

Modelling the transport of tailings over erodible bed during a tailings dam failure

Uthra Sreekumar

Thesis submitted to the University of Ottawa in partial fulfillment of the requirements for the

Doctorate in Philosophy Civil Engineering

Academic advisors:

Dr. Colin Rennie, Dr. Abdolmajid Mohammadian, Dr. Ioan Nistor



uOttawa

L'Université canadienne
Canada's university

Department of Civil Engineering
Faculty of Engineering
University of Ottawa

© Uthra Sreekumar, Ottawa, Canada, 2024

Abstract

Tailings and muddy slurries are highly concentrated, and the fluidized material can consist of a mixture of water and several solid phases. The bulk flow properties of viscous fluids are very complex and conventional flood routing models are not dependable for predicting tailings dam breach inundation extent as they do not consider the non-Newtonian visco-plastic nature of tailings. Tailings' transport and floods following a tailings dam failure are also not just confined to the hyper-concentrated fluidized material released but there is broader morphodynamic influence. During tailings flow, entrainment of additional solids can cause dramatic surge in sediment supply and significant changes in the morphology of channels. Also, tailings dams (TD) are usually located in valleys that are not easily accessible and hence one global digital elevation model (DEM) is used in most of the TD breach outflow modelling studies but the challenges this impose when calibrating visco-plastic rheological models has not been fully investigated. Implications of using relatively low resolution (18 m) GeoBase DEMs for model calibration is studied by comparing it with a model that is calibrated using a relatively high resolution (2.5 m) merged DEM generated from multiple products. The catastrophic breach of the Mount Polley tailings dam is studied to assess the model performance. The influence of rheological parameters, roughness coefficient and sediment concentration (C_v) on simulated variables is studied. It was concluded that when GeoBase DEM was used for back analysis of the event, a physically meaningful set of rheology values could not be assigned. Flow behaviour was strongly influenced by C_v and least influenced by Manning's values. Runout distance was more sensitive to viscosity than yield stress. Mudflow depth and arrival time increased with increase in viscosity and C_v . In this study, a robust non-Newtonian numerical model that can simulate coupled mudflow and sediment transport processes is also used to model downstream geomorphic changes during a tailings dam failure. Spatial and temporal variation of flow properties like density, viscosity, yield stress, sediment size fractions, and friction are considered in the model. Square mesh is used for modelling single phase tailings flow over fixed bed. Flexible triangular mesh will be adopted for quasi two-phase tailings flow as this helps reduce the computational time significantly compared with structured grid with the same average resolution where additional unnecessary grid points are added for local mesh refinement. High resolution multi-temporal Digital Elevation Models (DEMs) are used for the detection of geomorphic changes and estimation of erosion and deposition volumes. The results indicate that the final distribution of tailings deposits obtained from the model results is in good agreement with that obtained from topographic analysis. The model predicted the total volume of erosion and deposition with almost 93% accuracy. The tailings characteristics followed the full Bingham model during the propagation. Different runout scenarios obtained from the mudflow-morphodynamic model, and a mudflow-fixed bed model are analyzed, and it was concluded that maximum mudflow depth of the flood wave is higher when bed entrainment is considered. Sediment concentration is higher in the wavefront and middle regions and lesser in

the tail zone. The mudflow fixed bed model could underestimate the downstream flood arrival time. The results also confirm that the adopted approach can efficiently model the sediment budget in the study site and the volume of tailings and bed materials released to the downstream lake.

Acknowledgements

I would like to thank my thesis supervisors, Dr. Colin Rennie, Dr. Abdolmajid Mohammadian, Dr. Ioan Nistor, who have provided valuable and continuous support and guidance throughout my PhD studies. Their availability, enthusiasm, and valuable feedback, continued to inspire and motivate me to produce useful, timely and interesting research.

I would like to acknowledge Dr. Ying Zhang and Julie Lovitt of Canada Centre for Remote Sensing, Natural Resources Canada for their valuable comments and guidance during the early stages of this research. I would like to thank Dr. Hossein Kheirkhah Gildeh for helping with the tailings dam breach outflow review paper.

I would like to thank John Gallant (CSIRO Land and Water) for sharing the code used in the blending process of remote sensing data. I would like to thank all the technical staff at the University of Ottawa who have helped me at various stages to solve problems in the installation of software.

It's hard to put into words the appreciation I feel for my family. I would like to thank my dear father Sreekumar T.P. and my mother Renu A. who always motivated me to work hard and chase my dreams. I would like to especially thank my husband Arun Nair for his endless support without whom I could not have accomplished any of this work. Thanks to my brother Dr. Bharath Sreekumar for motivation and care despite being so far away from me.

This work was supported in part by grants from Canada Centre for Mapping and Earth Observation, Natural Resources Canada as well as to the NSERC Discovery Grants of Dr. Colin Rennie, Dr. Abdolmajid Mohammadian and Dr. Ioan Nistor.

Table of Contents

Abstract	ii
Acknowledgements	iv
Table of Contents	v
List of Figures	viii
List of Tables	xi
List of Symbols with SI units	xii
1. Introduction	1
1.1 Historical tailings dam failures	3
1.2 Types of tailings dams	7
1.3 Failure mechanisms	9
1.4 Theoretical Background	10
1.4.1 Tailings characteristics	10
1.4.2 Tailings dam breach analysis	13
1.5 Research needs	16
1.6 Objectives	19
1.7 Novelty	19
1.8. Contributions	20
2. Literature review - Tailings dam breach outflow modelling – a state-of-the-art review .	21
2.1 Abstract	21
2.2 Tailings Dam Breach Modelling	22
2.2.1 Breach Modelling	27
2.3 Tailings Rheological Characterization	32
2.4 Downstream routing analysis	35
2.4.1 Numerical modelling studies	35
2.4.2 Numerical models	37
2.5 Discussion	47
2.5.1 Uncertainties	47
2.6 Application of GIS and remote sensing in tailings dam breach analysis	50
2.6.1 Pre-event and post-event elevation data	51
2.6.2 Estimation of runoff coefficient	51
2.6.3 Spatial Resolution, Pixel Size, and Scale of images	53
2.7 Future Research Directions	54
2.7.1 Breach Parameters for Tailings Dam	55

2.7.2 Physically Based Breach Models	55
2.7.3 Data Base for Tailings Rheology	55
2.7.4 Downstream Routing Models	55
2.7.5 Climate change impacts	56
2.8 Conclusions	56
3. Modelling the transport of tailings after Mount Polley tailings dam failure using multi-source geospatial data	58
3.1 Abstract	58
3.2 Introduction	58
3.3 Methodology	60
3.3.1 Study site	60
3.3.2 Data Sources	61
3.3.3 Model setup	63
3.4 Results	73
3.4.1 Generation of bare earth elevation model	73
3.4.2 Calibration of the model using the merged DEM and GeoBase DEM	76
3.4.3 Model Sensitivity to DEM	82
3.4.4 Model Sensitivity to inflow sediment concentrations	83
3.4.5 Model Sensitivity to rheology parameters	84
3.4.6 Model Sensitivity to Manning's coefficient, n	84
3.5 Discussion	86
3.6 Conclusions	88
4. Numerical modelling of downstream morphological evolution during Mount Polley tailings dam failure	90
4.1 Abstract	90
4.2 Introduction	90
4.3 Methodology	95
4.3.1 Study site	95
4.3.2 Model setup	97
4.3.3 Developing breach hydrographs.	97
4.3.4 Topography and flow resistance	98
4.3.5 Sediment characteristics	98
4.3.6 Governing equations	99
4.3.7 Numerical model setup	104
4.3.8 Analysis of observed difference DEM and flood outlines	110
4.4 Results and discussions	112

4.4.1 Numerical results	112
4.4.2 Comparison of modelled and observed difference DEM.	115
4.4.3 Sediment budget and its sensitivity to model parameters	118
4.4.4 Comparing mudflow over erodible and fixed bed.	120
4.4.5 Event analysis and discussion	122
4.4.6 Limitations	123
4.4.7 Real-life applications	124
4.5 Conclusions	124
5. Conclusions	126
6. Recommendations for future work	128
Appendix A	129
Appendix B	138
Appendix C	144
References	151

List of Figures

Figure 1: Before and after NASA satellite photos of the Mount Polley mine disaster (Duluth Reader 2019)	5
Figure 2: Remediation areas: Mount Polley mine TSF dam failure (Golder Associates Ltd., 2015)	5
Figure 3: Lower Hazeltine Creek following the tailings dam failure showing some of the physical changes like overland flow that occurred (Golder Associates Ltd., 2015).	6
Figure 4 : Types of sequentially raised tailings dam (Vick 1983, 1990)	8
Figure 5: Model of Newtonian Fluids, which have linear stress strain relationship and stress-strain intercept of zero (Liu 2018).	10
Figure 6: Shear stress and shear rate relationships of different fluid models (Liu 2018).	12
Figure 7: Apparent and plastic viscosities of Herschel-Bulkley model (Liu 2018).	12
Figure 8: Graph showing the tailings outflow volume from the tailings dam (VF in $10^6 \times m^3$) vs. the volume of tailings stored at the dam (VT in $10^6 \times m^3$) (Rico et. al 2008).	14
Figure 9: Graph showing the dam height (H in meters) at time of failure, vs. peak discharge ($m^3 s^{-1}$) (Rico et. al 2008).	14
Figure 10: Graph showing tailings dam factor ($H \times VF$; H in meters and VF in $10^6 \times m^3$) vs. run-out distance of tailings (Dmax in km) (Rico et. al 2008).	15
Figure 11: Historical Failure Modes (Sample Size = 85, from Gildeh et al., 2020)	24
Figure 12: Conceptual TDBA Cases (source: CDA, 2021)	25
Figure 13: Stages of Embankment Dam Deformation Due to Liquefaction	26
Figure 14: Breach Outflow Classification Based on Solids Concentration (Source: CDA, 2021)	27
Figure 15: Stage-Storage Curve for Modelled Breach in HEC-RAS 2D	31
Figure 16: Comparison of Newtonian and Non-Newtonian Breach Modules in HEC-RAS 2D	32
Figure 17: Shear Stress vs Shear Rate for Fluid Deformation Models (Source: FLO-2D)	33
Figure 18: Dynamic Viscosity vs Concentration by Volume for Mud Flow of Various Sources as Described in FLO-2D Reference Manual (2023)	34
Figure 19: Yield Stress vs Concentration by Volume for Mud Flow of Various Sources as Described in FLO-2D Reference Manual (2023)	34
Figure 20: Available Software Packages for Application to Tailings Dam Breach and Runout Modelling (Source: CDA, 2021)	46
Figure 21: Flow chart showing different uncertainties in tailings dam breach studies.	50
Figure 22: The flow chart of the risk assessment for tailings pond due to flow contribution from the watershed. (Che et al. 2018)	53
Figure 23: Study site map including the spatial extent of the available pre-event dataset.	61
Figure 24: (a) post-event orthophoto b) Terrestrial map of the affected area.	63
Figure 25: Tailings dam breach outflow hydrograph and breach sediment concentration time series data developed using Tailing's Dam failure Volume Estimate Tool (TDVET).	66
Figure 26: Comparison between hill shade layers from (a1) 2013 digital surface model (DSM) (a2) post-processed digital elevation model (DEM) in 3D; (b1) DSM and (b2) DEM at the steep gorge entrance point to the Lower Hazeltine Creek.	67
Figure 27: (a) 2013 SPOT satellite imagery showing the downstream vegetated area at high risk and (b) the land cover map derived from it.	67
Figure 28: High resolution (2.5 m) digital elevation model (DEM) and GeoBase (18 m) DEM merged using (a) the Mosaic tool (b) using the blending process.	73
Figure 29: Terrain profile graph at a cross section in (a) 2.5m resolution digital elevation model (DEM) and GeoBase DEM b) 2.5m resolution DEM, GeoBase (18 m) DEM and DEM merged using	

