood depth maps of Princeton.

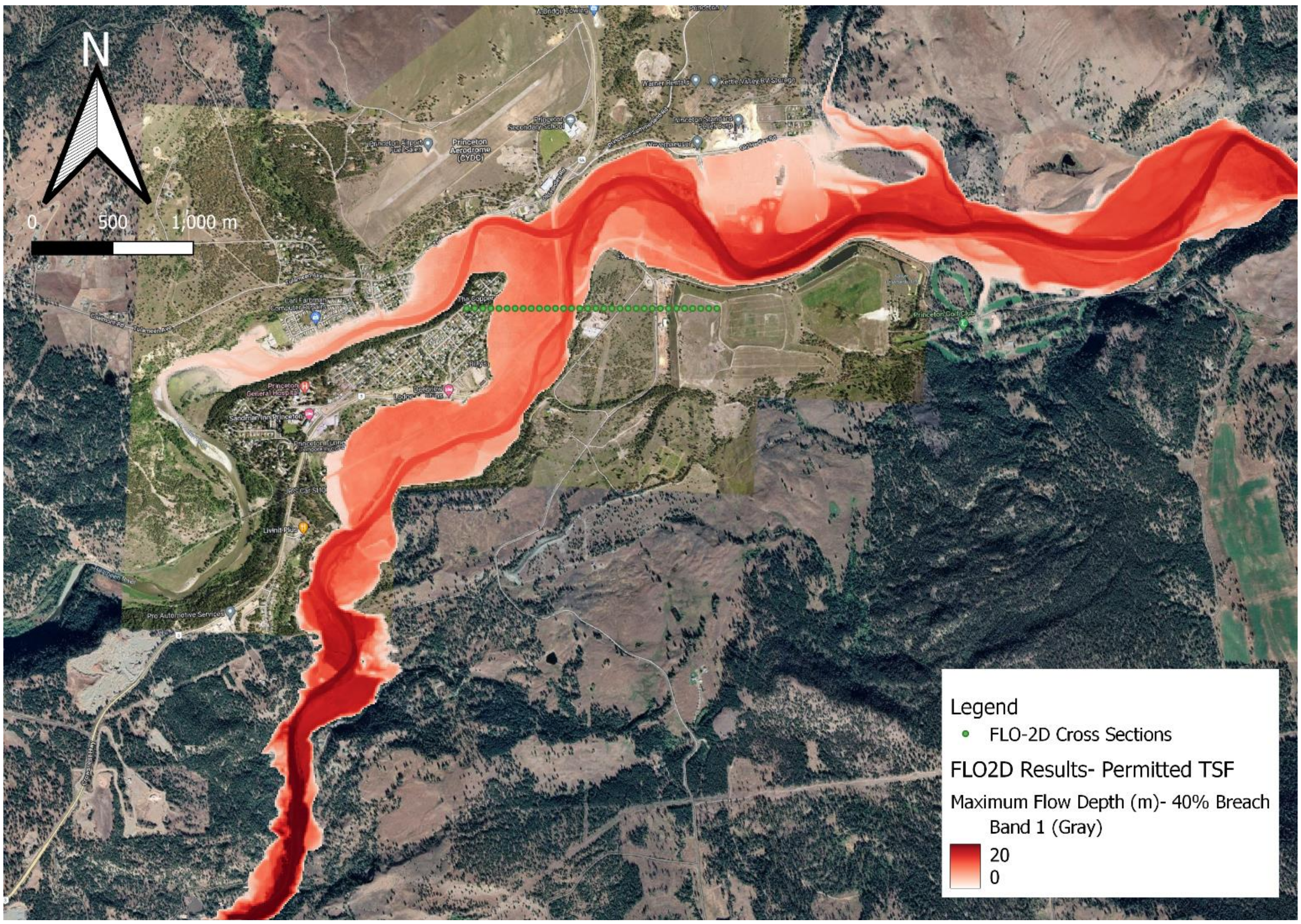

Figure 4-2: Maximum flow depths (m) in Princeton, BC from a 40% breach, 12 hour duration scenario for the permitted TSF at CMM (250 Mm^3). Debris flow is entering from bottom left and exiting at top right.

[10] Inundation area was calculated as the total area covered by tailings to a depth of 5 cm or more. Note that inundation areas for Washington State have a higher degree of uncertainty than those in BC, due to the artificial step in the digital elevation model that was available for our analysis (see Figure 3-4)

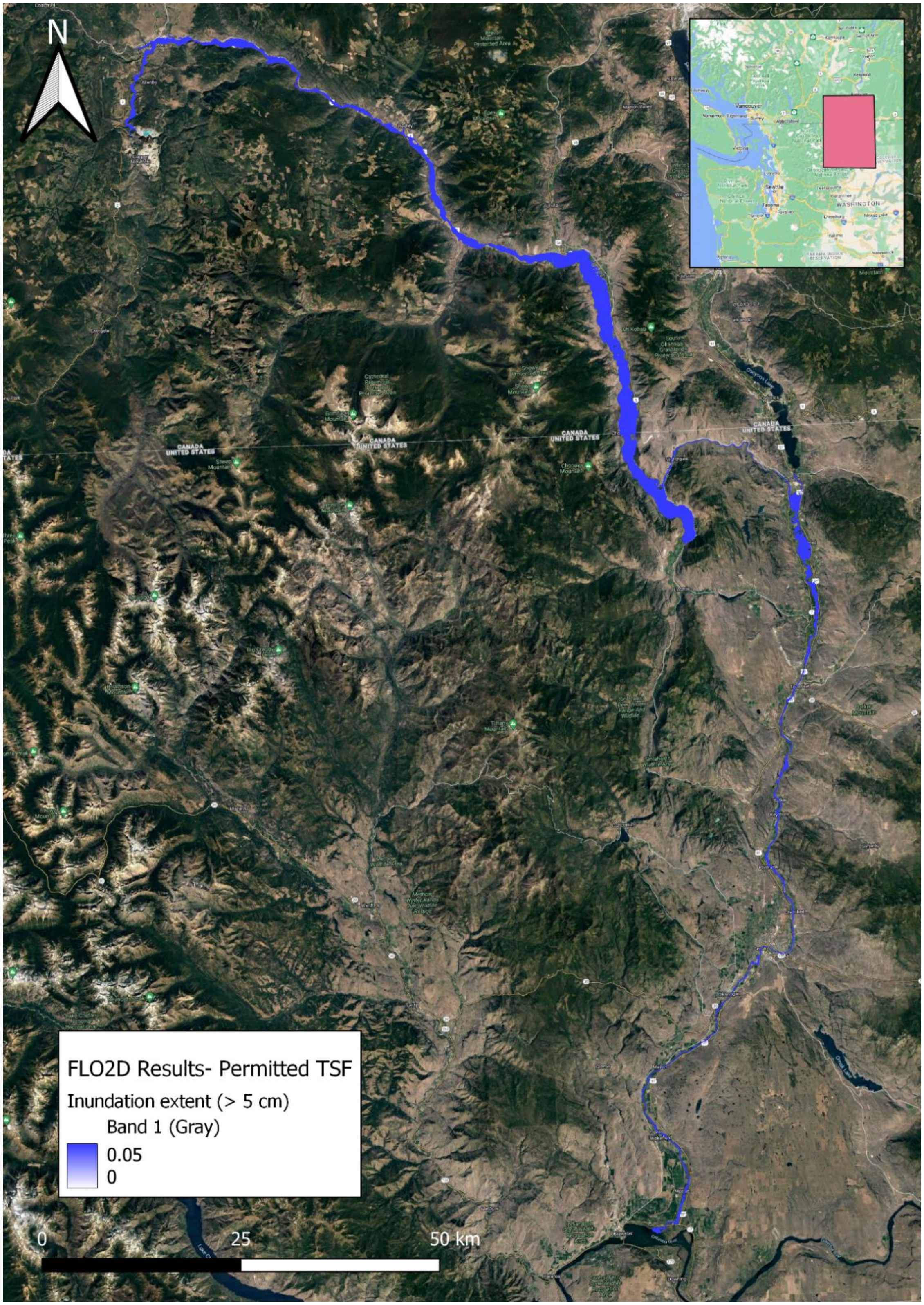

Figure 4-3: Inundation extent (> 5 cm depth) for the 40% breach, 12 hour duration scenario of the permitted TSF at CMM. 50 m spatial resolution, 480 hour simulation run time. CMM TSF is located in the upper left hand quadrant of the map, as illustrated in Figure A 20.

In addition to maximum flood depths and inundation area, FLO-2D model outputs also include times to maximum depth for each grid cell in the model domain. For each cross section we specified in the model, we can also extract and evaluate the hydrograph, showing the bulked debris flow and the sediment-only components of flow through time (Figure 4-4). In Princeton, model simulations estimate that the time to maximum depth would be 3.5 hours after the breach, with peak discharge values of 12,000 cubic-meters per second (CMS), though a more rapid 3-hour breach duration would see peak flows in 1.5 hours. Comparing these simulated peak flows to historical floods recorded at the streamflow gage 08NL007 suggest that such flows would be more than ten times greater than any streamflow ever measured in the town of Princeton. In this scenario, more than a quarter of the debris flow would consist of tailings sediment. Physical impacts of peak flow rates of this magnitude can be inferred from recent flooding in Princeton in the fall of 2021, in which floodwaters ravaged parts of downtown. Downstream, simulations estimate that the time to maximum flow would be approximately 10.4 hours in Hedley, 17.1 hours in Keremeos, and 28.3 hours at the US-Canada Border.

While model results are largely focused on impacts to the communities in British Columbia, our simulations suggest that even a breach of the permitted TSF would cross the border into the United States. Unfortunately, as discussed in Section 3.2, significant artifacts in the DEM at the US-Canada Border warrant cautious interpretation of model results in the United States. The nature of the DEM artifact is such that all model results in the US are likely an underestimate of the extent of any impacts from a breach at the CMM TSF for any given set of model assumptions and parameter values. Even with the DEM limitations, model results do suggest that the debris flow would continue down the Similkameen River and enter Lake Palmer, a deep (> 20 m) lake that is a part of the Sinlahekin Creek, a tributary to the Similkameen. At a specific gravity of 2.83 (i.e., 2.83 times denser than water), the debris flow would disperse into Lake Palmer, and displace the existing lake water. Simulations suggest that a double-peaked flood wave (the initial debris flow and the displaced Lake Palmer water; Figure A 22 and Figure A 23) would then flow with renewed vigor down the Similkameen River, before joining the Okanogan River. Model outputs suggest that this secondary debris flow would be largely contained within the river channel after this point, with limited overtopping of the channel into the floodplain.

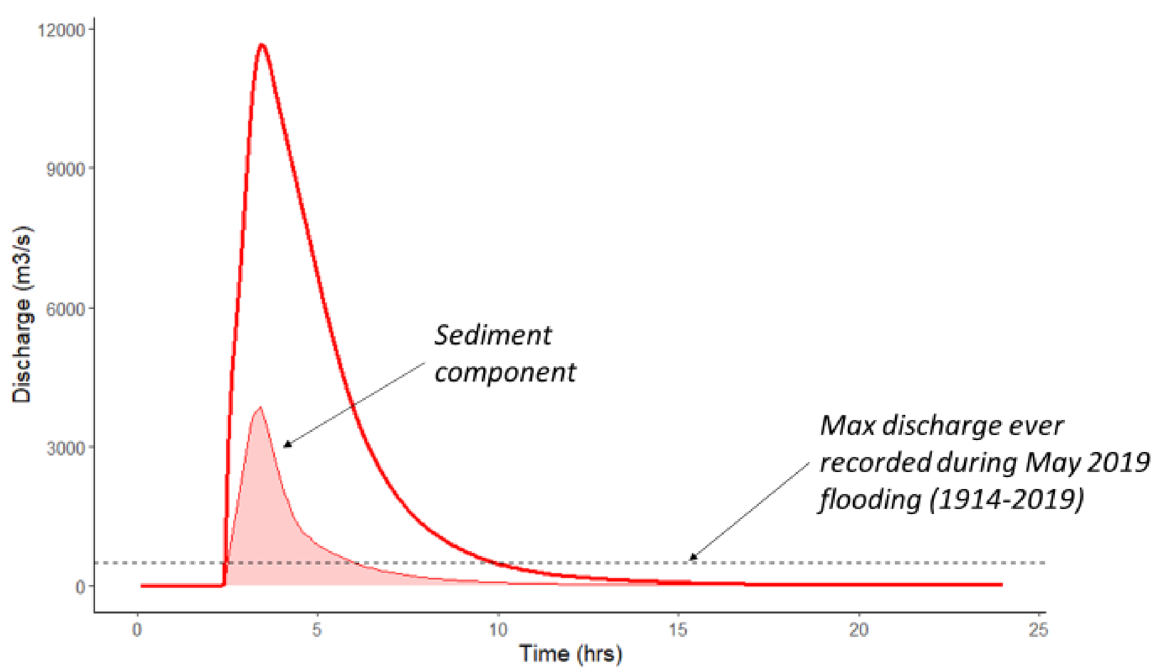

Figure 4-4. Timeseries hydrograph of the first 24 hours of the default permitted dam breach scenario. The bulked component (sediment and water; dark red line) is 12 times more than the maximum discharge ever recorded at gage 08NL007.

4.2. Breach Analysis Results: Proposed Expanded TSF

Our default breach scenario for an expanded CMM TSF used the same parameters as for the permitted TSF (e.g., 40% volume release over 12 hours). Model simulations confirm that a breach of equal proportions of an expanded CMM TSF would result in a more catastrophic debris flow characterized by greater inundation area, maximum flow depth, and peak flow discharge. In the maximum flow depth map of Princeton shown in Figure 4-5 for a 40% breach scenario, depths are projected to exceed 20 m, with portions of downtown Princeton along the Similkameen River channel inundated by depths of 10-14 m. Under this breach scenario, average maximum flow depths in the British Columbia model domain would be 4.4 m, with a maximum value of 43.2 m. The overall behavior of this debris flow would be very similar to that due to a breach of the permitted CMM TSF, though inundation areas would increase to 97 km^2 in British Columbia, and 176 km^2 across BC and Washington. Notable additional inundation areas include portions of the Tulameen River upstream of Princeton, BC (due to backflow from the elevated debris flow in the Similkameen River valley), portions of southern Hedley, at the confluence of Ewart Creek and the Similkameen River, upstream of Lake Palmer, and the floodplain of the Okanogan River between Okanogan and Tonasket, Washington (Figure 4-6).

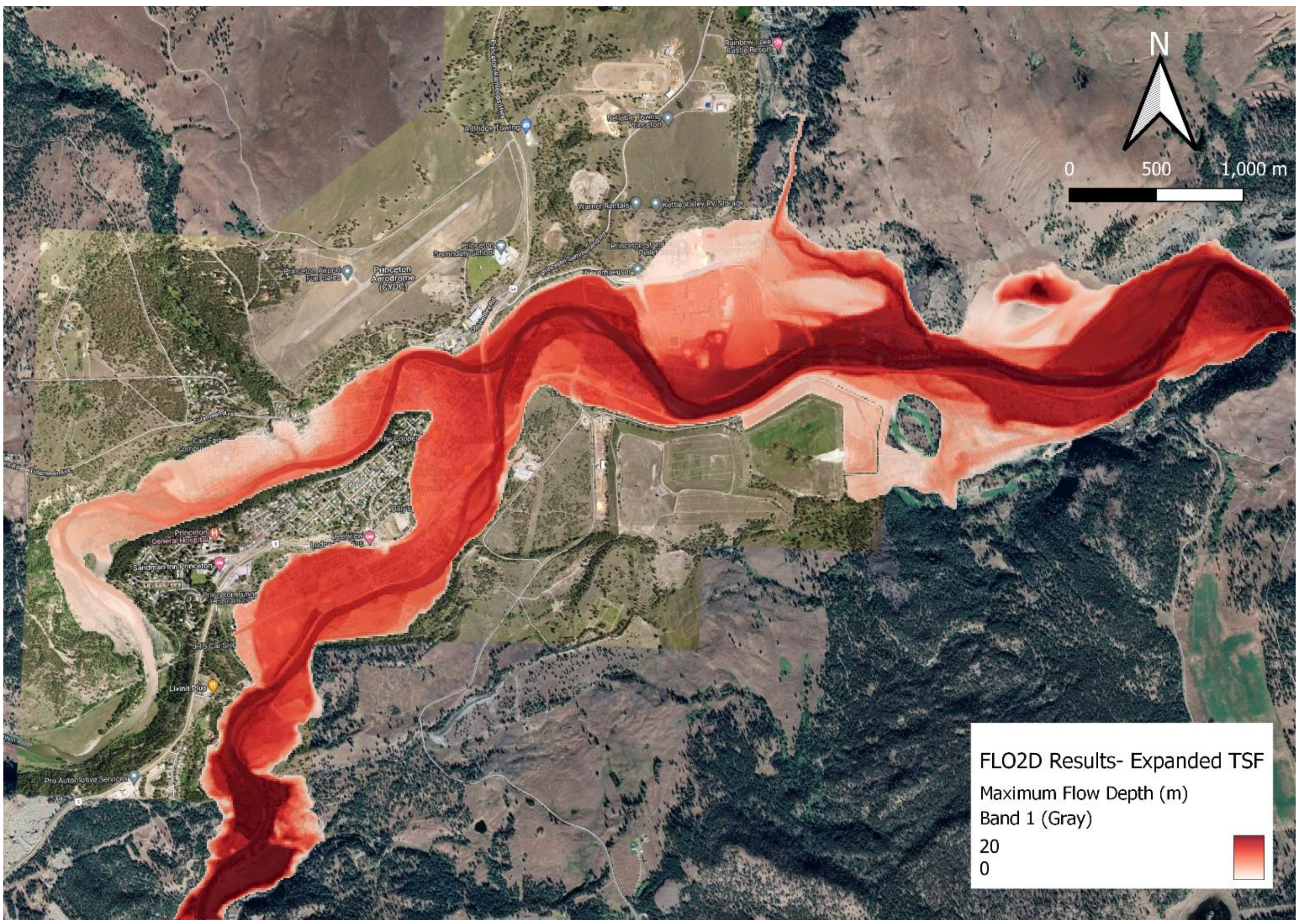

Figure 4-5: Maximum flow depths (m) in Princeton, BC from a 40% breach, 12 hour duration scenario for the expanded TSF at CMM (450 Mm^3).

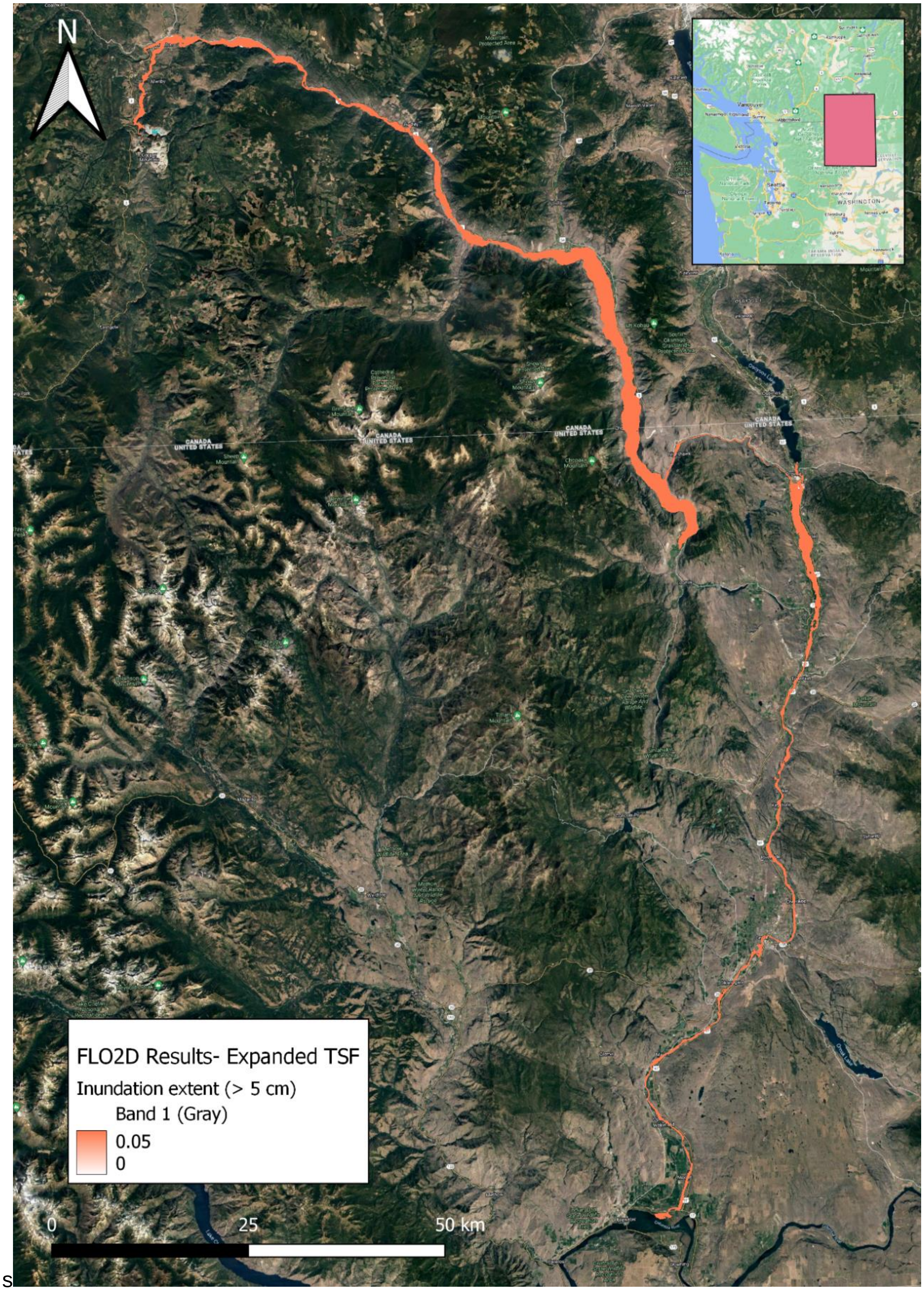

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Figure 4-6: Inundation extent (> 5 cm depth) for the 40% breach, 12 hour duration scenario of the expanded TSF at CMM. 50 m spatial resolution, 480 hour simulation run time. CMM TSF is located in the upper left hand quadrant of the map, as illustrated in Figure A 20.

While a larger debris flow would move faster, the time to peak flows would not change dramatically for more proximate locations such as Princeton: peak flows would still be projected to arrive in town in approximately 3.3 hours. The magnitude of this debris flow, however, would be 60% greater, at over 20,000 CMS (Figure 4-7). Comparing this to historical floods recorded at the streamflow gage 08NL007 suggest that such flows would be more than twenty times greater than any flows ever measured in the town of Princeton, with more than a quarter of this flow consisting of tailings sediment. Physical impacts of such flows would be catastrophic. Downstream, simulations estimate that the time to maximum flow would be approximately 9.5 hours in Hedley, 15.5 hours in Keremeos, and 23.6 hours at the US-Canada Border, or nearly 5 hours faster than peak flows from the equivalent permitted TSF breach scenario.

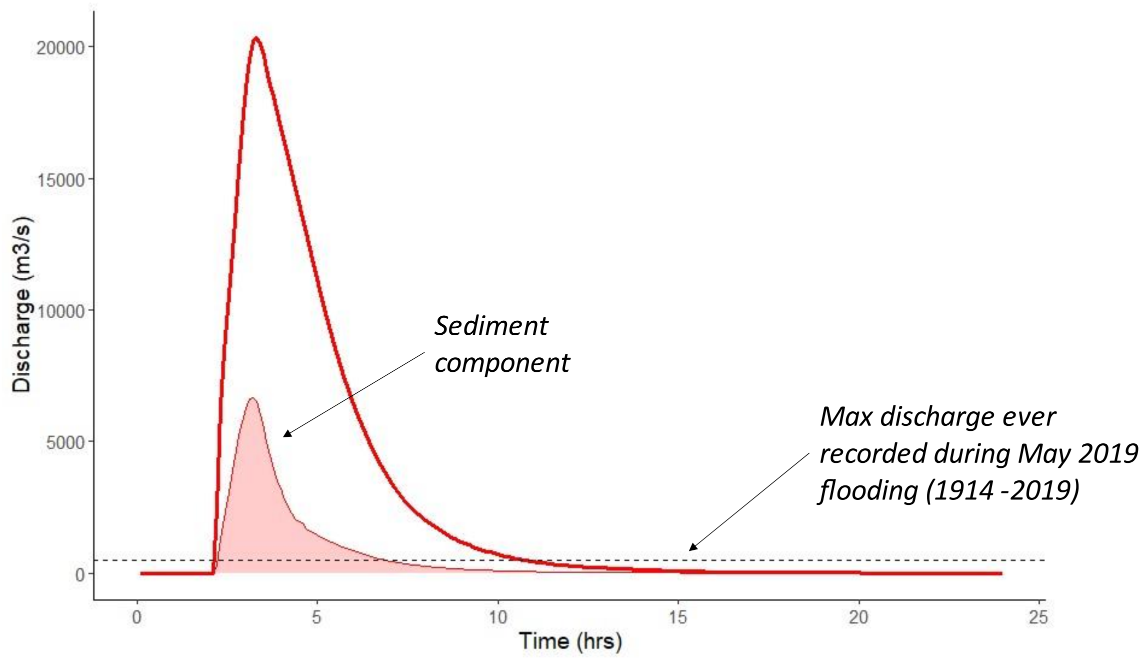

Figure 4-7: Timeseries hydrograph of the first 24 hours of the default expanded dam breach scenario. The bulked component (dark red line) is 12 times more than the maximum discharge ever recorded at gage 08NL007.

5. Discussion

FLO-2D model outputs reveal that any breach of the CMM TSF west dam as currently permitted would result in widespread and catastrophic downstream consequences, particularly for the town and community of Princeton (Figure 5-1). Additional impacts would occur for communities as far downstream as Chopaka, BC and Okanogan, WA, although the impacts to those communities would be substantially smaller. In Princeton, our modeling efforts suggest that maximum flow depths could approach 5-15 m within 1.5 to 5.5 hours, with peak flows an order of magnitude greater than any recorded flood along the Upper Similkameen River, which is consistent with the recent upgrade in the tailings dam classification from 'Very High' to 'Extreme'. This rating and consequence assessment suggests potential loss of life of more than 100 people, with extreme losses in critical infrastructure and economics, major environmental and cultural losses, and where restoration or in-kind compensation would be impossible (CDA, 2013). In addition to the risk of loss of life to the people and community of Princeton, virtually all sectors of the economy in the Similkameen River valley would be significantly impacted by the physical impacts of a large debris flow wave, the resulting inundation of the floodplain, and any longer term environmental impacts of widespread tailings distribution in the Similkameen and Okanogan River systems, including communities such as Hedley (Figure 5-2). In particular, the rich agricultural and recreational/tourism sectors of the Similkameen economy would likely be acutely vulnerable to the aftermath of a tailings dam breach.