open-source tool c) 2.5m resolution DEM, GeoBase (18 m) DEM and DEM merged after treatment of the edge offsets using the blending process.	75
Figure 30: Time evolution of simulated tailings transport after the breach using 2.5 m resolution digital elevation model (Flow depth above initial water level in the case of lakes)	78
Figure 31: Comparison between the Water Survey of Canada data measured at hydrometric station number 08KH011 showing rise in water level on August 4, 2014 (Source: Golder Associates Ltd. 2015) and the simulated water level variation at the hydrometric station using 10m x 10m grid size in the case of high-resolution digital elevation model (DEM) based simulation.	79
Figure 32: Comparison of the simulated flood extent with the observed flood extent map (a) in the case of high-resolution digital elevation model-based simulation (b) in the case of GeoBase (18 m) digital elevation model-based simulation (Flow depth above initial water level in the case of lakes). 80	
Figure 33: Maximum flow depth contours at the time the peak of the hydrograph reaches the confluence of the Hazeltine Creek and the Quesnel Lake (a) when inflow sediment concentration = 0.39 (b) when inflow sediment concentration = 0.21 and (c) when viscosity = 0.176 Pas.	83
Figure 34: (a) Study site map (Google Terrain source: Map data ©2015 Google) (b) Map showing terrestrial affected area after the breach and longitudinal profile and cross-sections used in the analysis (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023).	96
Figure 35: Triangular mesh used to refine the narrow Hazeltine Creek (Black line outlines the post-flood extent of Hazeltine Creek).	105
Figure 36: Tailings dam breach outflow hydrograph and breach volumetric sediment concentration time series data developed using Tailing’s Dam failure Volume Estimate Tool (TDVET).	106
Figure 37: (a) Observation points at which flow depth variation graphs are extracted (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023) (b) flow depth vs time at Observation point 1 (c) Observation point 2.	109
Figure 38: Flow chart showing the steps in modelling.	112
Figure 39: (a) Modelled bed elevation change at the end of 14 hrs (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023) (b) Elevation change distribution computed from measured pre- and post-event Digital Elevation Models (DEMs) (Google Terrain source: Map data ©2015 Google) (c) Error map showing the difference between observed and modelled bed elevation change (Google Terrain source: Map data ©2015 Google).	113
Figure 40: Bed elevation and fluid surface elevation across cross-section A (a) at the end of 1.5 hrs (b) at the end of 14 hrs, (c) Bed elevation and fluid surface elevation at the end of 14 hrs across cross-section B, (d) Bed elevation and fluid surface elevation across cross-section A at the end of 14 hrs in the case of mudflow- fixed bed model (Note: WSE – fluid surface elevation; BED – Final bed elevation; BED-INIT – Initial bed elevation; blue contours – velocity in m/s).	114
Figure 41: (a) Initial bed elevation (b) Modelled and observed bed elevation change (c) Error in model results (Mean error 12.9%) Note: Graphs a, b, and c are plotted along the longitudinal profile shown in Figure 34 (b) and R-A is shown in Figure 34(b) (d) Scatter plot of modelled vs. observed values of bed elevation changes.	116
Figure 42: Mudflow depth and change in bed elevation (a) t = 0.5 hrs and (b) t = 1.5 hrs, with and without considering bed entrainment.	120
Figure 43: Mud density distribution at time t = 1.5hrs after the dam failure (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023).	121
Figure B44: a) raster after filling the sinks b) flow direction raster c) stream network extracted from the flow accumulation raster.	138
Figure B45: Bare earth elevation model	139
Figure B46: Terrain profile plots at a cross section drawn across a) Polley Lake b) Quesnel Lake ...	139

Figure B47: Water level variation at the confluence of the Hazeltine Creek (HC) and the Quesnel Lake (QL) (using grid sizes 10m x 10m and 2.5m x 2.5m) and at the measurement station (using grid sizes 10m x 10m and 7m x 7m).	140
Figure B48: Time evolution of simulated tailings transport after the breach using GeoBase digital elevation model. Note: Flow depth above initial water level in the case of lakes.	141
Figure B49: Time evolution of simulated tailings transport after the breach using GeoBase DEM (when the parameters used to calibrate the high-resolution DEM based simulation are given as model inputs and sensitivity analysis is conducted) Note: Flow depth above initial water level in the case of lakes.	142
Figure B50: Comparison of the observed and the simulated water level variation at the hydrometric station in GeoBase DEM based simulation using 10m x 10m grid size (when the parameters used to calibrate the high-resolution DEM based simulation are given as model inputs).	143
Figure C51: Comparison between the modelled flood extent and terrestrial affected area map when (a) GeoBase DEM of resolution 18m is used (b) DEM of resolution 2.5m is used extracted (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023).	147
Figure C52: (a) The pre-event stream network generated from pre-event DEM (b) post-event stream network generated from the modelled final bed elevation raster (c) the comparison between pre-event and post-event stream networks (World imagery source: Map data © 2023 Esri, Maxar Earthstar geographics and the GIS User community)	148
Figure C53: Flow depth at the end of (a) 0.5 hr (b) 1 hr extracted (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023)	149
Figure C54: Flow depth at the end of (a) 0.5 hr (b) 1 hr (c) 1.5 hr (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023)	150

List of Tables

Table 1: Rheological flow resistance formulations	38
Table 2: Calibrated Manning's n coefficients assigned to different land cover classes for 2.5m resolution model and GeoBase (18 m) DEM based model.	77
Table 3: Statistical measure of the flood extent accuracy for each model.	82
Table 4: Summary of the results from model sensitivity analysis.	85
Table 5: Summary of bed fractions of different sediment classes along the 9 Hazeltine Creek (HC) reaches (R1 to R9). Source: Data from Minnow Environmental Inc (2007).	99
Table 6: Rheological flow resistance formulations.	103
Table 7: Sediment properties	107
Table 8: Summary of key geomorphic results	114
Table 9: Comparison between the volume calculated from observed and modelled difference Digital Elevation Model (DEM).	117
Table 10: Model sensitivity analysis to particle size.	119

List of Symbols with SI units

V_F - total outflow volume in m^3

V_T - total impounded volume m^3

D_{max} - run-out distance travelled in km

H – Dam height in m

$\alpha_1, \beta_1, \alpha_2, \beta_2$ - the empirical coefficients which depend on the material properties and considered as calibration factors.

Q_{max} – Peak discharge in m^3/s

i_s - the source/sink term

h - the flow depth in m

S_f - the friction slope

g - gravitational acceleration in m/s^2

S_o - bed slope

u - the depth averaged velocity in one of the eight flow directions, x in m/s

i, j - the number of flow directions

$t+1$ represents the next time step

Δt - the time step

A_s - surface grid area in m^2

τ_c - cohesive yield stress in Pa

τ_{mc} - Mohr-Coulomb shear in Pa

τ_v - viscous shear stress in Pa

τ_t - turbulent shear stress in Pa

τ_d - dispersive shear stress in Pa

ρ_s density of debris in kg/m^3

ρ_m is density of mixture in kg/m^3

l is the Prandtl mixing length in m

e_n is energy restitution coefficient,

C_v is volumetric sediment concentration

α_1 is averaged impact angle of solid in degrees.

n_{td} is the modified flow resistance

m is an exponent (6.0896)

b is a coefficient (0.0538)

S_{td} is the turbulent-dispersive slope

S_y is the yield stress slope

S_v is the viscous slope

S_{td} is the turbulence slope

γ_m

γ is specific weight of the fluid in N/m^3
 K is a resistance parameter
 μ is viscosity in Pa.s
 ρ is the sediment-water mixture density in kg/m^3
 h is the flow depth in m
 z_b is the bed elevation
 u, v are the components of the depth-averaged flow velocity along x and y coordinates in m/s
 E_p is the depth averaged volumetric concentration of p^{th} sediment size-class, with $p = 1, \dots, N$
 and N the number of sediment size-classes transported
 $\rho_{b,p}$ is the density of solid class p in kg/m^3
 $\tau_{b,x}, \tau_{b,y}$ are bed shear stress components in x and y directions in Pa
 g_ψ is the bed-normal projection of the gravity in m/s^2
 D_p is the deposition flux of p class in m/s
 E_p is the erosion flux of p class in m/s
 P_p is porosity
 α_p is constant = 1
 $\omega_{s,p}$ is settling velocity for class p in m/s
 m_p is hindering effect constant = 4
 $F_{b,p}$ is the fraction of sediment class p in the bed layer
 E_p, E_p^* are the equilibrium sediment concentrations for class p and averaged volumetric concentration of class p
 $|\mathbf{u}|$ is the flow velocity vector in m/s
 E_p^* is the equilibrium solid transport rate by volume per unit time and width for the p^{th} sediment size-class,
 $d_{s,p}$ is the corresponding medium diameter in m
 β_p is the equilibrium formula factor for class p
 n and n_p are the global and size-specific Manning's roughness parameters respectively
 $|\tau_b|$ is the bed shear stress in Pa
 X_p is the relative buoyant density of the p^{th} sediment class in kg/m^3
 τ is the turbulent shear stress of the flow in Pa
 S_f being the friction slope
 $\tau_{c,p}$ is the size-specific critical shear stress for incipient motion of the solid material in Pa .
 τ_μ is the viscous stress in Pa
 τ_y is the yield stress in Pa
 τ_t is the turbulent shear stress in Pa
 τ_d is the dispersive stress in Pa
 τ_f is the Coulomb-type frictional stress in Pa

q is the unit flux m^2/s

θ is the bed slope

θ_b is the friction angle of the solid material in degrees

C_f is the frictional coefficient

ρ_w is the water density in kg/m^3

1. Introduction

Tailings are the byproducts of mining operations after extracting valuable minerals and it can contain fine solids ranging from sand-sized to silt-sized, wastewater, and chemicals. Tailings dams are common mining storage facilities constructed from waste rock to impound these waste solids and water generated in a mine processing plant (Wang et al. 2014). A tailings dam accident can cause detrimental impacts on public safety and environment in the downstream areas (Mao et al. 2017). There has been a recent surge in the number of tailings dam failures, and it can be due to several factors like lack of proper dam management, slope instability, foundation failure, natural hazards, etc. Based on magnitude-frequency statistics, tailings dam breaches with more than 1Mm³ outflow volume took place at an average recurrence interval of 2 to 3 years over the period of 1965–2020 (Rana et al. 2021). Moreover, tailings dams are constructed in sequential lifts i.e., initially there is a starter dam and as it gets filled with tailings, the dam is lifted using the tailings themselves. As a result of this, the failure rate of tailings dams is very much higher compared to other dams and it is extremely challenging for the mining operators to ensure the stability of these dams (Roche et al. 2017).