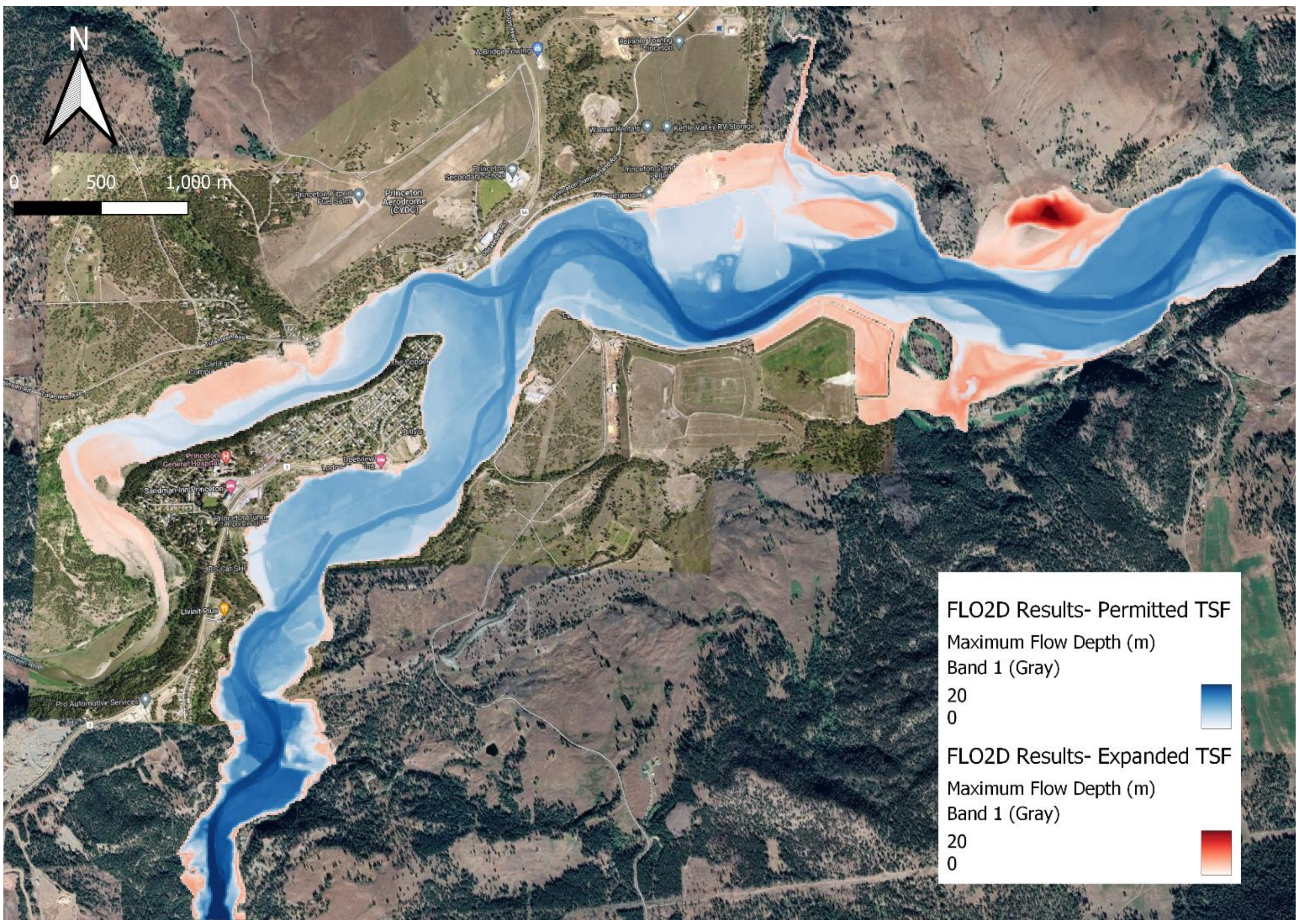

Figure 5-1: An overlay of maximum flow depths (m) in Princeton, BC from a 40% breach, 12 hour duration scenario for the permitted TSF (250 Mm3; in blue colorbar) and the expanded TSF (450 Mm^3; in red colorbar)

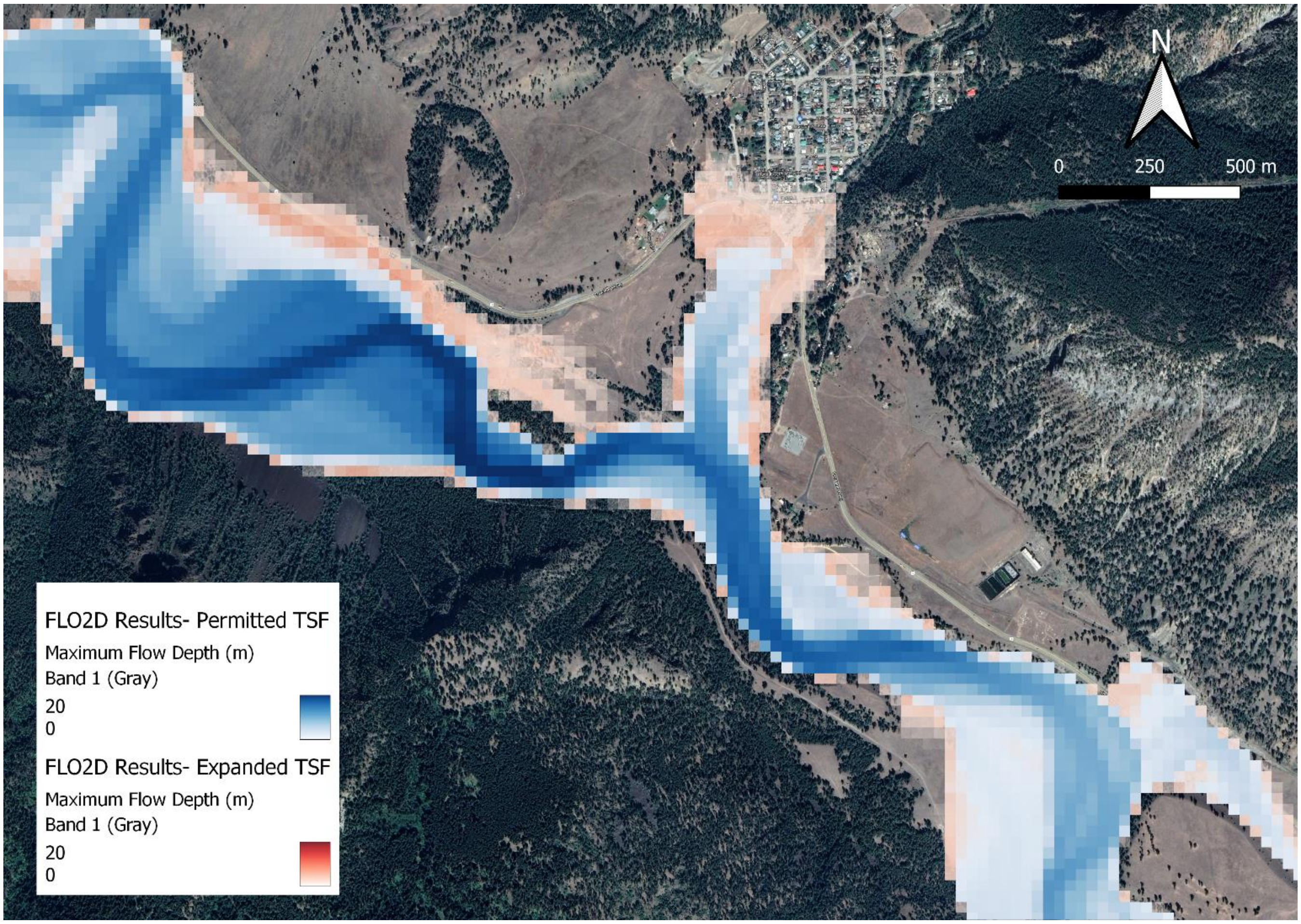

Figure 5-2: An overlay of maximum flow depths (m) in Hedley, BC from a 40% breach, 12 hour duration scenario for the permitted TSF (250 Mm3; in blue colorbar) and the expanded TSF (450 Mm3; in red colorbar)

Our modeling efforts also suggest that a debris flow wave from a tailings dam breach of the CMM TSF is very likely to propagate more than 100 km downstream, across the US-Canada border and into Washington; such findings are consistent with the runout distance estimated from the empirical relationship derived by Laurrari and Lall (2018). Though data artifacts in the best-available DEM of North America prevent more precise quantifications of these trans-boundary impacts, an assessment of the hydrograph at a cross section just upstream of the US-Canada border insight into the magnitude and timing of a debris flow into the United States (Figure 5-3), which even 100 km downstream, is still several times larger than any recorded flood event at a nearby USGS streamflow gage. Major loss and deterioration of habitat and watershed characteristics are likely along the lower Similkameen River, with particularly significant impacts to Lake Palmer, where many of the CMM tailings would likely settle out.

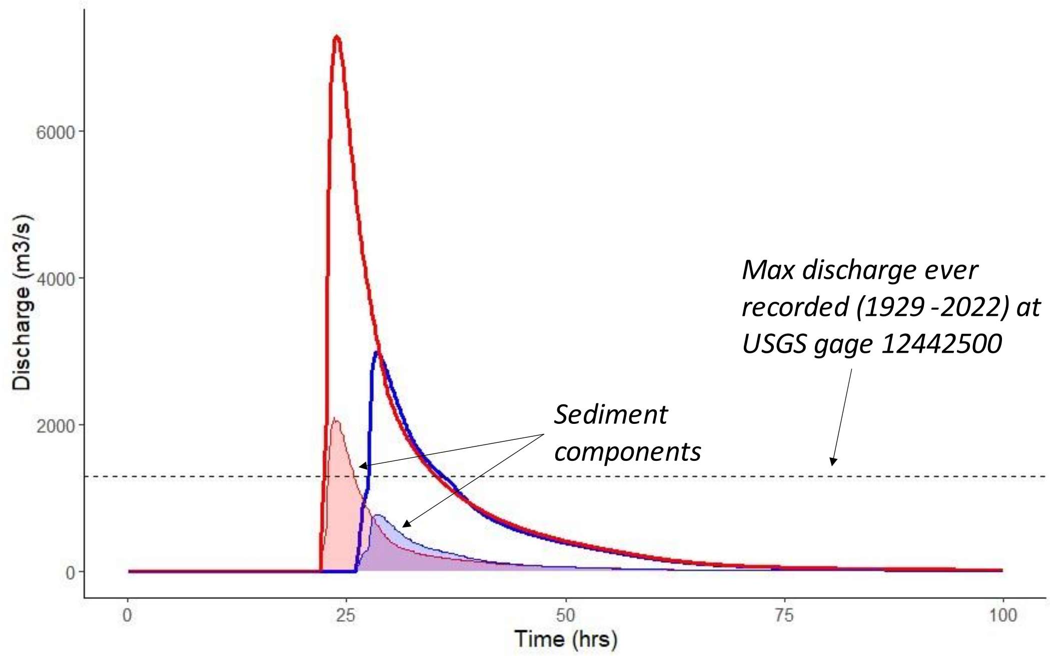

Figure 5-3: A hydrograph at the US-Canada Border showing the debris flow flood wave from a 40% breach of the permitted (blue) and expanded (red) TSF relative to the largest recorded flood at a downstream streamflow gage on the Similkameen River (USGS 12442500). Shaded portions of the hydrograph represent the sediment component of the bulked flow.

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7. Appendix

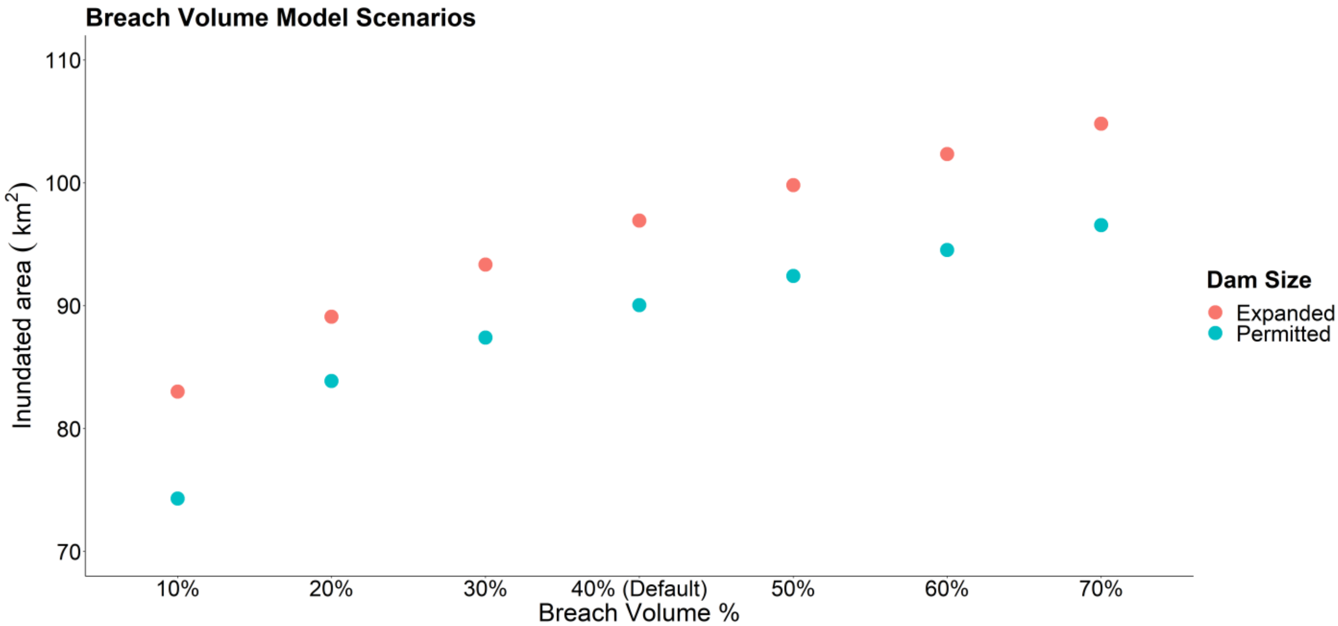
As described in Section 4, the FLO-2D model runs document significant potential for inundation of the Similkameen floodplain, with potentially catastrophic damage for upstream communities like Princeton, BC if a tailings dam breach were to occur. While Section 4 summarizes results under the default model parameters, this section describes in more detail the sensitivity of these results to variation in parameters including the total breach volume, breach duration, tailings sediment concentration, landscape roughness, and other required inputs to the model. Each model output table displayed in the subsequent sections contain the following calculations for each model scenario: bulk inflow (combined sediment and water components of the tailings breached from the dam); floodplain storage (amount of sediment component remaining on the floodplain after completion of model run); outflow volume (amount of bulked tailings leaving the model domain); maximum flow at Princeton (flow in cubic meters per second at the first cross section in the model); time to maximum flow at Princeton (time it takes for the flow to reach its peak at the first cross section in the model); and inundated area (maximum land coverage of tailings in the model domain).

7.1. Sensitivity to breach volume

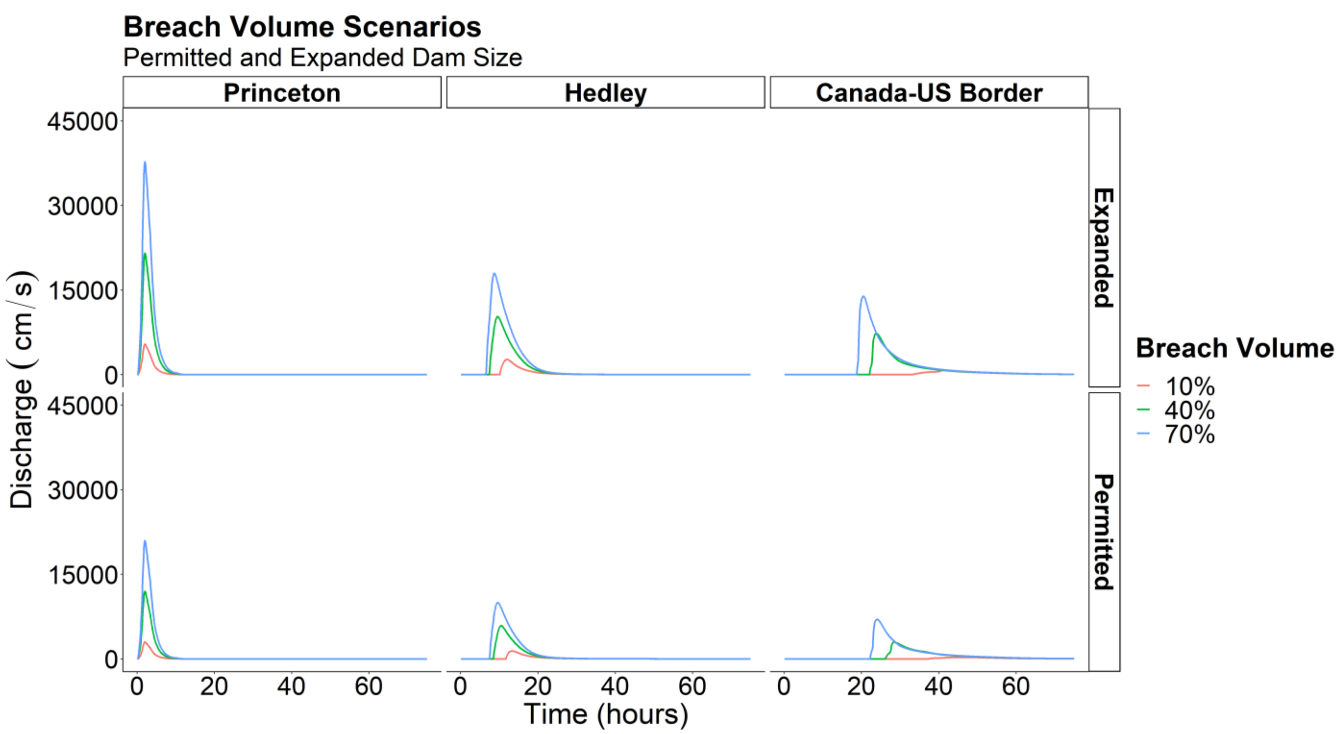
Among the scenarios we evaluated, the volume of the tailings dam breach is the most significant factor in determining the spatial extent of deposited tailings from the bulk TSF. We selected a range of breach volumes – expressed as percentages of total storage volume - to evaluate the range of inundation impacts (Table A 1). A plot depicting the difference in inundated areas for each model scenario is shown in A 2. The percent difference in inundated area between the lowest breach volume percentage (10%) and the highest (70%) is 23% for the permitted TSF, and 21% for the expanded TSF. The increase in inundated area between smaller and larger breach scenarios is accompanied by an increase in both the height and the speed of the flood wave with increasing breach volume. Timeseries plots (hydrographs) displaying the range of discharge volumes for different breach scenarios along three cross sections of the Similkameen are depicted in A 3.

A 1. Breach Volume Sensitivity Analysis – Model Output

Dam Size	Breach Volume %	Bulk Inflow (mil m^3)	Floodplain Storage (mil m^3)	Outflow Vol (mil m^3)	Maximum Flow at Princeton (m^3/s)	Time to max flow at Princeton (hrs)	Inundated Area (km^2) in BC
permitted	10%	31.47	8.84	22.62	3435.53	3.94	74.31
	20%	62.93	6.36	56.57	6391.19	3.64	83.88
	30%	94.4	4.27	90.13	9176.57	3.49	87.4
	40%	125.87	4.8	121.07	11797.3	3.43	90.05
	50%	157.34	4.86	152.48	14522.21	3.35	92.42
	60%	188.8	5.3	183.51	17370.86	3.19	94.53
	70%	220.27	5.67	214.6	20037.26	3.23	96.56
expanded	10%	56.64	7.4	49.24	5832.38	3.67	83.01
	20%	113.28	4.75	108.54	10804.47	3.42	89.1
	30%	169.92	4.91	165.01	15612.68	3.26	93.34
	40%	226.57	5.67	220.89	20713.99	3.27	96.93
	50%	283.21	5.67	277.54	25535.22	3.23	99.82
	60%	339.85	5.79	334.06	30402.93	3.09	102.34
	70%	396.49	6.3	390.18	34963.63	3.1	104.81



A 2. Breach volume model scenarios for both the permitted (blue) and expanded (red) dam sizes. Breach volumes range from 10-70% of storage capacity.



A 3. Timeseries hydrographs of low (10%), middle (40%), and high (70%) breach volumes at three cross sections along the Similkameen for the permitted dam (bottom row) and expanded dam (top row) in cubic meters per second.

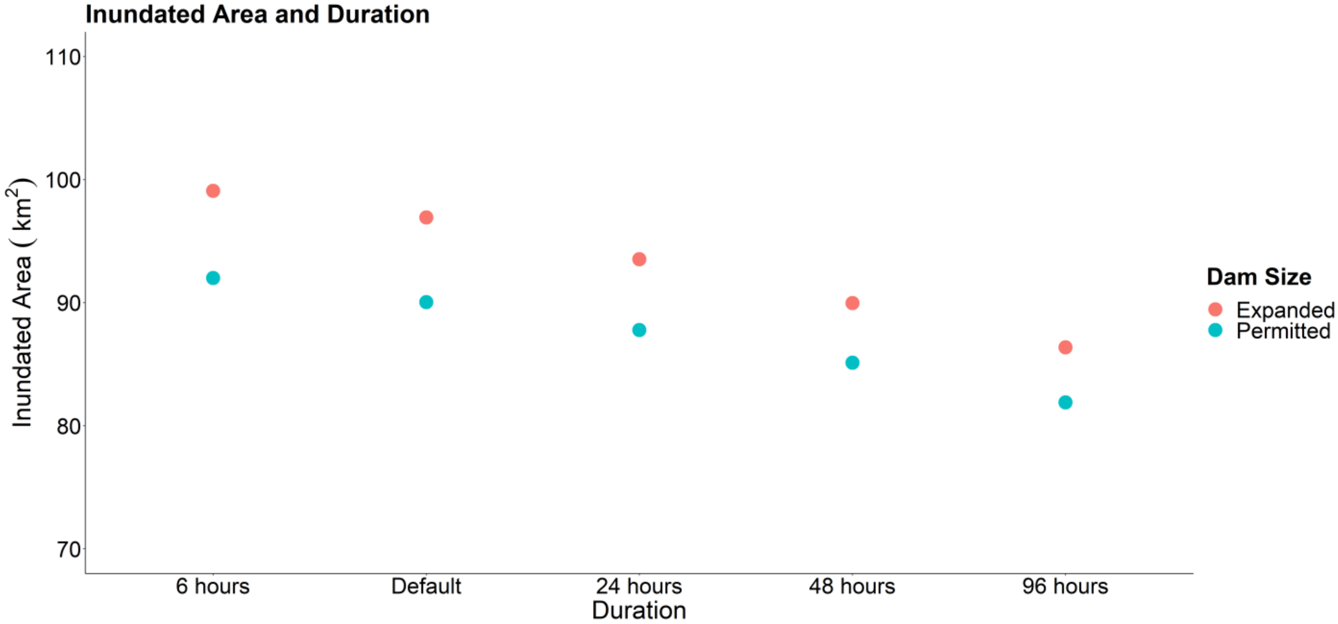
7.2. Sensitivity to breach duration

A literature review of historical breach events yielded limited estimates of breach release duration (length of time from start of failure to end of breach release). The EPA assessment for mining impacts to Bristol Bay (U.S. EPA, 2014) examined a series for breach failure events ranging from 30-minutes to 4-hours in duration. The limited record of breach failure release duration data generally indicates that TSF breach events commonly occur quickly with event durations measured in hours (Wahl, 1998). Given the large scale of the planned Bulk TSF, we examined both short breach scenarios consistent with the observations from Wahl (1998), as well as much longer breaches. For these sensitivity analyses, we developed a series of inflow scenarios using a consistent release volume and altered the discharge hydrograph durations to generate 3-hour, 6-hour, 12-hour, 24-hour, 48-hour and 96-hour events. Results from these simulations provide an overall assessment of the range of impacts that could be expected given the uncertainty surrounding what a possible failure might look like for the bulk TSF.

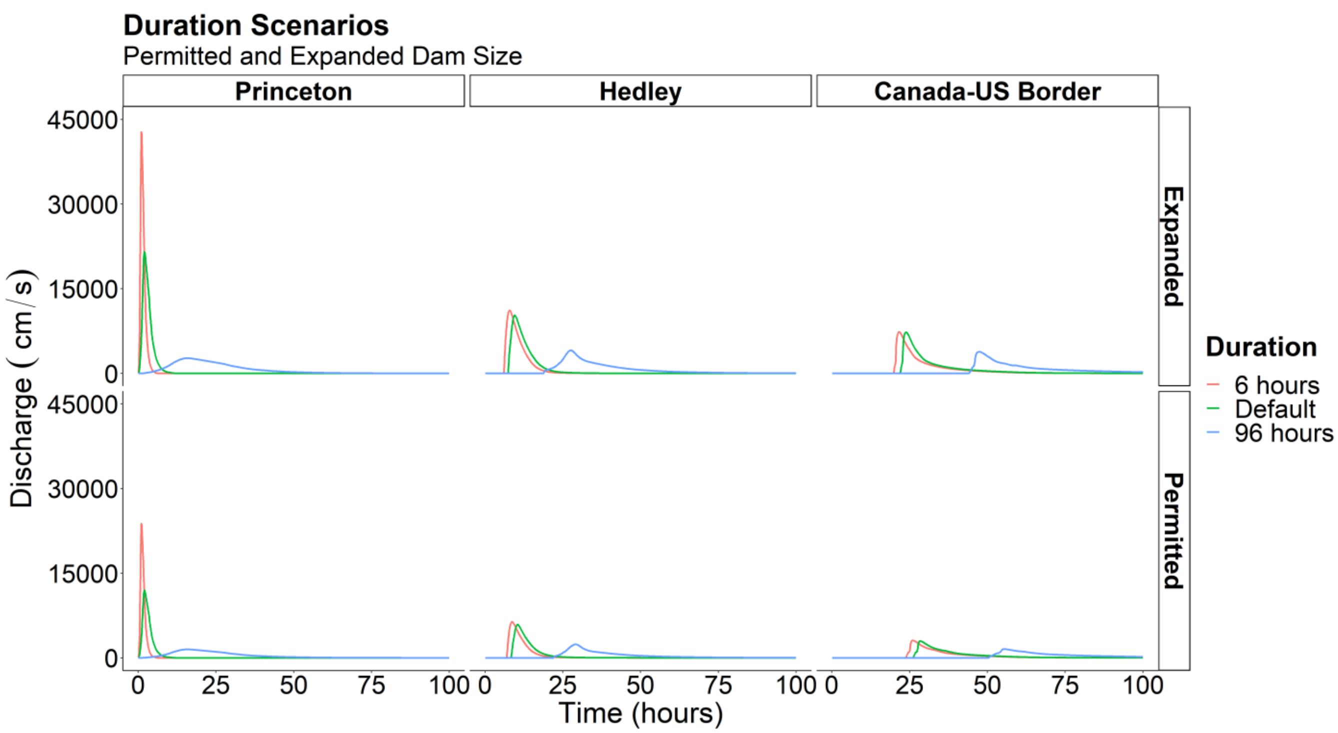
The results of the breach duration scenario analysis show that model outputs are moderately sensitive to breach duration, in terms of the volume of tailings stored on the floodplain and the maximum watershed area inundated by the tailings breach (Table A 4). Our default value that we kept constant during other model sensitivity tests was a 12-hour breach. For the permitted dam, the 12-hour breach scenario stores 4.8 million m^3 on the floodplain with an inundated area of 90 km^2, while the more catastrophic 3-hour breach scenario stores 14 million m^3 on the floodplain with an inundated area of 92 km^2 (A 5). Timeseries depicted at different cross sections along the river show that our default at 12 hours and anything shorter than that reaches Princeton in under 5 hours, while a longer breach duration at 96 hours drastically slows the tailings movement and peak discharge speed (A 6).