A tailings dam accident can lead to loss of life, serious irreversible ecological disaster, and property loss (Mao et al. 2017). There can be both immediate and long-term impacts on local biodiversity after the collapse. When tailings enter watercourses downstream, the materials can have physical impacts like increased turbidity and chemical impacts like the release of toxic contaminants, which can harm aquatic organisms. Decreased water quality and oxygen content, and loss of vegetation, aquatic species, and nursery habitats are the immediate impacts. Bioaccumulation of heavy metals can change water chemistry and negatively impact the regenerative capacity of the ecosystem. All these severely impact the services these ecosystems provide to people and can have social implications like floods, reduced fish catches, loss of tourism revenue, reduced carbon capture, and decreased clean water supply (Kossoff et al. 2014). Mining operators and shareholders demand a clear understanding of the potential risks and an assurance that there is proper risk management by adopting mitigation measures, emergency plans, exclusion zones, and flood protection structures (Moon et al. 2019).

For ensuring the safety of downstream environment and human settlements, numerical risk analysis needs to be performed which involves understanding flow characteristics such as

velocity and depth and identifying the possible extent of the downstream impact area. Typically, modelling of the flood wave propagation along the downstream valley is undertaken using hydraulic models (Derdous et al. 2015). Large-scale tailings dam-break and run-out events can be considered numerically as a complex deformation problem, making them challenging and difficult to solve. Even though there are many limitations for numerical modelling, the use of numerical techniques is crucial for having a better understanding of the kinematics of tailings dam breach. Through these flood simulations, flood paths, flood-prone areas, and flood magnitude can be estimated. Understanding these hydraulic characteristics is critical for designing tailings storage facilities and safeguarding the surrounding infrastructure. The delineation of the flood extent assists urban planners and emergency responders in planning for the safe evacuation of the downstream vulnerable population (Llano et al. 2017).

Analysis of remote sensing data using Geographic Information System (GIS) has become a mainstream technology in studying, identifying, and monitoring natural hazards. This technology provides tools by which spatial data can be collected and analyzed for pre-disaster preparedness and post-disaster restoration (Luscombe and Hassan 1993). Earth observation satellite images have large scale scientific applications like environmental monitoring, weather prediction, and archaeological surveys. These images are significant data sources for rebuilding historical records and monitoring the performance of different hydraulic structures like dams (Schumann et al. 2018). Tailings dams are situated mostly in valleys where the land surface is covered by vegetation under different slopes. Remote sensing data can yield vegetation information and slope of the land surface pixel by pixel. Digital elevation models (DEMs) can be used to derive topographic attributes or terrain information in general. Based on DEMs, different landform characteristics such as slope gradient (i.e., the rate of vertical change of a slope compared to the horizontal distance), shadow landform map (map used to visualize landforms hidden in shadows), and slope aspect (measure of slope's orientation in space measured in degrees taken clockwise from North) can be derived (Che et al. 2018). Along with DEM, surface roughness is a critical modelling variable as it represents resistance to flow in channels and floodplains and it can be estimated using landcover maps derived from satellite imageries. Land use types and elevation change, which can be retrieved from remote sensing data, are major factors influencing tailings breach runoff (Johnson 2009).

Using GIS techniques in integration with hydraulic modelling software, potential dam-break flood hazard can be forecasted, and an early warning system could be set up. Visualization of the spatiotemporal variations of dam-break floods, risk assessment of dam-breaks, flood disaster management and land use planning downstream can also be implemented (Derdous et al. 2015). Geometric data can be prepared and directly imported into the hydraulic model. Moreover, the data generated by the hydraulic model can be moved to GIS and inundation maps can be prepared to conduct further analysis. (Pandya and Jitaji 2013). The present study will explore means to optimize dam breach outflow modelling using geospatial data.

1.1 Historical tailings dam failures

Throughout history, several dam failures have caused immense damage to life and property. The wave generated after a dam collapse is different from a river flood as it can get to the valley floor with utmost violence without any warning. A very recent example of dam failure is the collapse of the Edenville Dam in Michigan on 19th May 2020 due to heavy rain. The rising water also breached the Sanford dam located downstream. Satellite imageries were used to understand how the flood wave transformed the landscape. The failure of the Edenville dam emptied the lake it protected upstream and devastated the downstream areas. Flood warnings were given across the state, residents were asked to evacuate, and a state of emergency was declared (Mitchell, 2020). There have also been hundreds of tailings dam disasters in the world from the beginning of the 20th century (Rico et al. 2008). The failure rate of tailings dams in the past 100 years was around 1.2%, which is higher than the accident rate of water retention dams (0.01%) according to the International-Commission-on-Large-Dams (Azam and Li 2010).

An example for the tailings dam failure is the Mount Polley tailings dam disaster that took place on 4th August 2014, in British Columbia, Canada. After the breach of the Mount Polley gold and copper mine tailings pond, mining waste along with water and slurry was transported into Polley Lake. The spill flooded Quesnel Lake and Cariboo River as well. Satellite imageries of Mount Polley mine before and after the breach are shown in Figure 1. Water quality monitoring results showed elevated levels of arsenic, selenium, and zinc. The zinc levels exceeded the exposure limits for aquatic life. Consequently, a part of the salmon

fishery was closed (Mount Polley tailings spill, 2019). The ore from the open-pit copper and gold mine consisted of materials with a mean particle size of 50 μm (Petticrew et al. 2015). The tailings storage facility was composed of three embankments namely the Main Embankment, the South Embankment, and the Perimeter Embankment. The mean heights of the main, perimeter and south embankments before the breach were nearly 55 m, 34 m and 25 m, respectively. The breach occurred in the perimeter embankment releasing about 25 Mm^3 of tailings along with water i.e., about 10.6 Mm^3 supernatant water, 6.5 Mm^3 interstitial water, 7.3 Mm^3 tailings solid, 0.6 Mm^3 construction materials (Mahdi et al. 2019). Surface investigations provided clear proof of shearing, lateral displacement, and rotation of the embankment as the cause of the breach. It was a sunny day failure and there was a freeboard of 2.3m with respect to the core on the day before the breach (Report on Mount Polley tailings storage facility breach, 2015).

Tailings and water released from the tailings pond generated a debris flow which eroded the floodplain and channel of Hazeltine Creek. The area impacted by the debris flow extended from the dam downslope to Hazeltine Creek and to Quesnel Lake as shown in Figure 2. Prior to the dam breach, the Polley Plug area was dominated by wetlands with ponds and interconnecting channels and Hazeltine Creek was about 5 m in width and 0.3 m in depth flowing through a forested valley. The channel bed consisted of cobbles and gravel. The Hazeltine Creek Canyon was the steepest and narrowest section of the creek, and the banks and beds of Hazeltine Creek were generally stable (Golder Associates Ltd., 2015). After the breach, thick tailings deposit blocked the outlet of Polley Lake, and the deposits measured more than 3.5m depth in certain areas near the breach location. In the upper Hazeltine Creek, a steep and quickly eroding region was developed and the slopes adjacent to the creek became unstable. In this area, tailings deposits were thin and spatially heterogeneous. The floodplain was eroded, and tailings materials were deposited to variable depths varying from 0.15 m to 1.5 m within the Lower Hazeltine Creek. The tailings dam breach caused changes to the physical environment around Hazeltine Creek as shown in Figure 3. The impacted zone was about 136 hectares in area and the topsoil was removed to varying depths along the Hazeltine Creek to Quesnel Lake (Golder Associates Ltd., 2015).



July 29, 2014



August 5, 2014

Figure 1: Before and after NASA satellite photos of the Mount Polley mine disaster (Duluth Reader 2019)

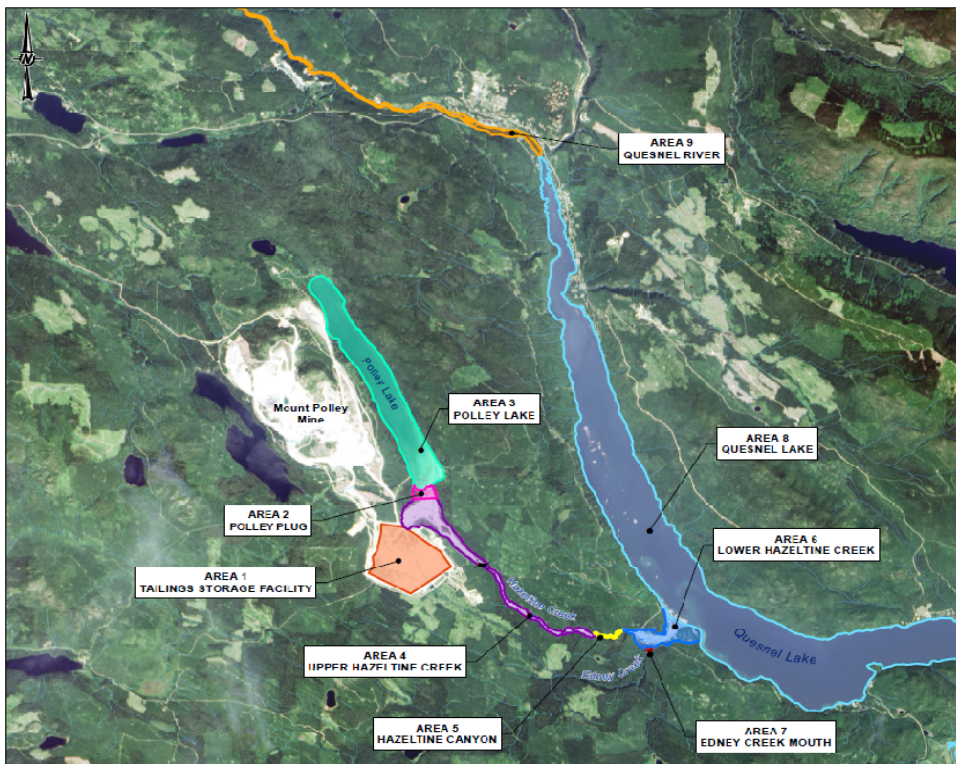


Figure 2: Remediation areas: Mount Polley mine TSF dam failure (Golder Associates Ltd., 2015)



Figure 3: Lower Hazeltine Creek following the tailings dam failure showing some of the physical changes like overland flow that occurred (Golder Associates Ltd., 2015).

There are several other examples of tailings dam failure. The Xiangfen tailings dam in China collapsed in 2008, causing 381 deaths. The Fundao mine tailings dam in Brazil failed in 2015 releasing 32 million cubic meters of tailings. The incident polluted about 650 km of rivers before flowing into Atlantic Ocean and caused serious environmental impacts (Burritt and Christ, 2018). The Brumadinho dam disaster in Brazil and the Siberia gold mine disaster in Russia, both in 2019, respectively killed 232 and 15 people (Yu et al. 2020).