A 4. Duration time Sensitivity Analysis – Model Output

Dam Size	Duration (hrs)	Bulk Inflow (mil m^3)	Floodplain Storage (mil m^3)	Outflow Vol (mil m^3)	Maximum Flow at Princeton (m^3/s)	Time to max flow at Princeton (hrs)	Inundated Area (km^2) in BC
permitted	3	125.87	13.79	112.09	25651.76	1.48	92
	6	125.87	4.92	120.95	18527.72	2.24	92.01
	12	125.87	4.8	121.07	11797.3	3.43	90.05
	24	125.87	4.29	121.58	6983.5	5.57	87.78
	48	125.87	4.65	121.22	3751.04	9.73	85.13
	96	125.87	6.12	119.75	1852.76	17.86	81.9
expanded	3	226.57	21.11	205.45	47831.22	1.35	99.32
	6	226.57	5.78	220.79	33063.71	2.01	99.09
	12	226.57	5.67	220.89	20713.99	3.27	96.93
	24	226.56	5.64	220.92	11797.72	5.46	93.54
	48	226.56	4.54	222.03	6288	9.42	89.97
	96	226.56	5.47	221.1	3123.37	17.35	86.37



A 5. Breach duration model scenarios for both the permitted (blue) and expanded (red) dam sizes. Breach durations range from 6 hours to 96 hours.



A 6. Timeseries hydrographs of low (6 hours), middle (12 hours), and high (96 hours) breach durations at three cross sections along the Similkameen for the permitted dam (bottom row) and expanded dam (top row) in cubic meters per second.

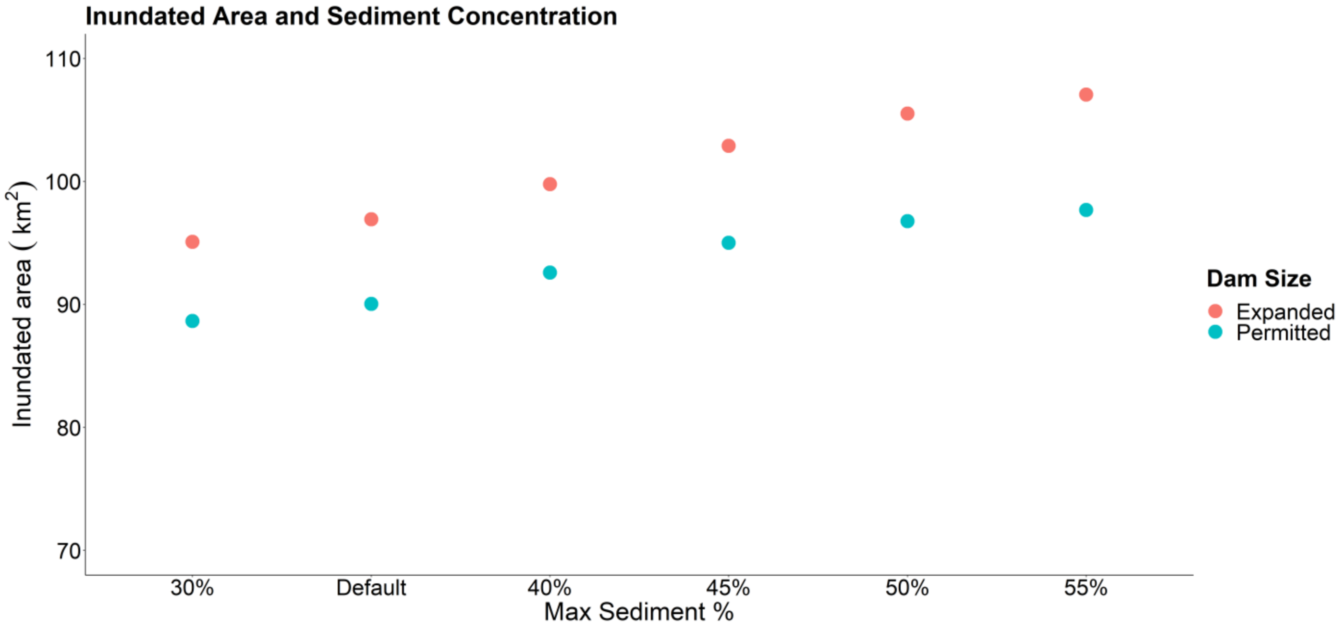
7.3. Sensitivity to maximum sediment concentration

Total inundation area was found to be moderately sensitive to the sediment concentration of the inflow breach hydrograph. A literature review of dam failure mudflow events indicates that the sediment flows resulting from these dam failures are typically characterized by sediment concentration by volume values ranging from 10% to 55% (Julien & Leon S., 2000; Major & Pierson, 1992; J. S. O'Brien et al., 1993; Jim S. O'Brien & Julien, 1988). The FLO-2D Reference Manual and Mudflow Guidelines documentation (FLO-2D, 2017) defines hyper-concentrated sediment flows as flows with average sediment concentrations greater than 20% by volume. Therefore, all simulations implemented breach hydrographs with greater than 20% average sediment concentration to adequately represent a breach from a tailings pond. As described in Section 3.4, the breach hydrograph includes both a water and sediment component over a given time. Just as water discharge changes over time, so does the sediment concentration (see Figure 5-1 for reference). We use the term maximum sediment concentration for clarity, since the breach inflow hydrograph does not have a static sediment concentration over time.

The FLO-2D model results using a maximum sediment concentration of 55% distribute more sediment on the floodplain compared to the 35% results for both dam sizes (for the permitted dam size, 71 million m^3 versus 4 million m^3, respectively) (A 7). However, the inundated areas across all model scenarios do not change substantially (98 km^2 for 55% and 88 km^2 for 35% for the permitted dam) (A 8). The model is sensitive to the maximum sediment concentration, but this sensitivity decreases in importance from upstream to downstream.

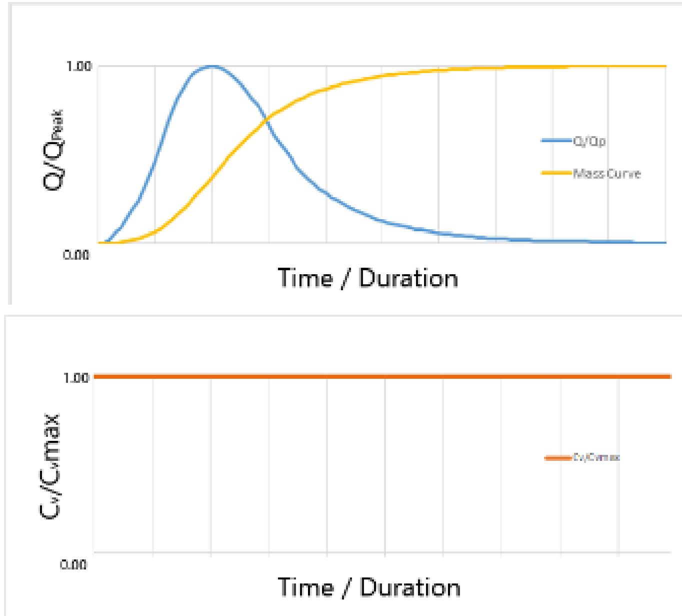
A 7. Maximum Sediment Concentration Sensitivity Analysis – Model Output

Dam Size	Maximum Sediment Concentration %	Bulk Inflow (mil m^3)	Floodplain Storage (mil m^3)	Outflow Vol (mil m^3)	Maximum Flow at Princeton (m^3/s)	Time to max flow at Princeton (hrs)	Inundated Area (km^2) in BC
permitted	30	121.16	4.28	116.88	10296.17	3.43	88.65
	35	125.87	4.8	121.07	11797.3	3.43	90.05
	40	131.08	7.71	123.37	15663.82	3.41	92.59
	45	136.96	18.25	118.71	21304.22	3.64	95.02
	50	143.56	40.97	102.6	29981.56	3.97	96.77
	55	151.11	70.95	80.16	28498.91	4.27	97.68
expanded	30	218.09	5.21	212.89	18314.61	3.31	95.09
	35	226.57	5.67	220.89	20713.99	3.27	96.93
	40	235.94	7.01	228.94	25648.97	3.25	99.78
	45	246.53	13.75	232.78	35607.55	3.5	102.9
	50	258.42	35.57	222.85	47925.88	3.73	105.52
	55	272	73.77	198.23	53881.24	3.96	107.07



A 8. Maximum sediment concentration model scenarios for both the permitted (blue) and expanded (red) dam sizes. Maximum sediment concentrations range from 30-55%.

In addition to analyzing maximum sediment concentration, two different sediment concentration time series scenarios were also evaluated. The sediment concentration model input is defined as the ratio of the total discharge made up of tailings material with water comprising the remaining portion. One scenario simulates a peak maximum sediment concentration that happens shortly after the breach, while the other simulates a constant sediment composition of the tailings throughout the duration of the breach (A 9). These hydrograph shapes were selections made in FLO-2D's "Tailings Dam Failure Volume Estimate Tool" (TDFVET) as scalable unit hydrograph options. Model comparisons results in large differences in floodplain storage volume (i.e. 4.8 million m^3 compared to 86 million m^3 for the permitted dam size) (A 10).



A 9. Alternative hydrograph and sediment concentration composition timeseries evaluated in model scenarios.

A 10. Sediment Concentration Composition Sensitivity Analysis – Model Output

Dam Size	Model Scenarios	Bulk Inflow (mil m^3)	Floodplain Storage (mil m^3)	Outflow Vol (mil m^3)	Maximum Flow at Princeton (m^3/s)	Time to max flow at Princeton (hrs)	Inundated Area (km^2) in BC
permitted	variable through time	125.87	4.8	121.07	11797.3	3.43	90.05
	constant	153.85	86.13	67.72	12275.75	3.68	90.45
expanded	variable through time	226.57	5.67	220.89	20713.99	3.27	96.93
	constant	276.92	89.92	187	22235.6	3.59	98.21

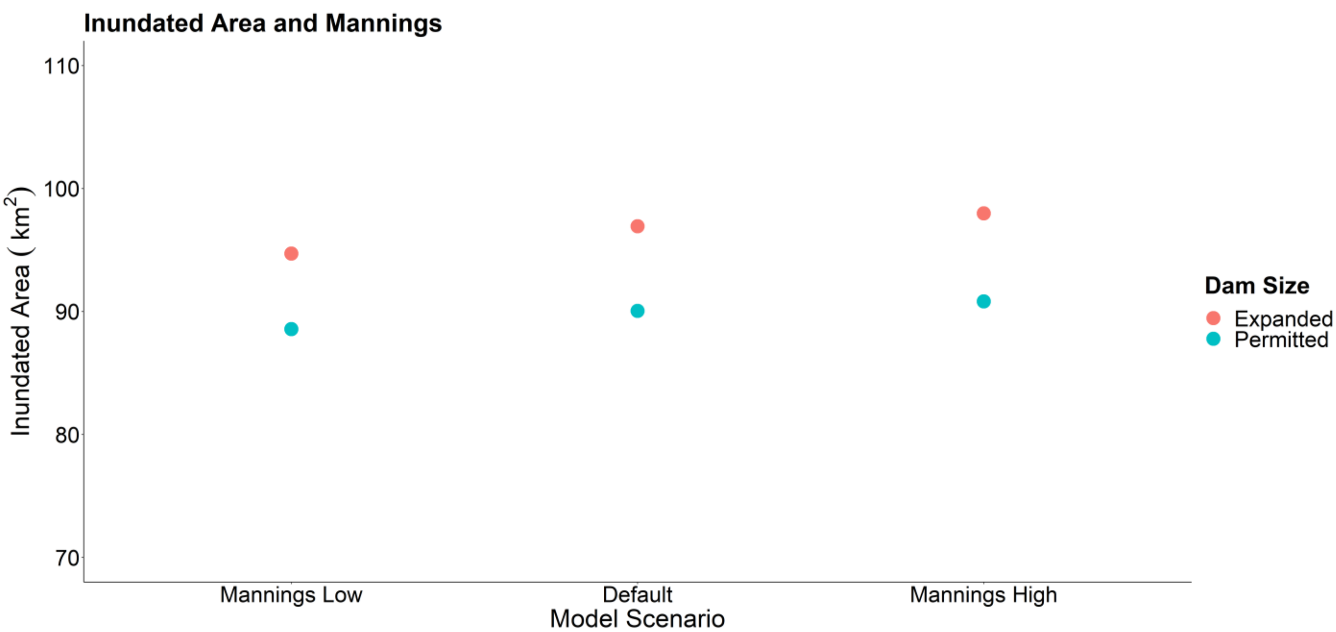
7.4. Sensitivity to surface roughness

Manning's n is a simplified metric that represents how rough a landscape is: a smoother landscape (lower Manning's n; an extreme example would be a concrete channel) will convey flow more easily, whereas a rougher landscape (higher Manning's n; an extreme example would be a mountain stream choked with boulders and logs) will provide more resistance to flow. Typically, Manning's n is derived by observing the features on the landscape and using lookup tables from hydraulics textbooks to assign values. We extracted land use classes from the 2015 North American Land Change Monitoring System (NALCMS) dataset, and we also explored model sensitivity to the choice of Manning's n.