The WISE-Uranium Project (Chronology of major tailings dam failures (wise-uranium.org)) provides information on other historical tailings dam failures. Williamson tailings dam in Tanzania collapsed in November 2022 and resulted in the release of 12.8Mm³ of tailings. The mud wave travelled over 8 km destroying houses and farmland and three injuries have been reported. Jagersfontein dam in South Africa collapsed in September 2022. The mud then entered other dams like Wolwas dam, Prosesspruit dam and a tributary to Rietrivier which flowed into Kalkfontein Dam. The tailings dam located in the Wenquan township, Shanxi Province, China collapsed in March 2022. Part of the factory area was buried, and a large pit was formed in the tailings pond. The released mining waste resulted in the burial of arbor forest land and blockage of several ditches and roads. The tailing dam in the Banjhiberana village of Odisha, India failed in January 2022 and about 20-30 hectares of farmland were submerged, and a security guard was missing. The tailings dam located in the Yedikardes village of Turkey

collapsed in November 2021, and resulted in the release of 4500 tons of lead, zinc and copper tailings. The Catoca tailings dam in Angola collapsed in July 2021, and Lova River downstream of the dam got polluted and rendered the drinking water in the Muatova neighborhood in the City of Lucapa unsafe. The Tielu tailings dam located in China collapsed in March 2020 and resulted in the release of supernatant water and tailings through a drainage tunnel while the embankment remained intact. Nossa Senhora do Livramento tailings dam in Brazil collapsed in 2019 and tailings flowed 1-2km and disrupted a power line. The tailings dam located at Cobriza mine in Peru collapsed in 2019 and tailings travelled to Mantaro River and polluted the water. Cieneguita mine tailings dam in Mexico collapsed in 2018 and tailings travelled 29 km downstream and most of the tailings have been deposited along the course of the Canitas River. The Cadia tailings dam located in Australia collapsed due to the existence of a low-density foundation layer in the vicinity of the slump. Mishor Rotem tailings dam in Israel collapsed and the toxic wastewater surged through the dry Ashdod riverbed and left a wake of ecological destruction which was more than 20km long. Tonglvshan tailings dam in China collapsed in 2017 and the tailings flooded the fishpond downstream of approximately 27 hectares. Two people were reported dead, and one was reported missing. Satellite images for some of the historical tailings dam failures are presented in Appendix A.

1.2 Types of tailings dams

As a result of the recent catastrophic and high-profile tailings dam failures, a review of the design and management of tailings storage facilities is essential. Based on the construction method, there are three types of tailings dams: upstream, downstream, and centerline.

Upstream tailings dams are constructed using tailings themselves by moving the crest further upstream of the starter dam. Even though the usage of tailings reduces costs, upstream tailings dams are less stable in the event of an earthquake or under static loading. This is due to liquefaction and loss of strength of tailings materials.

Downstream tailings dams are designed by progressively raising the embankment further downstream of the starter dam, with an internal drain or filter. These dams need more tailings to build than upstream dams but are found to be more stable under dynamic loading (e.g., in the event of an earthquake).

Centerline tailings dams maintain the original centerline of the starter dam while being progressively raised. They require less material to build than downstream tailings dams and have a zone of compacted tailings which holds up the impervious core. These dams are more stable than other tailings dams under dynamic loading. (McLeod and Bjelkevik 2017). Different types of tailings dams are shown in Figure 4.

However, the recent tailings dam failures in Brazil, Russia, and British Columbia have illustrated that even modern dams designed to latest engineering specifications could collapse. Moreover, the dams in Brazil were designed by applying the less stable “upstream” method and the Mt. Polley dam was constructed using the more stable “modified centerline” method.

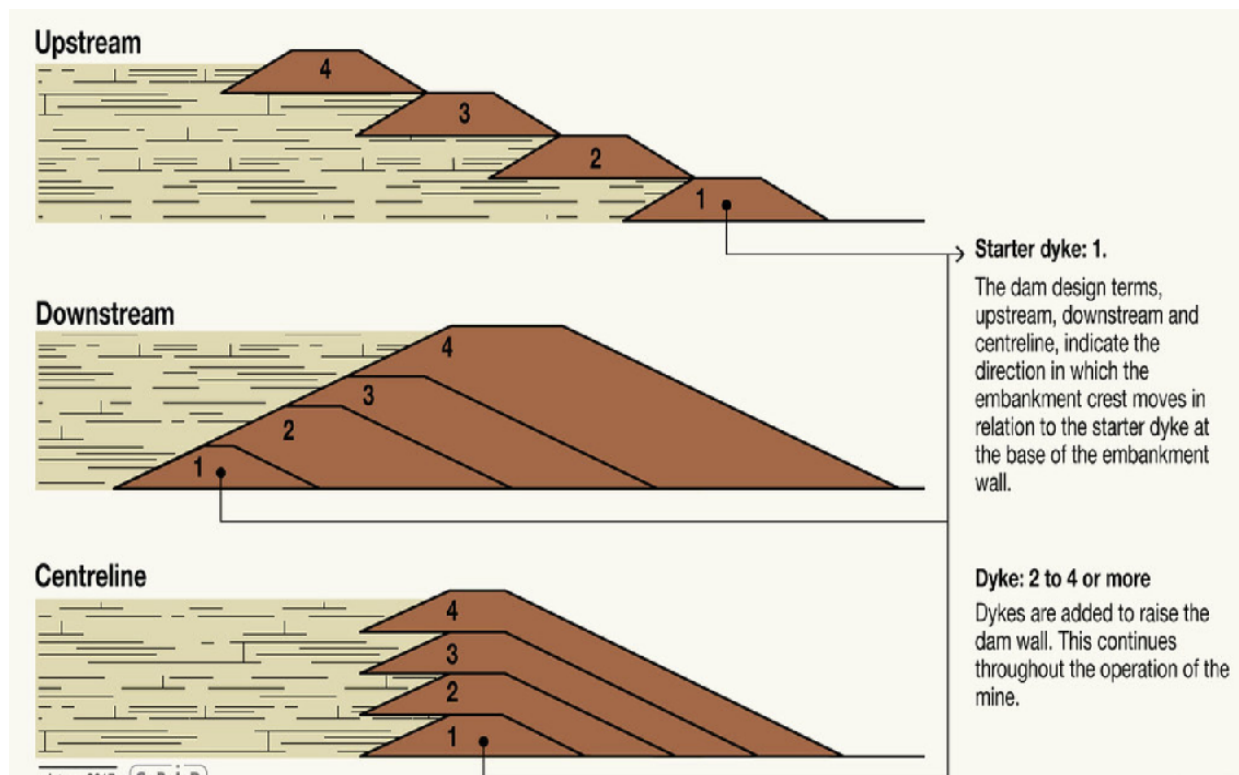


Figure 4 : Types of sequentially raised tailings dam (Vick 1983, 1990)

1.3 Failure mechanisms

Typical failure mechanisms include overtopping, foundation crack, seepage and piping, slope instability, and earthquake-induced failure.

Overtopping – Overtopping happens when the flood passage (spillway) cannot release water quickly enough and water passes over the top of the dam and spills over. Overtopping may occur during heavy rains and floods, and this can erode the embankment in a short time. This is followed by the breach, tailings flow, and collapse. In February 1994, the Merriespruit gold tailings dam in South Africa failed due to heavy rainfall and the subsequent overtopping. A large volume of liquefied slurry spilled over 2km within 5 minutes and resulted in the death of 17 people and damage to properties (Daneshvar and Zsaki 2010).

Foundation failure– If the foundation is not sufficiently strong, sudden loading can cause deformation and this may lead to overall collapse. The Mt. Polley tailings dam collapsed as the foundation was weaker due to its construction on a glacial layer. The surface investigations suggested that breach occurred because of shearing, lateral displacement, and overtopping of the embankment. (Report on Mount Polley tailings storage facility breach, 2015).

Slope instability – The study of slope stability is important in the design and construction of tailings dams and one important factor that causes slope instability is the change in water level due to heavy rain (or snow) events. On December 17, 2012, the Gullbridge mine disaster happened due to the instability of the embankment slope (CDA 2007). Slope failures can also happen if geotechnical properties are not correctly characterized.

Earthquake – In the event of an earthquake, there can be the development of excess pore water pressure, leading to liquefaction and failure. In Chile, seismic loading of a magnitude of about 7 caused liquefaction and failure of two copper tailings dams in 1965. The resulting slurry flow killed more than 200 people. (Liu 2018)

Seepage and Piping – Piping develops when there is internal erosion which can erode the embankment and can lead to local dam failures (Yong et al. 2001). In 1979, a tailings dam in British Columbia failed because of piping in the sand beach of the dam resulting in considerable damage to the property. Embankment failure of a platinum tailings dam occurred in Bafokeng, South Africa on 11th November 1974, because of concentrated seepage and piping through

cracks. Twelve people were killed in a mine shaft inundated by the tailings and tailings were transported 45 km downstream (Blight et al. 1981).

1.4 Theoretical Background

1.4.1 Tailings characteristics

Most of the hydraulic and sediment transport models assume that the fluid has “Newtonian” characteristics. A Newtonian fluid has a linear stress-strain ratio and zero intercept as shown in Figure 5. Sediment laden fluids with lower volumetric sediment concentrations can also be included in this category (Hessel, 2002). However, for sediment-laden fluids with higher volumetric concentrations (i.e., more than 530g/l), this assumption fails. An increase in sediment concentration affects the fluid properties by altering the stress-strain relationship (Pradhan et al. 2018). Rheology is defined as the science of deformation and fluid flow (Boger et al. 2012) and for the tailings flow it is important to consider the rheological properties like shear stress, shear rate, and yield stress.

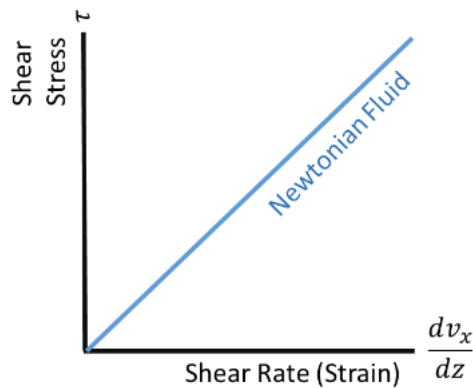


Figure 5: Model of Newtonian Fluids, which have linear stress strain relationship and stress-strain intercept of zero (Liu 2018).

As mentioned earlier, to investigate the relationship between shear stress and shear strain rate, we need to consider two types of fluid behavior, Newtonian and non-Newtonian. In a Newtonian fluid the ratio between shear stress and shear strain rate, called viscosity μ , is constant but in a non-Newtonian fluid, it is not. Non-Newtonian fluids are classified into three types.

- i) Type 1: In these fluids, shear stress varies only with shear strain rate. The shear stress and shear strain rate relationship of Type 1 fluid models are shown in Figure 6. This group of fluids is further classified into three categories:
- Pseudo-plastic fluids or shear-thinning fluids. These are the fluids in which the apparent viscosity decreases with an increase in the shear rate (viscosity at any time is known as apparent viscosity and it changes with shear rate). Common examples of this type of fluids are wall paint and blood.
 - Dilatant fluids or shear-thickening fluids. In these fluids, the apparent viscosity increases with the increase in shear rate. Typical examples of dilatant fluids are corn starch solution and honey.
 - Bingham fluids or visco-plastic fluids. These fluids have a distinguishing feature – yield stress. Yield stress in rheology is defined as the minimum stress required to initiate flow.

Type 1 fluids are best described by the Herschel-Bulkley model (Henriquez and Simms 2009). This is mainly because this model has three features, a yield stress τ_0 , a plastic viscosity $k(\mu p)$, and a power index n . If $n < 1$, the fluid is shear-thinning which falls under Type 1, if $n > 1$, the fluid is shear thickening which falls under Type 2, and if $n = 1$ the fluid becomes a Bingham fluid. The graph showing the shear stress- shear rate relationship of Herschel-Bulkley model is shown in Figure 7. Carbopol solutions and thickened tailings can be simulated by the Herschel-Bulkley model (Labanda et al. 2004).