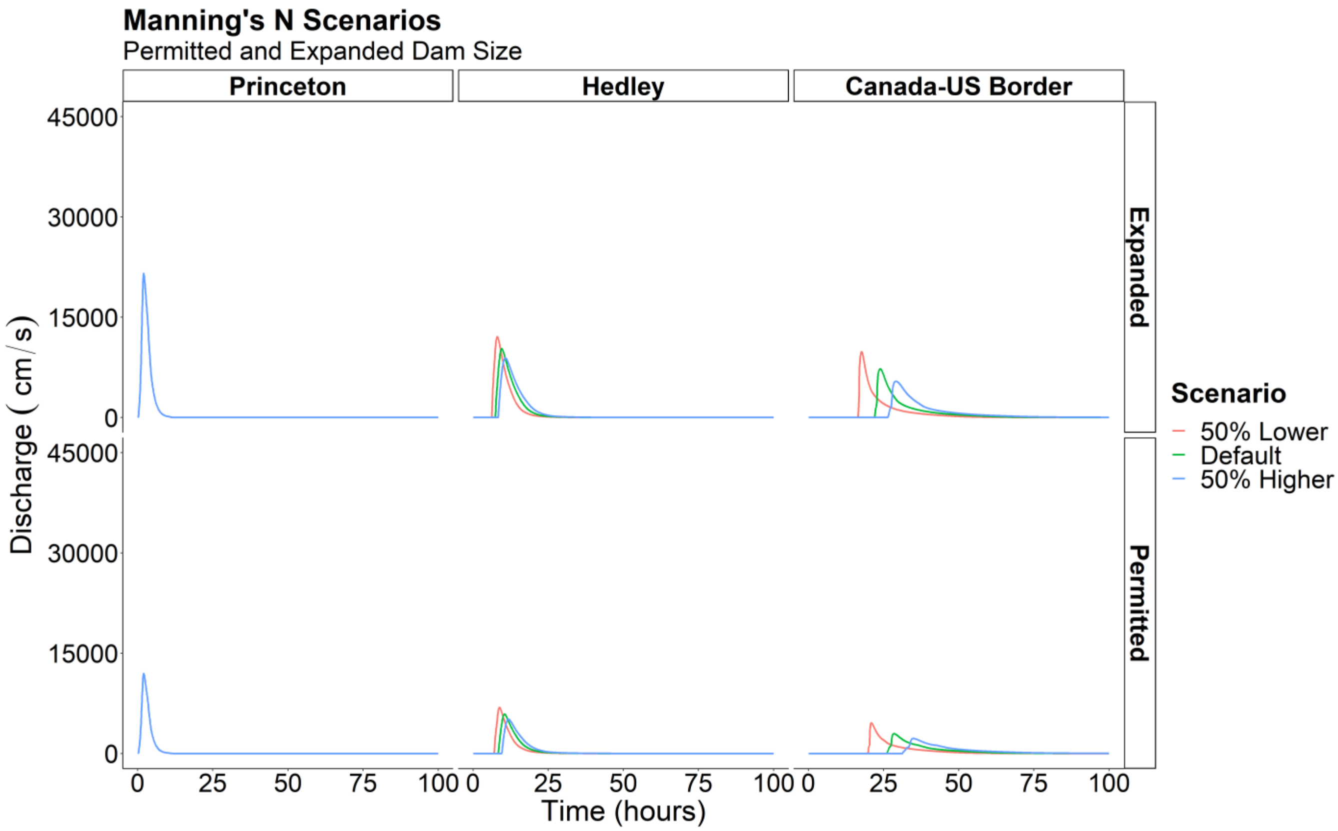
Based on the landscape features in the Similkameen watershed, an appropriate range of Manning's n values is between approximately 0.04 (low roughness assigned to channel flow) and 0.30 (high roughness assigned to denser floodplain vegetation). We developed two model runs that were identical in all respects except Manning's n: in one run, all grid cells were assigned a Manning's n value 50% more than our NLCD default values, and in the second run all grid cells were assigned a Manning's n value of 50% less than our NLCD raster. The changes in Manning's n values affected the timing and magnitude of the tailings flood wave, as well as the floodplain inundation area. With a Manning's n value of 0.04, 82% of the inflow left the model (18% stored on the floodplain) leaving an inundated area of 219 km^2. With a Manning's n value of 0.30, 72% of the inflow left the model (28% stored on the floodplain), leaving a larger inundated area of 262 km^2 (A 11). The difference in inundated areas and flow depths are shown in A 13, while the difference in hydrographs is shown in A 12. The inundated area plot shows the Manning's shows that the scenarios were minimally sensitive.

A 11. Manning's N Sensitivity Analysis – Model Output

Dam Size	Model Scenarios	Bulk Inflow (mil m^3)	Floodplain Storage (mil m^3)	Outflow Vol (mil m^3)	Maximum Flow at Princeton (m^3/s)	Time to max flow at Princeton (hrs)	Inundated Area (km^2) in BC
permitted	50% higher	125.87	5.44	120.43	11235.25	3.69	90.81
	raster values	125.87	4.8	121.07	11797.3	3.43	90.05
	50% lower	125.87	4.19	121.68	11872.45	3.13	88.56
expanded	50% higher	226.57	6.35	220.21	19787.64	3.39	97.97
	raster values	226.57	5.67	220.89	20713.99	3.27	96.93
	50% lower	226.56	5.03	221.54	20674.79	2.96	94.7



A 12. Manning's model scenarios for both the permitted (blue) and expanded (red) dam sizes. Manning's n values range from 50% lower to 50% higher.



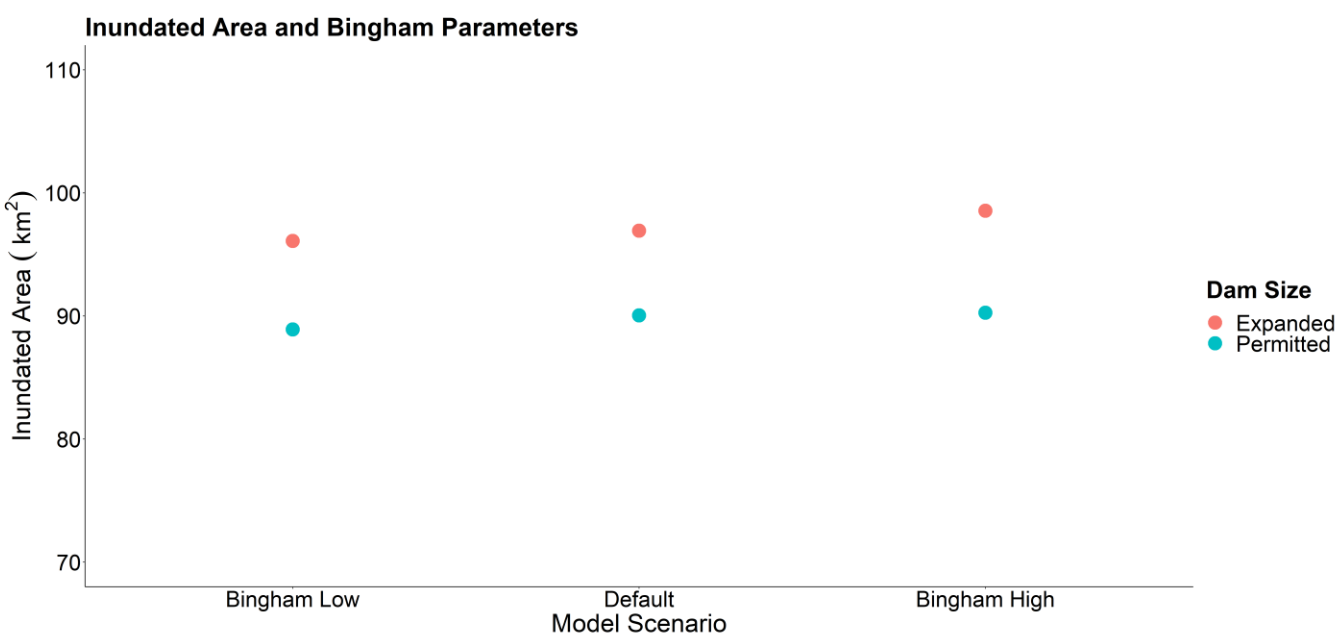
A 13. Timeseries hydrographs of low, middle, and high manning's n vales at three cross sections along the Similkameen for the permitted dam (bottom row) and expanded dam (top row) in cubic meters per second (CMS) Hydrographs are nearly identical at Princeton in both dam size scenarios.

7.5. Bingham parameters

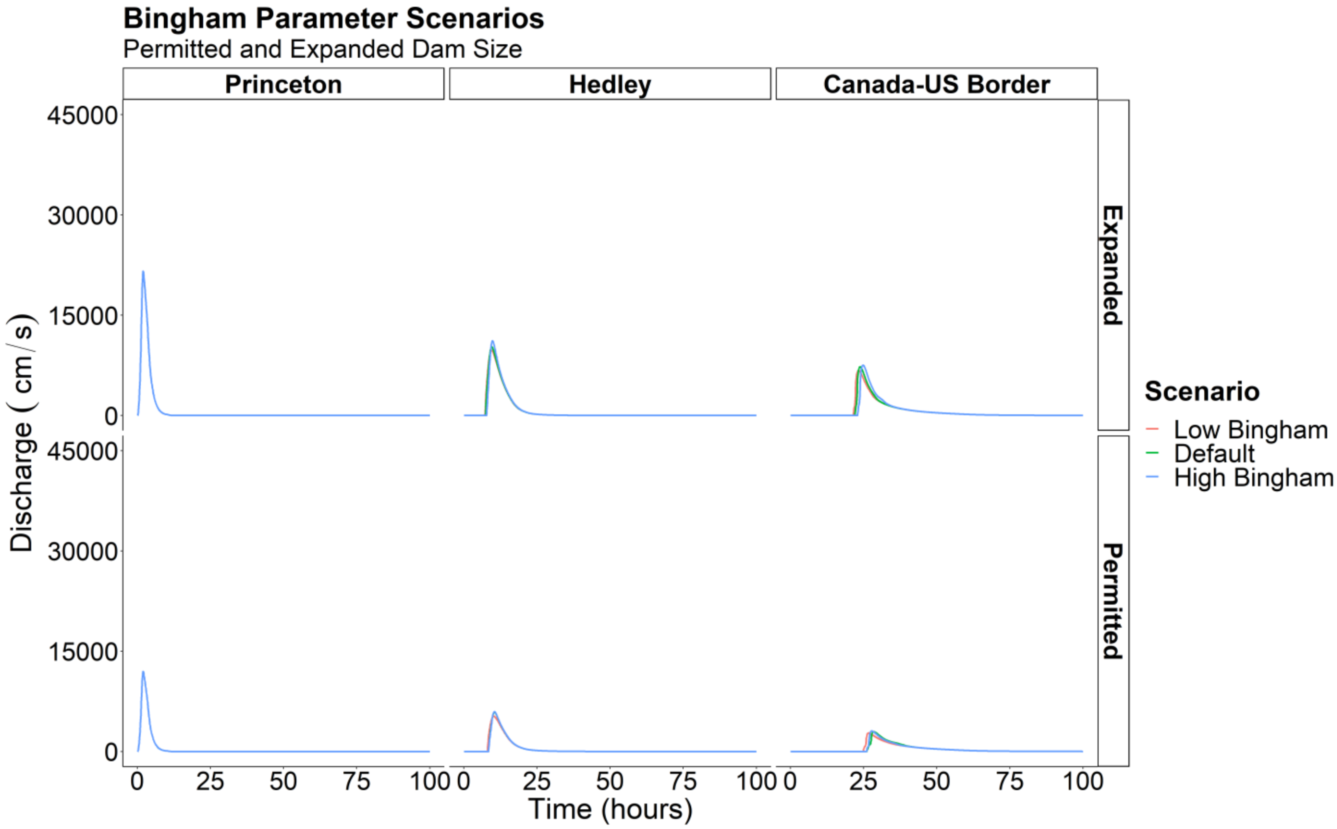
For mudflow simulations in FLO-2D, the tailings are characterized as a non-Newtonian fluid. Fluid motion for these non-Newtonian fluids is controlled both by the fluid stresses that dominate in clear water flows, and by the interactions among fine-grained sediment particles within the fluid. As introduced in Section 3.4, we examined three scenarios with variable mudflow parameters to examine the sensitivity of the model outputs to the yield stress properties of the non-Newtonian flow (A 14). The inundated areas are similar in all three model runs (A 15). The timeseries facet plot also show that the model results have similar flow depths along the Similkameen River (A 16). The FLO-2D model results using the less viscous mudflow parameters results in less volume stored within the floodplain while also producing a slightly larger area of inundation when the higher viscous parameters. Therefore, the model is largely considered to be insensitive to the range of yield stress parameters evaluated.

A 14. Bingham Parameters Sensitivity Analysis – Model Output

Dam Size	Model Scenarios	Bulk Inflow (mil m^3)	Floodplain Storage (mil m^3)	Outflow Vol (mil m^3)	Maximum Flow at Princeton (m^3/s)	Time to max flow at Princeton (hrs)	Inundated Area (km^2) in BC
permitted	High viscosity/yield stress	125.87	4.47	121.39	12240.79	3.38	90.26
	Medium viscosity/yield stress	125.87	4.8	121.07	11797.3	3.43	90.05
	Low viscosity/yield stress	125.87	4.22	121.65	10576.55	3.3	88.91
expanded	High viscosity/yield stress	226.57	6.54	220.03	23088.39	3.3	98.54
	Medium viscosity/yield stress	226.57	5.67	220.89	20713.99	3.27	96.93
	Low viscosity/yield stress	226.56	5.39	221.17	19419.38	3.22	96.09



A 15. Bingham parameter model scenarios for both the permitted (blue) and expanded (red) dam sizes. Bingham parameters range from low (low viscosity and yield stress coefficients) to high (high viscosity and yield stress coefficients).



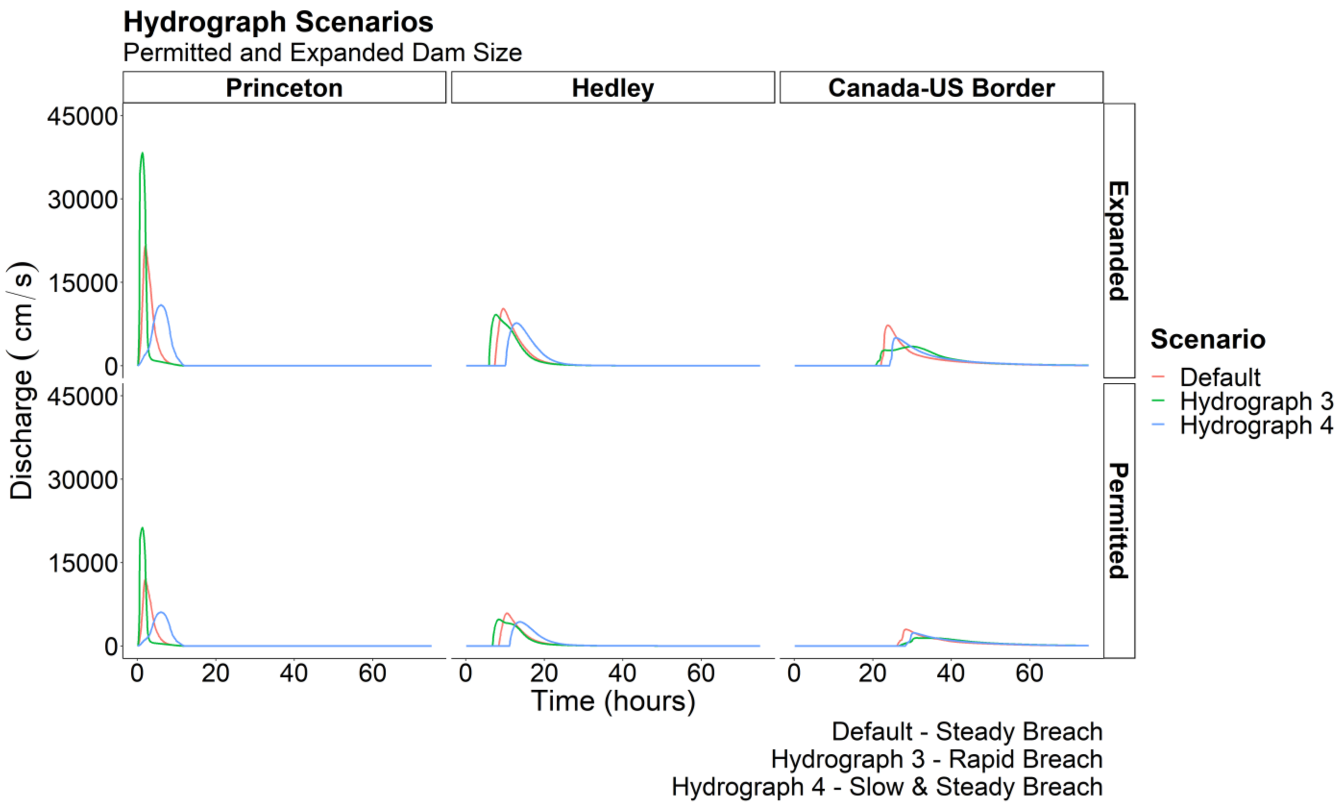
A 16. Timeseries hydrographs of low, middle, and high Bingham parameter values at three cross sections along the Similkameen for the permitted dam (bottom row) and expanded dam (top row) in cubic meters per second.

7.6. Sensitivity to breach hydrograph shapes

We examined three different hydrograph shapes (ranging from flashy or more gradual) that may correspond to possible mechanisms of failure (e.g., a slow overtopping of the dam vs. catastrophic liquefaction of the tailings and dam). These hydrograph shapes were selections made in FLO-2D's "Tailings Dam Failure Volume Estimate Tool" (TDFVET) as scalable unit hydrograph options. Results are displayed in A 17 and A 18. The sharp, flashy scenario produced higher discharge rates and floodplain storage volumes compared to the slower, more gradual hydrograph scenarios. However, inundated areas for all three different hydrograph shape scenarios are largely the same.

A 17. Hydrograph Sensitivity Analysis – Model Output

Dam Size	Model Scenarios	Bulk Inflow (mil m^3)	Floodplain Storage (mil m^3)	Outflow Vol (mil m^3)	Maximum Flow at Princeton (m^3/s)	Time to max flow at Princeton (hrs)	Inundated Area (km^2) in BC
permitted	fast rise	136.88	25.3	111.58	16575.53	2.28	90.7
	medium rise	125.87	4.8	121.07	11797.3	3.43	90.05
	slow rise	115.71	3.58	112.13	5956.78	7.34	86.06
expanded	fast rise	246.38	13.74	232.64	30981.03	2.17	97.84
	medium rise	226.57	5.67	220.89	20713.99	3.27	96.93
	slow rise	208.27	4.55	203.72	10776.24	7.41	91.62



A 18. Timeseries hydrographs of slow rise (blue), and mid rise (red), and fast rise (green) hydrographs at three cross sections along the Similkameen for the permitted dam (bottom row) and expanded dam (top row) in cubic meters per second.

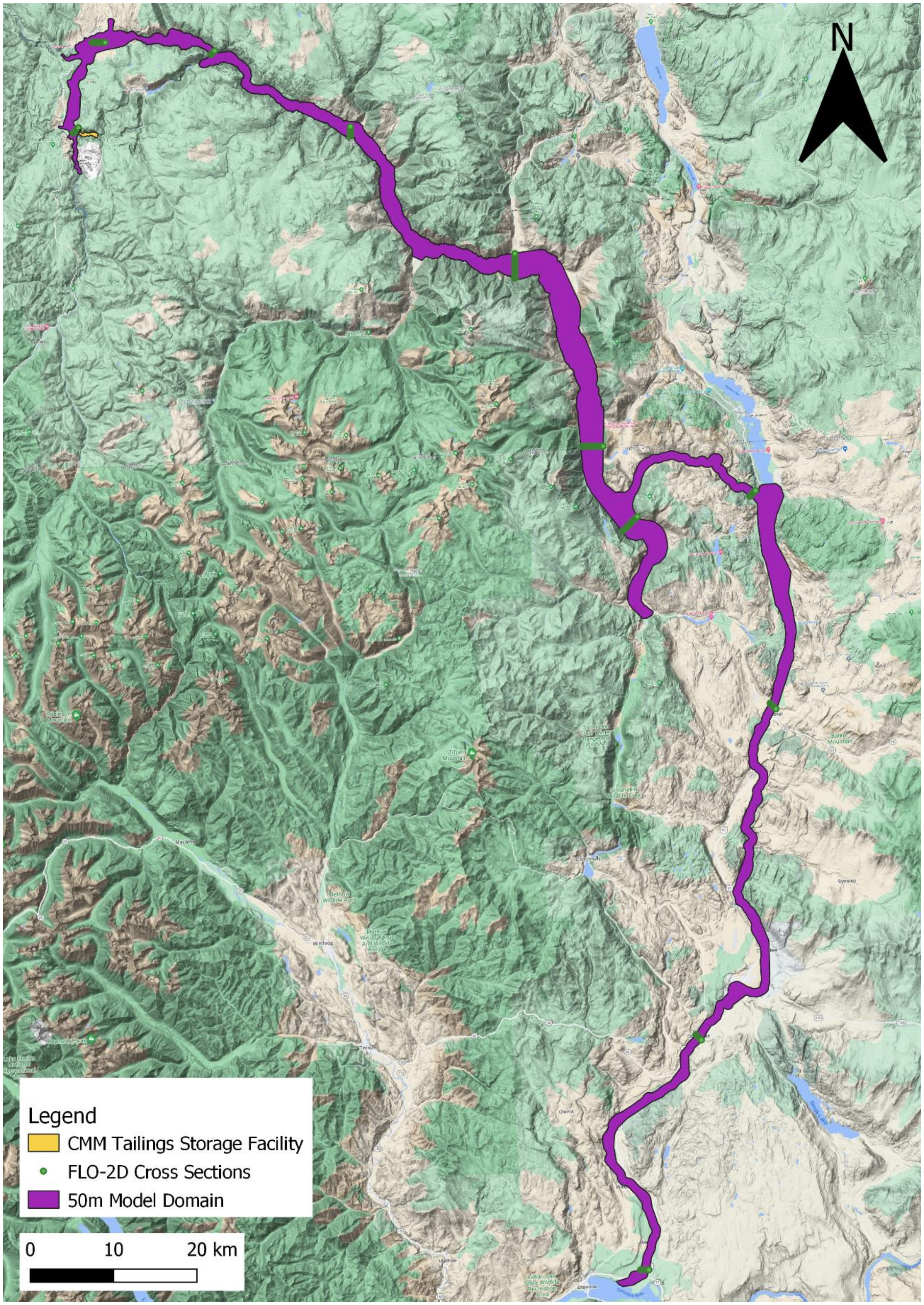
7.7. Sensitivity to breach location

Location of where the breach occurred was examined in the model scenario in order to see whether a breach at the crest of the dam or at the toe of the dam would make a large difference in the floodplain volume storage or inundated area. As seen in A 19, breach location is virtually insensitive to both parameters, with a 0.8% difference in floodplain storage and a 0.1% difference in inundated area between permitted dam size scenarios.

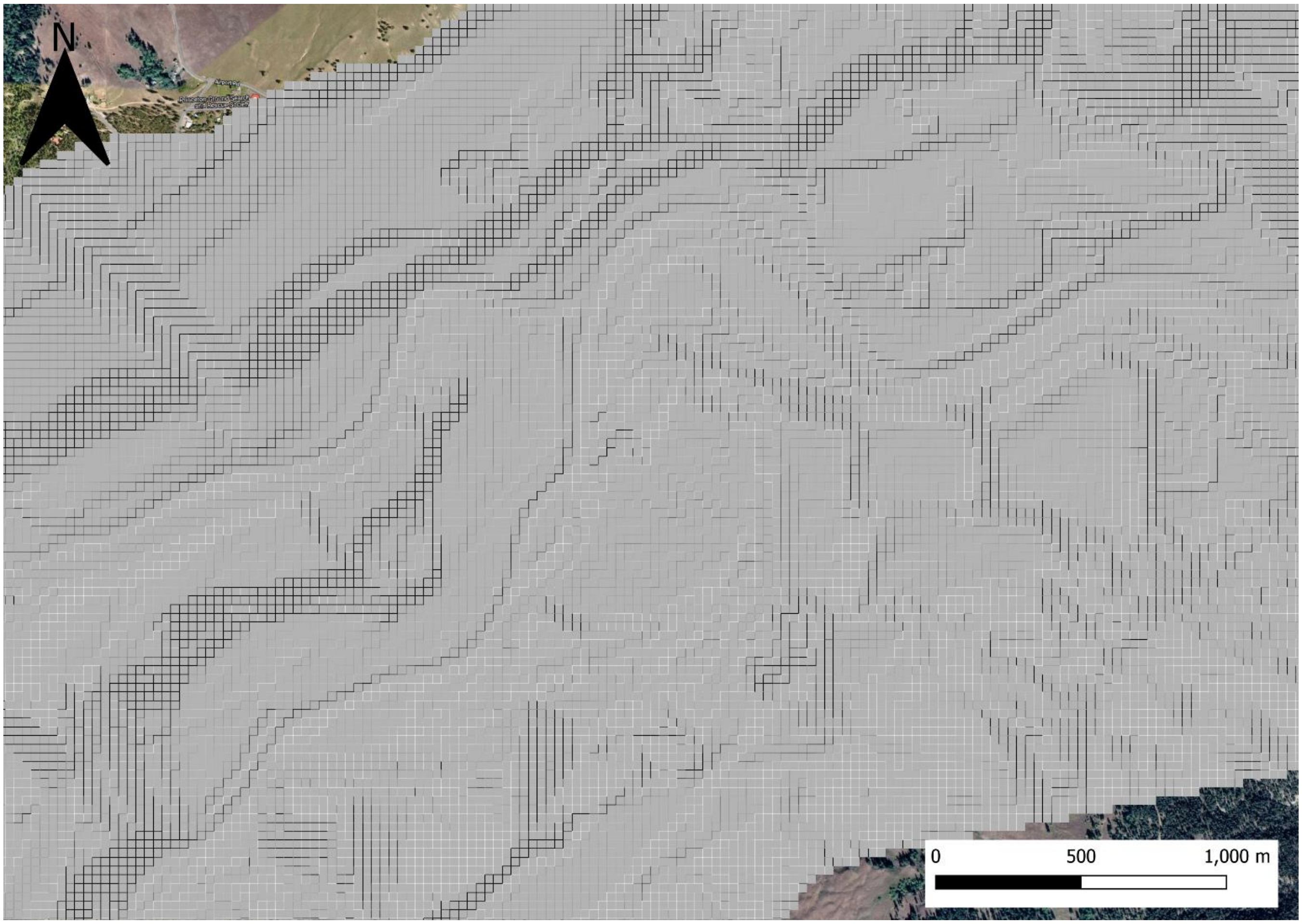
A 19. Breach Location Sensitivity Analysis – Model Output

Dam Size	Model Scenarios	Bulk Inflow (mil m^3)	Floodplain Storage (mil m^3)	Outflow Vol (mil m^3)	Maximum Flow at Princeton (m^3/s)	Time to max flow at Princeton (hrs)	Inundated Area (km^2) in BC
permitted	at crest	125.87	4.84	121.03	11797.3	3.43	90.15
	at toe	125.87	4.8	121.07	11841.69	3.47	90.05
expanded	at crest	226.56	5.41	221.16	20713.99	3.27	96.06
	at toe	226.57	5.67	220.89	19695.84	2.98	96.93