- ii) Type 2: Time-dependent fluids- In this kind of fluid, the shear stress and shear rate are related. Additionally, the relationship is also influenced by duration of shearing. This time-dependent property is known as thixotropy, and the fluids are referred to as thixotropic fluids.
- iii) Type 3: Visco-elastic fluids- these fluids exhibit both elastic and viscous features when undergoing deformation. They react elastically and possess a recovery phenomenon (Liu 2018).

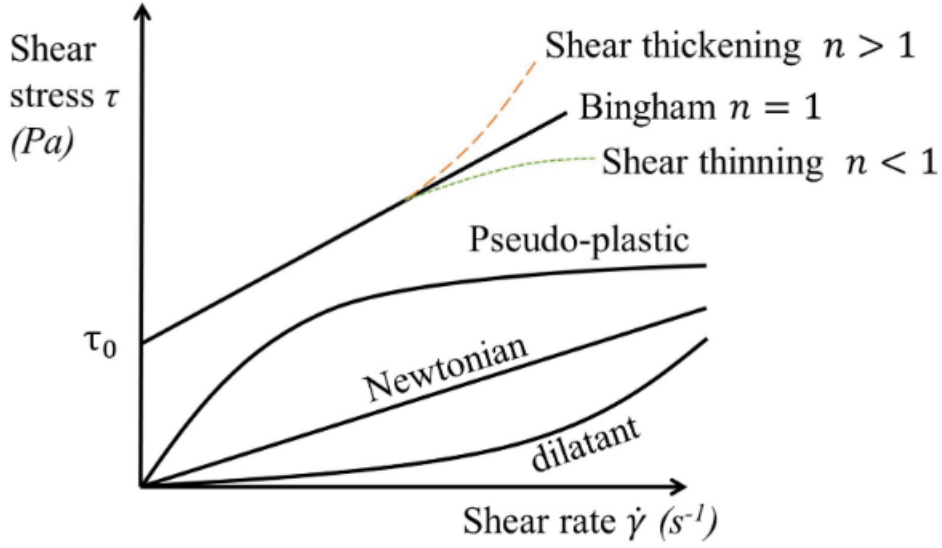


Figure 6: Shear stress and shear rate relationships of different fluid models (Liu 2018).

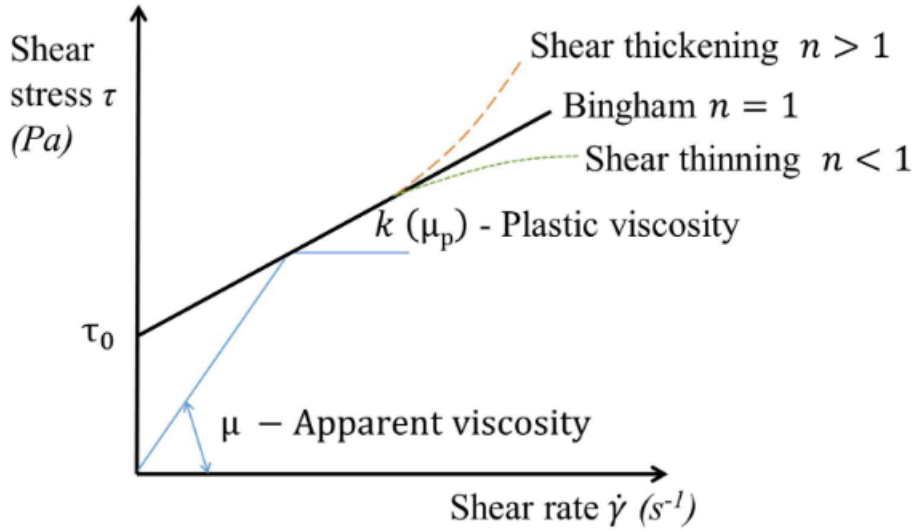


Figure 7: Apparent and plastic viscosities of Herschel-Bulkley model (Liu 2018).

Typically, due to high solids concentration in tailings, these fluids require yield stress or minimum shear stress before flowing as a fluid. Hence, the flow behavior of tailings is different from water (Newtonian fluid) at increased shear rates, and therefore, for estimating inundation areas when conducting a dam break assessment, material rheology must be considered. Laboratory tests may, therefore, be required to derive the key parameters for better

modelling of the non-Newtonian fluid behavior. This could be challenging and hence, published values could also be used as an estimate and the uncertainty can be minimized by conducting sensitivity analysis (Moon et al. 2019).

1.4.2 Tailings dam breach analysis

Breach assessments are crucial in the permitting process of new tailings storage facilities. For conducting a breach assessment, different parameters need to be estimated. These include the total outflow volume of tailings (V_F) and the distance to which the tailings may be transported downstream, which is called the run-out distance (D_{max}) (Larrauri and Lall, 2018). Typically, tailings resist flow and only a portion of the tailings are released as opposed to the total loss of water as in the case of a water dam break. If the breach location is near the supernatant pond, initially a flood wave propagates followed by the liquefied tailings. Consequently, the methods developed to determine the outflow volume and the inundation extent are different for tailings dams than for water storage dams. Because of the lack of a standardized approach to accurately predict the tailings dam breach outflow characteristics, empirical equations developed after studying the past failures, the storage volume of tailings, and dam height can be used to obtain an initial estimate of the outflow volume of tailings and the run-out distance. (Rico et al. 2008; Larrauri and Lall, 2018).

Rico et al. (2008) presented some empirical relationships after studying 28 tailings dam accidents with full information on outflow volume and flood runout distance. According to this, the total outflow volume (V_F) can be calculated using the total impounded volume (V_T) and this relationship is shown in Equation (1) and the run-out distance travelled in km (D_{max}) can be obtained using V_F and the dam's height in meters (H) as given in Equation (2).

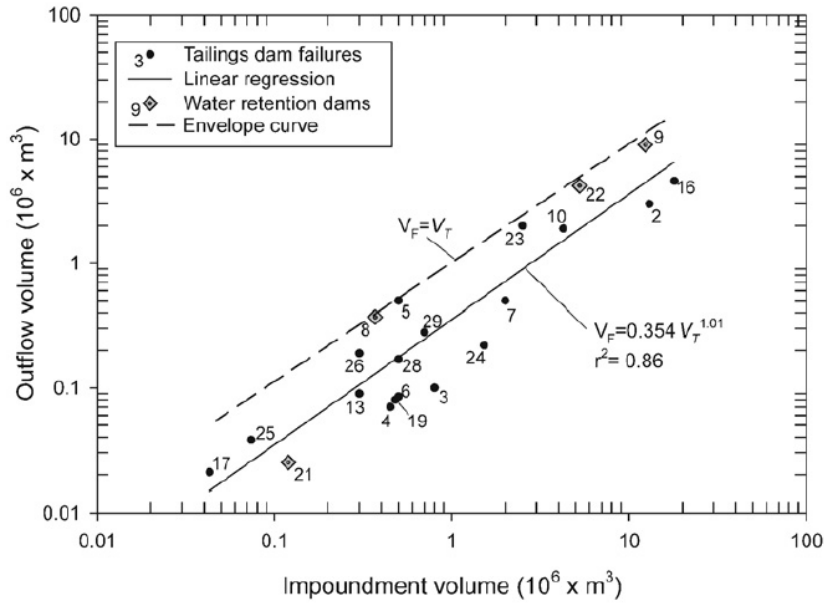


Figure 8: Graph showing the tailings outflow volume from the tailings dam (V_F in $10^6 \times m^3$) vs. the volume of tailings stored at the dam (V_T in $10^6 \times m^3$) (Rico et. al 2008).

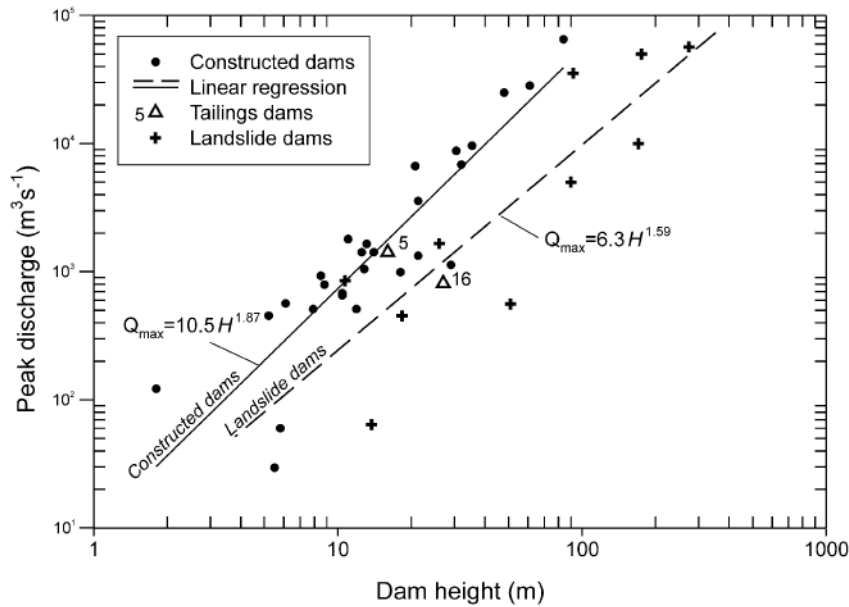


Figure 9: Graph showing the dam height (H in meters) at time of failure, vs. peak discharge ($m^3 s^{-1}$) (Rico et. al 2008).

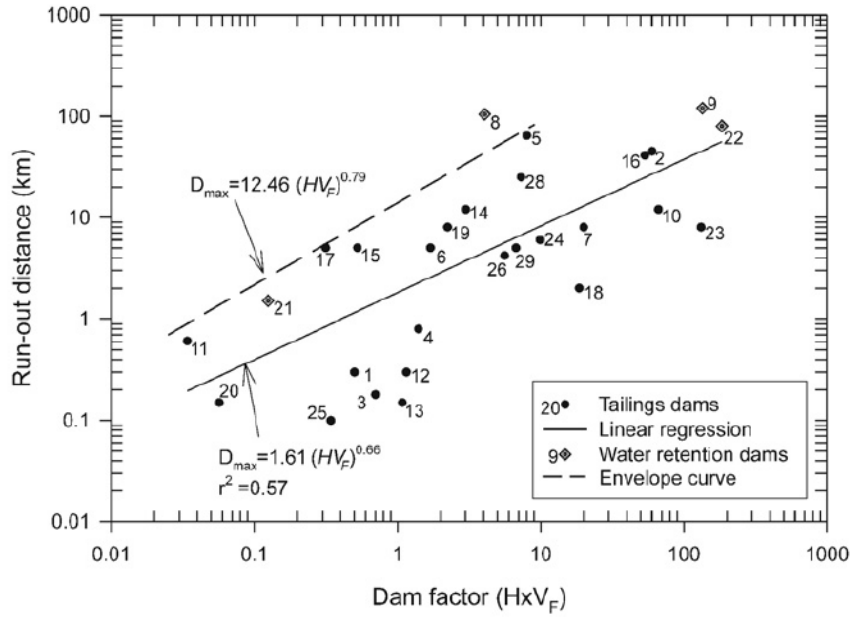


Figure 10: Graph showing tailings dam factor ($H \times VF$; H in meters and VF in $10^6 \times m^3$) vs. run-out distance of tailings (D_{max} in km) (Rico et. al 2008).

$$V_F = 0.354 \times V_T^{1.01} \quad (1)$$

$$D_{max} = 1.61 \times (H \times V_F) \quad (2)$$

Rico et al. (2008) developed another empirical equation to estimate peak discharge (Q_{max}) after the dam breach as given by Equation (3).

$$Q_{max} = 10.5H^{1.87} \quad (3)$$

Graphs showing these empirical relationships are shown in Figures 8, 9, 10. Furthermore, a breach does not develop instantaneously but over a period especially in the case of overtopping (Clemente et al. 2011; Davies 2002). It is difficult to estimate the exact breach development time in each failure scenario. Barker and Schaefer, 2007 conducted a study on dam breach in earth-fill dams and they applied a mean breach development time of two hours based on the Washington State Dam Safety Guidelines. There are several softwares to predict the outflow hydrograph like HR- BREACH, and HydroCAD (Dibike et al. 2018).

The HR-BREACH model is widely used for the prediction of breach initiation and development in either homogenous or composite water reservoir embankments. It incorporates soil mechanics, hydraulics, and structural analysis into a single model (Floodsite 2009). Failure by overtopping and failure by piping are the two failure modes available. The formation of a breach can proceed through head-cut erosion or surface erosion. Modelling is done by dividing the embankment into sections on the basis of a user-defined section spacing and estimating erosion, flow, and stability at these sections. There are no constraints on the erosion at each of these sections and therefore, the breach growth happens due to the influence of hydraulic stresses and not due to any predetermined shape. The flow is calculated by using a simple broad crested weir equation for identifying the likely critical flow section, and an energy balance to determine the flow depths upstream and downstream from that section in a quasi-steady approach. Firstly, an equilibrium or erosion equation is used for calculating the erosion at each section and then side slope stability analysis is used (Samuels et al. 2008). Hydrographs vary depending on the failure modes. For instance, a shorter hydrograph can be observed for earthquake-induced failure modes (Kunkel 2011) and twin hydrograph peaks (hydrographs with two peaks) can be noticed in piping failures. This is because of an initial water and tailings outflow, followed by a second release of liquefied tailings (Liu 2018).

“Tailing’s dam failure volume estimate tool (TDVET)” developed by O’Brien et al. (2015) can be used to estimate the partial breach volume after tailings dam failure and to develop the breach outflow hydrographs. This tool employs empirical correlations of documented tailings dam failures and thus, it reduces failure uncertainty and defines worst-case scenario. The breach volume typically ranges from 10 to 35% of the impounded tailings volume based on historical data. The final product of this tailing dam failure assessment tool is the breach outflow hydrograph and sediment concentration time series graph that will constitute the volume of water and sediment that is to be routed downstream to define the flood extent (FLO- 2D Software Inc. 2019).

1.5 Research needs

The rheological properties of tailings like viscosity (η) and yield stress (τ_y) were neglected in some tailings dam breach studies and, the flood wave was modelled like a water dam-break. This can cause the predicted results to deviate largely from actual tailings breach outflows. In most of the previous studies, the simulation was validated only based on the flood extent seen

in the post-event satellite imageries and depth validation was not conducted. Only the lateral expansion of water was considered and, according to Lim and Brandt (2019b), it will be advantageous to perform water surface elevation analysis in addition to flood extent analysis. If only the flooding extent is analyzed, it may erroneously be concluded that lower resolution DEMs can produce results equal to higher resolution DEMs. Vertical inaccuracies may be present if low resolution DEM is used and thus there can be errors in the depths calculated. It is important to perform depth validation along with flood extent validation to assess the performance of the model.

Since tailings dams are usually located in valleys which are not easily accessible, one global DEM is used in most of the studies but their accuracy and impacts when calibrating visco-plastic rheological models have not been fully investigated. Several assumptions and simplifications may be involved when modelling tailings flow. For example, there can be uncertainties in rheology parameters, inflow sediment concentration, surface roughness along with uncertainties in underlying topography. The sensitivity of these parameters on simulated variables like flood extent, flow depth and flood arrival time is not well-understood.

In flood modelling studies, high resolution terrain models are often used to represent the area of real interest, and low resolution or global digital elevation models are used beyond the focus area. This can lead to the need for blending two different resolution DEMs and for this there are different possibilities in various GIS tools. However, there can be height differences at the merging location due to less accurate details in the coarser DEM, broader scale variations or difference in horizontal or vertical datum. For numerical modelling, the two DEMs need to be joined seamlessly so that there are no abrupt steps at the transition (Gallant 2019). To align both the DEMs horizontally, to avoid sudden changes in slope or height at the merging location and to smoothen the transition, a blending process was developed by Gallant (2019). However, the impact and viability of the blending process for hydrodynamic modelling has not been assessed.

In most of the tailings dam breach studies, the erosion of the downstream terrain along the tailings spill path and transport of eroded materials were neglected. These conservative approaches may impact the volume and concentration of sediments reaching a downstream river or lake. Based on the study conducted by Pudasaini and Krautblatter (2021), erosive

landslide can reduce or enhance mobility and no clear-cut understanding of when and how this occurs has been made. The implications of considering or neglecting downstream floodplain erosion on tailings flow dynamics like velocity, flow depth and arrival time and dam risk assessment are not well-understood. Several granular debris flow modelling studies were reported in the last years to understand the dynamics of landslides and debris flows. In most of these debris flow hazard studies, single-phase models are used, and it is assumed that the solid phase is distributed uniformly over the flow column. The spatial and temporal variation of debris flow density were neglected in the mass and momentum conservation equations. Two phase models were used in some of the debris flow modelling studies but if the difference in phase velocities of the solid and liquid layers are too large, there can be the appearance of complex eigenvalues and loss of hyperbolicity which can make numerical modeling more challenging due to large numerical errors and instability. There are few approaches to avoid the loss of hyperbolicity, but those techniques require computationally expensive iterative algorithms.

The entrainment of different sediment classes into the multi grain mixture was not considered separately in most of the studies. This is a major limitation of these studies since sediment particles of different particle size and properties can be present on the landscape and each solid phase has its own entrainment and settling properties and it is important to include them while modelling. Furthermore, these studies focused on debris flow modelling and have not yet been applied to conduct simulation of tailings dam failures and to model morphological evolution of channels. Also, large-scale unsteady flows like tailings dam breach outflow often occur along steep terrain and require a highly refined mesh to capture the irregular terrain characteristics. Most of the mud/ debris flow models use structured meshes and this can increase the computational time due to the increased number of grid points needed for local mesh refinement and can be problematic during real-time flood forecasting. Sediment budgets allow to estimate volume rate of sediment entering and leaving a defined region and this helps to determine if there is overall surplus or deficit of material. No modelling studies to date have conducted sediment budget studies following a real tailings dam failure and predicted the magnitude of geomorphic response.

1.6 Objectives

The main objectives of this study are:

- 1) To analyse the implications of using high resolution (2.5 m) DEM generated from multiple sources and open-source GeoBase DEM for the tailings dam breach outflow modelling and flood extent validation.
- 2) To conduct an objective sensitivity analysis to understand the influence of different input parameters on output variables like flood extent, mudflow depth and flood arrival time.
- 3) To model downstream geomorphic changes during a tailings dam failure using a non-Newtonian numerical model that can simulate coupled mudflow and sediment transport processes.
- 4) To compare variable properties mudflow-morphodynamic model with a constant properties' mudflow-fixed bed model
- 5) To evaluate the magnitude of downstream geomorphic response by conducting a sediment budget study. The catastrophic breach of the Mount Polley tailings dam will be studied to assess the model performance and to examine the dynamic characteristics of the tailings from initiation to deposition.

1.7 Novelty

- The implications of using global DEMs for the calibration of a model are studied by comparing it with a model that is calibrated using a merged DEM generated from multiple sources like Unmanned Aerial Vehicles (UAV) photogrammetry data.
- The viability of open-source tools such as Raster Mosaic tool in ArcGIS Pro software (ESRI 2020) and a blending process developed by Gallant (2019) for merging elevation data from multiple sources are evaluated and compared.
- Flow depth validation along with flood extent validation was performed for comprehensive understanding of the model performance. A comprehensive sensitivity analysis will be performed and the influence of other input parameters like rheological parameters, Manning's n values and inflow sediment concentration on simulated variables flood extent, flow depth and flood arrival time will be also investigated. A

two-dimensional quasi-two-phase mudflow model, RiverFlow 2D will be used to simulate tailings dam breach outflow over non-uniform erodible bed. To the best of the author's knowledge, this is the first non-Newtonian tailings outflow numerical modelling study to simulate morphological evolution of the downstream channel. The model considers multiple sediment size fractions, variable density, viscosity, yield stress and friction angle in space and time and is applied to a real accident. The variable properties mudflow-morphodynamic model (where density, viscosity, yield stress vary with space and time) will be compared with a constant properties' mudflow-fixed bed model.

- In this study, a sediment budget study was conducted to evaluate the magnitude of downstream geomorphic response including sediment supply, transfer, and deposition and to explore the factors contributing to morphological evolution.

1.8. Contributions

Chapter 2 corresponds to the review article:

- Sreekumar, U., Gildeh, H. K., Mohammadian, A., Rennie, C., Nistor, I., 2024. Tailings dam breach outflow modelling – a state-of-the-art review. *Mine Water and the Environment* (submitted).

Chapter 3 corresponds to the article:

- Sreekumar, U., Rennie, C., Mohammadian, A., Nistor, I., Lovitt, J., and Zhang, Y., 2022. Modelling the transport of tailings after Mount Polley tailings dam failure using multisource geospatial data. *Canadian Journal of Civil Engineering*. 49(12): 1870-1884. <https://doi.org/10.1139/cjce-2021-0596>

Chapter 4 corresponds to the article:

- Sreekumar, U., Nistor, I., Rennie, C., Mohammadian, A., 2023. Numerical modelling of downstream morphological evolution during Mount Polley tailings dam failure. *Journal of Hydraulic Engineering*. DOI: 10.1061/JHEND8/HYENG-13497

2. Literature review - Tailings dam breach outflow modelling – a state-of-the-art review

Tailings flows are generally highly sediment-laden flows and are non-homogeneous and non-Newtonian fluid events. Fluid properties may change significantly as they flow down steep watershed channels. An increase in sediment concentration affects fluid properties by altering the stress-strain relationship, and it is important to consider rheological properties such as shear stress, shear rate, and yield stress (Pradhan et al. 2018). Therefore, laboratory tests may be required to derive key parameters for better modelling of non-Newtonian fluid behaviour. This could be challenging; hence, published values have been used as estimates, and the uncertainty can be minimized by conducting a sensitivity analysis (Moon et al. 2019). Based on Labanda et al. (2004), thickened tailings can be simulated using the Herschel-Bulkley model. Several granular debris flow modelling studies have been conducted in recent years to understand the dynamics of landslides and debris flows. Debris flow models are widely used for tailings dam failure risk assessment, even though tailings flows are more mobile than rock avalanches, nonvolcanic debris flows, and waste dump failures (Ghahramani et al. 2020).

In this section, recent advances in modelling approaches for tailings dam breach analysis and downstream flood wave routing are critically reviewed. This section evaluates different mudflow modelling studies that involve single-phase, quasi-two-phase, and two-phase modelling approaches; dam breach outflow modelling; tailings rheological characterization; and application of geographic information system (GIS) and remote sensing to tailings dam breach analysis. Recommendations for further research are drawn up based on the findings. This section will both direct future research and help dam engineers and practitioners to keep up with current best practice industry standards and to include state-of-the-art practices in their work. Sections 2.2 and 2.3 that involve tailings dam breach modelling and rheological characterization were first drafted by Dr. Hossein Kheirkhah Gildeh. The focus of the research conducted by Uthra Sreekumar has been on tailings dam breach outflow modelling, sediment transport modelling and application of GIS.