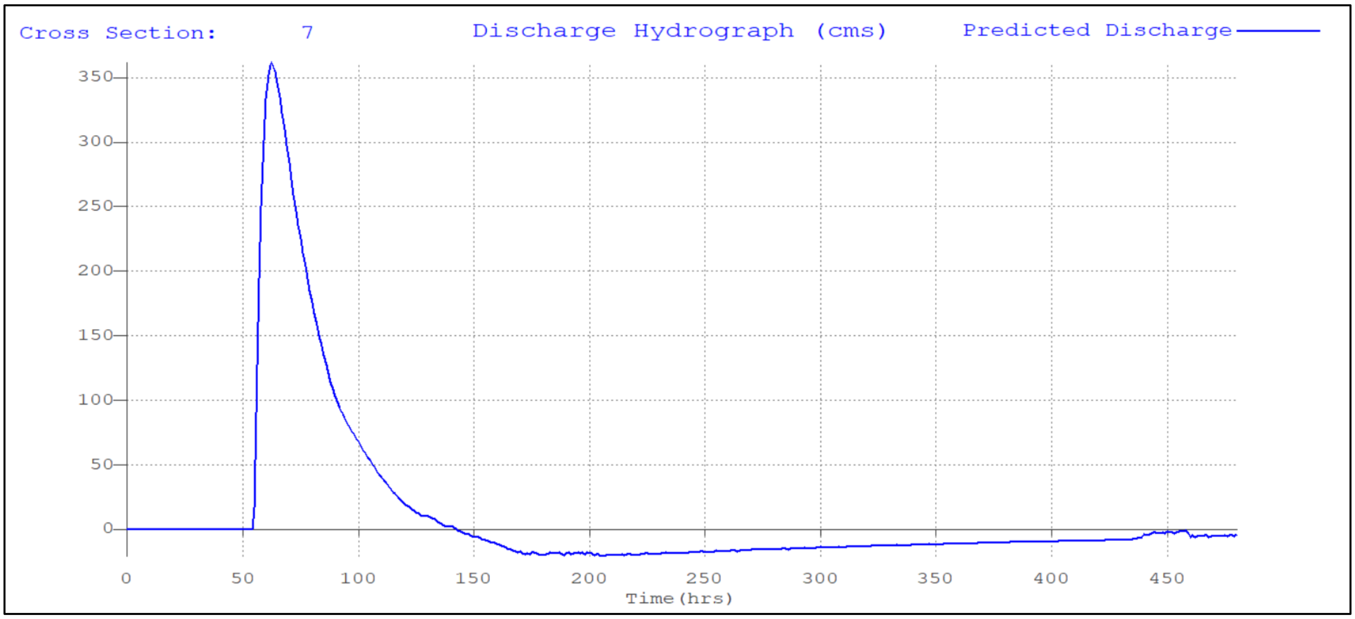
7.8. Additional Figures



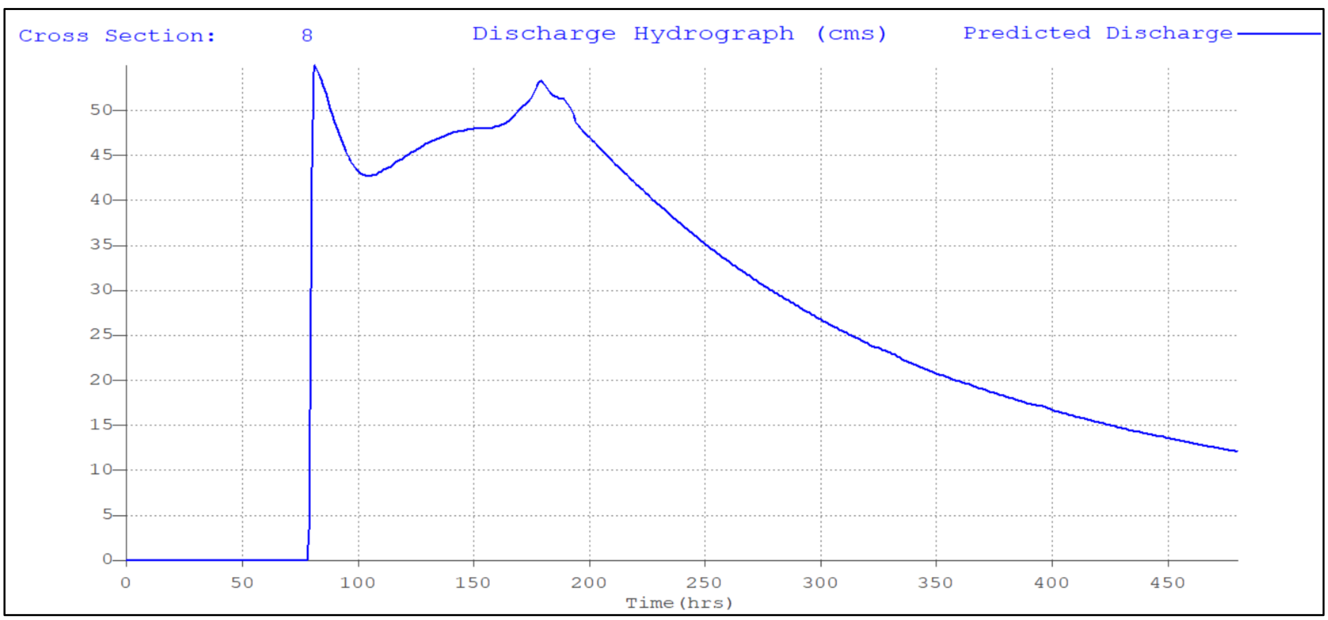
A 20: Overview map of the 50 m model domain, extending from British Columbia, Canada into Washington, United States.



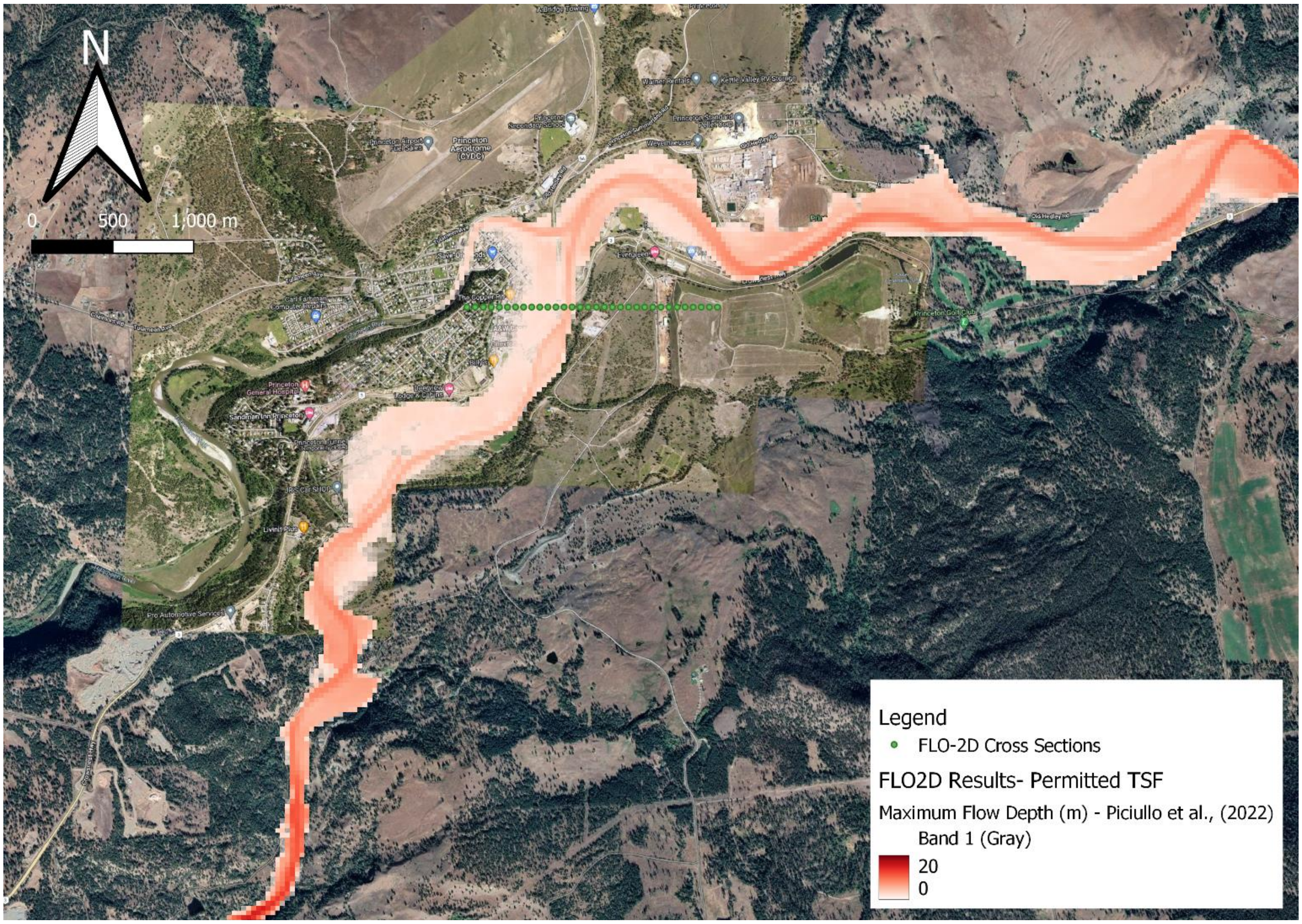
A 21: Hillshade rendering of the 30 m interpolation of the DEM used in the FLO-2D simulations with the 30 m model domain. The raw underlying DEM includes both the 1 m lidar DEM and the 10 m NHDPlus-HR DEM, where needed. An example of the seam between these two datasets can be seen in the NE corner of the hillshade image (NE-SW trending line).



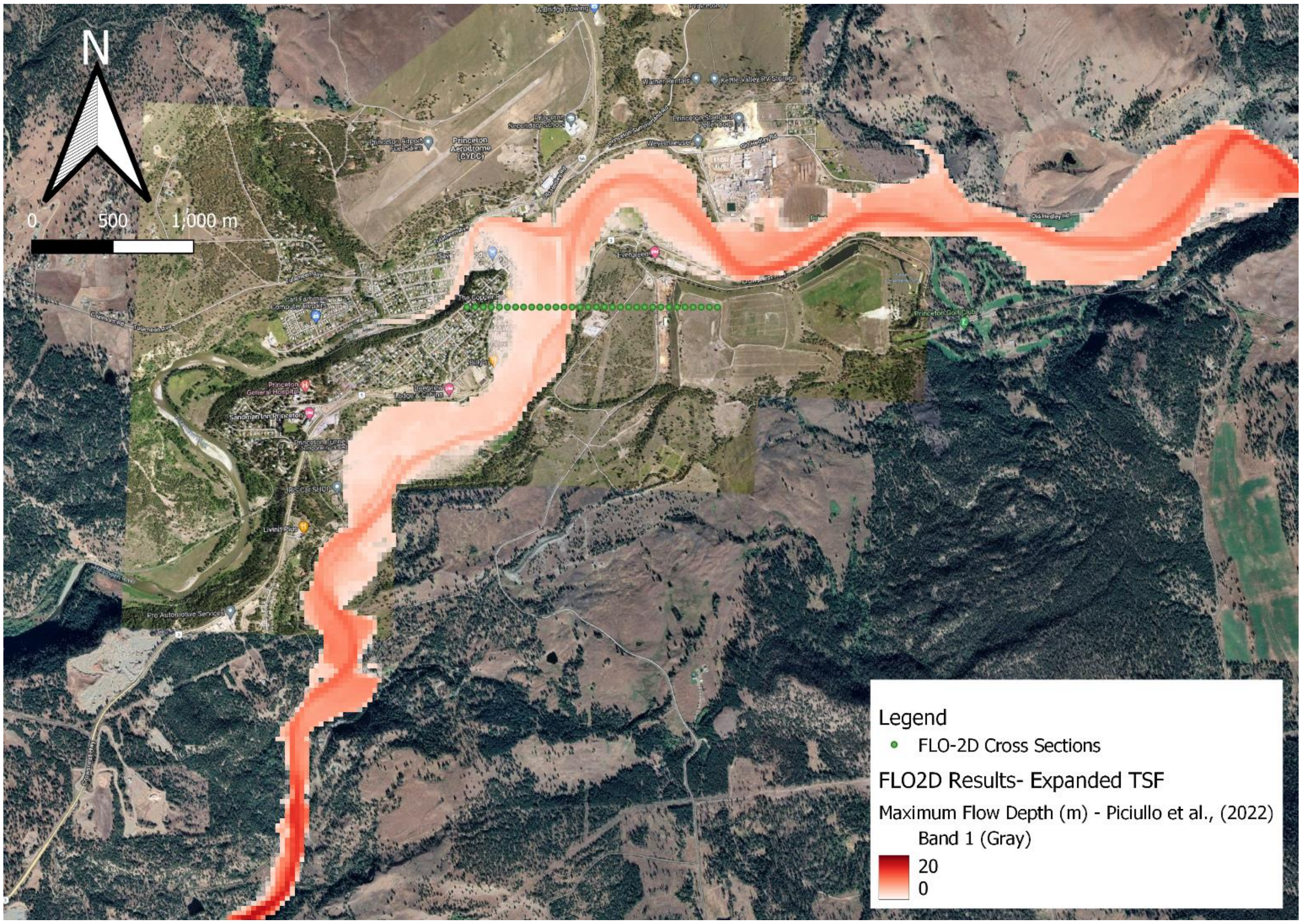
A 22: Hydrograph at the cross-section below Lake Palmer, WA showing the debris flow into the lake around hour 60-70, followed by the outflow of the displaced water back downstream into the Similkameen River, as denoted by the negative flows from hour 150 onward. Default 40% breach scenario for the permitted CMM TSF.



A 23: Hydrograph at the cross-section just about Okanogan, WA showing a double peak flow, where the initial peak represents the leading edge of the debris flow, and the secondary peak represents the Lake Palmer displaced outflow. Units of flow are in cubic-meters per second. Default 40% breach scenario for the permitted CMM TSF.



A 24: Maximum flow depths (m) in Princeton, BC from a 15.0 Mm³ breach, 12 hour duration scenario for the permitted TSF at CMM (250 Mm³), as predicted by Equation 1 in Piciullo et al., (2022). Equation 2, which uses both dam height and storage volume as predictors, is nearly identical to our 20% breach scenario.



A 25: Maximum flow depths (m) in Princeton, BC from a 23.6 Mm³ breach, 12 hour duration scenario for the expanded TSF at CMM (450 Mm³), as predicted by Equation 1 in Piciullo et al., (2022). Equation 2, which uses both dam height and storage volume as predictors, is nearly identical to our 20% breach scenario.