2.1 Abstract

Tailings dam breach modelling studies have received considerable attention recently due to the surge in the number of tailings dam failures and catastrophic consequences due to downstream

flooding. Numerical models are crucial tools in risk management for assisting urban planners and emergency responders in planning for the safe evacuation of the vulnerable communities located downstream in the so-called “shadow area” of such dams. Several challenges and uncertainties exist when conducting risk assessments of tailings dam failure. In this study, recent advances in modelling approaches for tailings dam breach analysis and downstream flood wave routing are summarized and critically reviewed. This study evaluates different mudflow modelling studies that involve single-phase, quasi-two-phase, and two-phase modelling approaches; dam breach outflow modelling; tailings rheological characterization; and application of geographic information system (GIS) and remote sensing to tailings dam breach analysis. Recommendations for further research are drawn based on the findings. This study will both direct future research and help dam engineers and practitioners to keep up with current best practice industry standards and to include state-of-the-art practices in their work.

2.2 Tailings Dam Breach Modelling

Tailings dam breach modelling is often used in the mining industry. These studies are often required by regulators to approve the design of an impoundment, i.e., they want to ensure that the risks of such facilities are characterized properly and that mine owners have an emergency response plan (ERP) and emergency preparedness plan (EPP) in place to implement in case of a hypothetical dam failure. This practice has changed globally in the past 7 years, and it is not just a check box to fulfill regulatory requirements. For instance, a technical bulletin by the CDA (2021) on tailings dam breach assessment and a global industry standard on tailings management by Global Tailings Review (2020) were published to begin addressing the global concern regarding tailings dams and their potential failure. Added to this are the confidential internal guidance by mine owners that are used for management and risk evaluation of their tailings facilities. From a public perspective, tailings dam breaches have taken many lives and caused severe environmental damage worldwide. This demands due diligence in the design and risk identification of tailings storage facilities (TSFs).

In Canada, the CDA is a leading dam association worldwide working on guidelines to better define and frame the tailings dam breach analysis/assessment (TDBA). The CDA recently published a technical bulleting on TDBA (2021), which is being used as a widely accepted guideline worldwide. The guideline provides an overview of modelling options for runout analysis as well as breach modelling, which will be further discussed in this paper.

This section only focuses on breach modelling. Modelling of the released volume downstream (i.e., routing of the flood wave) will be reviewed in a subsequent section. To this end, it is necessary to understand the mechanism of tailings dam breach. CDA (2021) identified three general failure modes for tailings dams: 1) collapse of the foundation due to applied forces that could happen due to liquefaction triggered by earthquake or other mechanisms, surface erosion, piping, and internal erosion; 2) overtopping due to insufficient freeboard or spillway capacity, spillway malfunction, settlement of the crest, or misoperation of TSF; and 3) contaminated seepage failure to the natural environment. Multiple causes can be identified for each failure mode. Gildeh et al. (2020) reviewed 85 historic tailing dam failures and found that the most common failure mechanisms include liquefaction, overtopping, and slope stability, accounting for 60% of all failures (Fig. 1). The failure mode, in conjunction with hydrologic conditions at the time of failure, forms the dam breach scenario. There are two common hydrologic conditions used in dam breach analysis/assessment (DBA): 1) fair-weather, which suggests normal conditions without a storm, and 2) flood-induced, which refers to extreme precipitation, snowmelt, or flooding. The term "sunny day" is interchangeably used for "fair-weather"; however, it is not an accurate term, as there could be no storm or precipitation on a cloudy fair-weather day.

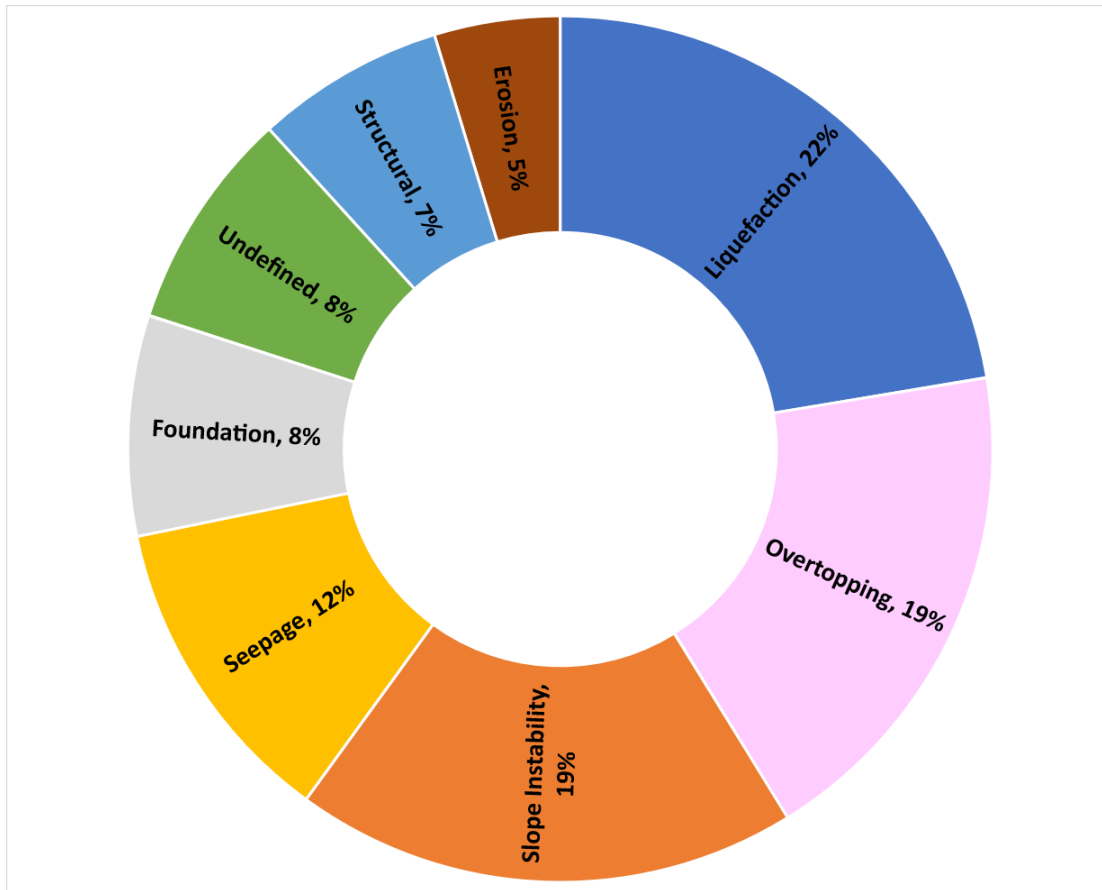
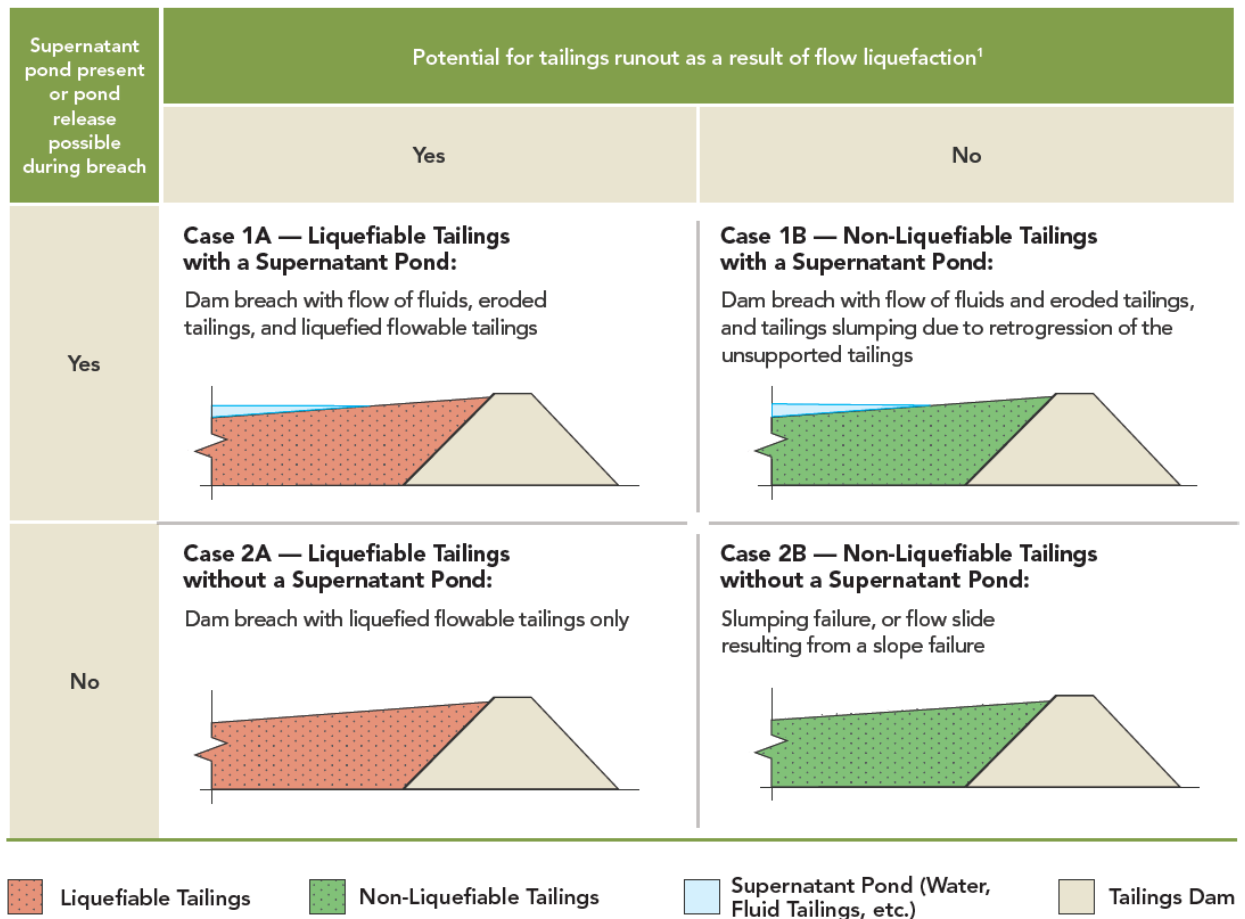


Figure 11: Historical Failure Modes (Sample Size = 85, from Gildeh et al., 2020)

The breach mechanism of a tailings retaining dam is different and more complex than that of a water-retaining dam. In most historical breaches, it was observed that not all contained volume was released, and the release volume was highly dependent on a) supernatant pond volume of the surface of TSF and b) flowable tailings volume due to liquefaction (CDA 2021). CDA (2021) uses these two variables and defines four general cases to characterize TDBA (see Fig. 2). For more details on each case, refer to the CDA (2021) guidelines.



Notes:

- Regardless of the failure mode, the flow liquefaction referred to in this figure is related to the flow potential of tailings after the dam is breached.

Figure 12: Conceptual TDBA Cases (source: CDA, 2021)

The type of breach outflow varies with the amount of water and tailings released. For example, it is expected that more tailings will erode due to pond presence in Cases 1A and 1B than in Cases 2A and 2B. It is noteworthy that the eroded tailings are different than the tailings released due to liquefaction. A schematic of different stages of embankment dam deformation and breach with respect to liquefaction failure is shown in Fig. 3. Post-triggering liquefaction results in deformation of the dam, including settlement of the dam crest (Fig. 3a and 3b). At some point, the dam crest settles below the water level in the tailings basin, and the tailings basin pond water starts moving as a sheet flow over the deformed surface of the interior dam (Fig. 3c). With further deformation of the dam, more water flows over the deformed surface (Fig. 3d), and erosion of the surface may start if the flow-exerted shear stresses exceed the critical shear stress of the surface materials. As the deformation reaches equilibrium, the flow rate over the deformed surface may reach its maximum (Fig. 3e). This flow rate depends on the available

volume of water in the tailings basin, water level in the tailings basin when deformation stops, and amount of erosion over the deformed surface. If the initial discharged volume is relatively small, the maximum breach outflow may occur sometime after deformation ends. The volume of water leaving the tailings basin results in erosion of the fine tailings and erosion of some of the deformed surface materials. When water overtops the total breach width due to deformation, a small amount of eroded surface is added to the outflow, and fine tailings in the upstream cell start eroding. The flowing water over the deformed surface then concentrates at the center area and cuts deeper, sending a greater amount of eroded tailings downstream.

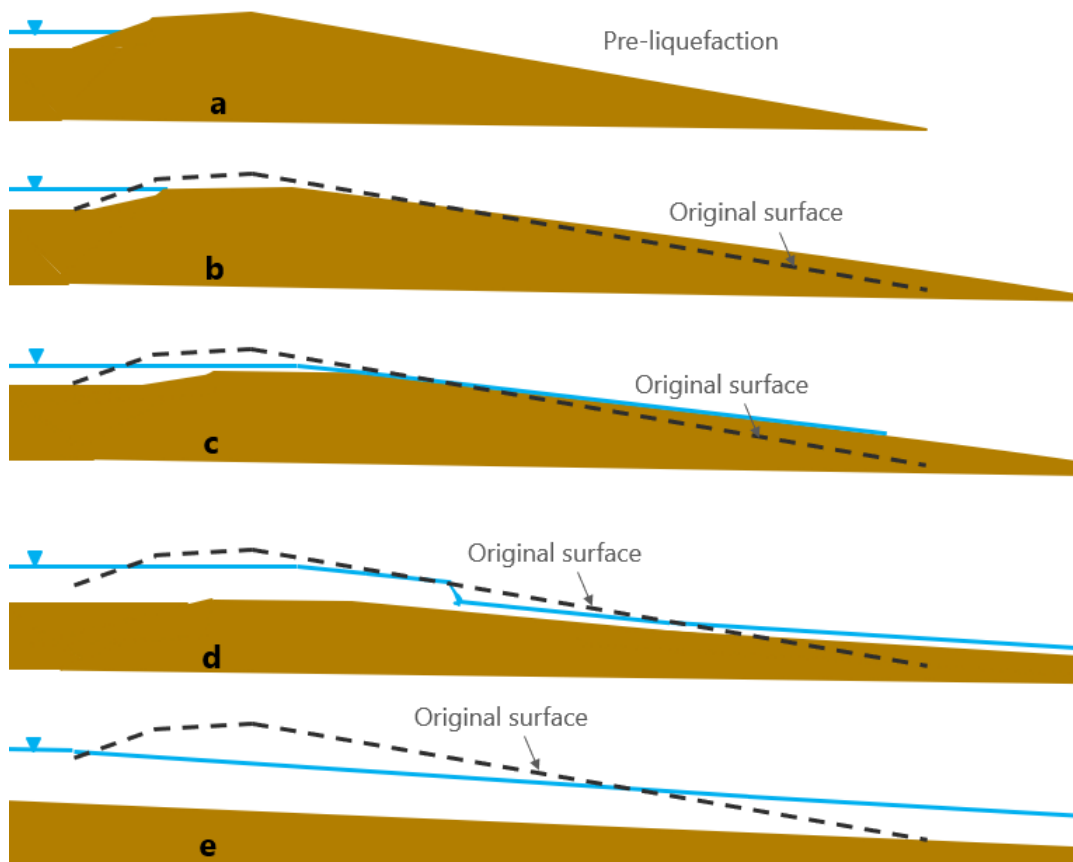


Figure 13: Stages of Embankment Dam Deformation Due to Liquefaction

The physical behaviour of the breach and released volume depends on many parameters that define the tailings rheology and flowability, such as the tailings composition, chemistry, gradation, and immediate downstream topography (CDA, 2021). However, O'Brien (1986) classified breach outflow based on the solids concentration, as shown in Fig. 4.

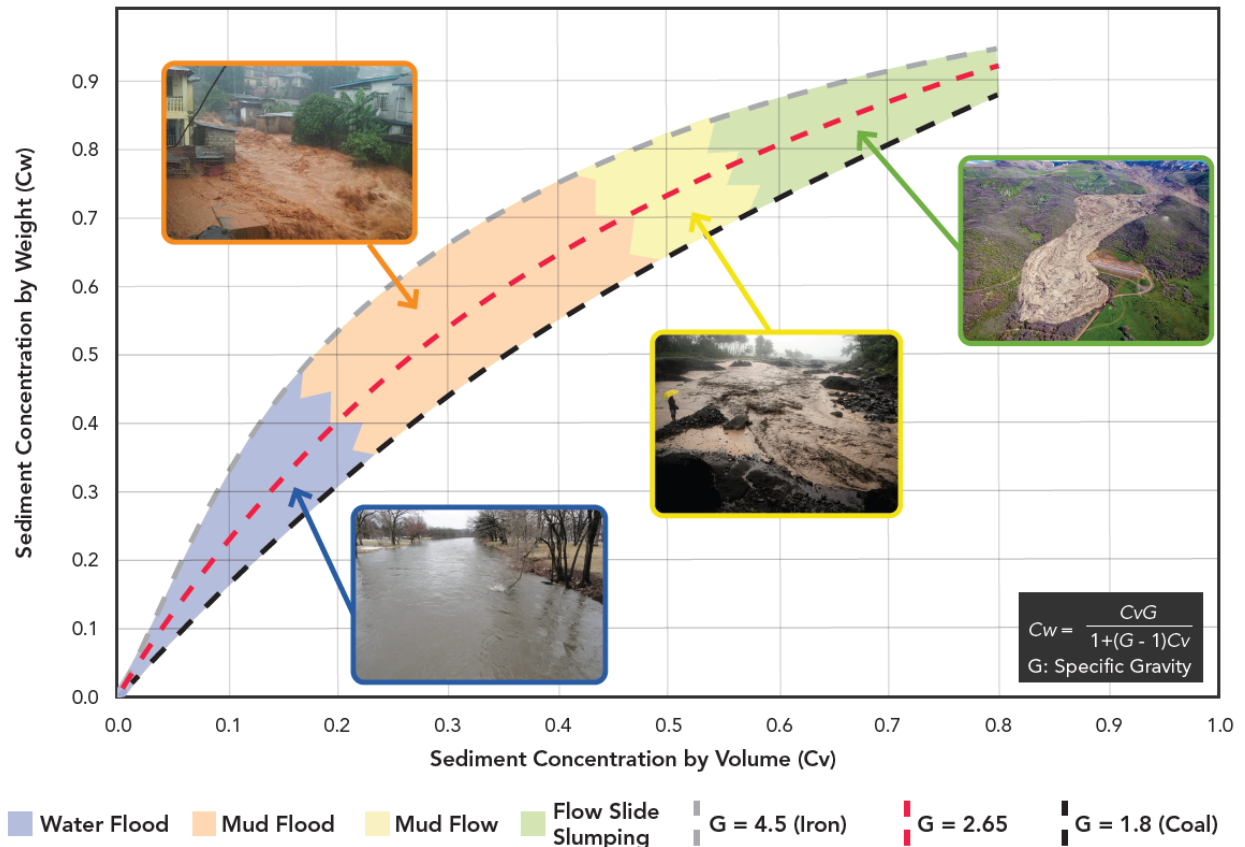


Figure 14: Breach Outflow Classification Based on Solids Concentration (Source: CDA, 2021)

2.2.1 Breach Modelling

Breach modelling identifies the shape of the breach hydrograph and its peak that is routed downstream. The breach prediction methods for earthen dams (i.e., most tailings dams) can be classified into three types: 1) parametric models, 2) semi-physically based models, and 3) physically based models. It is noteworthy that almost all breach models were developed for water-retaining dams and not for tailings dams. Therefore, it should be noted that the common practice of using these breach models is based on significant simplification.

2.2.1.1 Parametric Models

These models predict breach parameters, such as breach width and formation time, as well as breach hydrograph shape and its peak, using regression analysis of historical dam failures (Ghahramani et al., 2022). These models are very popular because of their speed and ease. The input parameters commonly include the following: total volume of reservoir (V_r); volume of water above the bottom of final breach (V_w); height of breach (h_b); height of water above the bottom of final breach (h_w); and dam height (h_d). For a list of available parametric models

refer to West et al. (2018).

Researchers continue to improve empirical or parametric model approaches for tailings dam breach analysis. White et al. (2023) re-evaluated earlier waste dump failure databases by adding more site-specific parameters to improve the correlation between deposit volume, fall height and run-out length. For coal mine dump failures, an empirical run-out length estimate relationship has been developed by analysing the 1966 Aberfan failure. Additional data in other locations should be used for further analysis and for expanding its applicability. Huamanyauri et al. (2023) compared methods in estimating the volume released during tailings dam breach. Statistical and geometric methods were used, and the study could not derive any conclusion as to which method is more conservative than the other. The geometric method was more robust than the statistical method as more factors like dimensions of tailings storage facility were considered. More studies need to be conducted to understand which method is more appropriate.

2.2.1.2 Semi-Physically Based Models

These models often use breach dimensions, breach development time, or soil erosion rate to generate the breach hydrograph (Gildeh et al., 2020). These models ignore physical processes and use simplified hydrodynamic equations, such as weir flow equations, to estimate breach hydrographs. When using semi-physically based models, there is no advancement in the accuracy of predicting breach hydrographs over parametric models but the process of developing hydrographs is improved (West et al., 2018). HEC-RAS and FLDWAV are examples of the most popular semi-physically based models.

Tellez et al. (2023) recently performed tailings dam break analysis using HEC-RAS for a downstream raised tailings storage facility in South America. In this study, potential failure modes were analyzed, and sensitivity analysis was conducted to understand the effects of breach geometry on the results. The sensitivity analysis revealed that the downstream inundated area does not depend on the breach geometry itself but other factors like released volume and rate. In this study as well, predicting the final tailings storage facility involved many challenges and assumptions.

McKellar et al. (2023) conducted physical and numerical modelling (using XBEACH) of tailings dam breach processes and studied the impacts of upstream slope angle, presence of tailings dam beach and failure mechanisms like seepage failure, notch overtopping and wide-

width overtopping. It was concluded that flatter upstream slope can have significant impact on the outflow hydrograph and the presence of tailings dam beach can reduce the peak outflow. The work on the effects of failure mechanisms is still ongoing and hence remain unanswered. Lepage et al. (2022) studied a large-scale dam breach at Ghost Dam in Alberta using HEC-RAS. While not a tailings dam, this recent study is informative for TDBA in populated areas. They first performed a probable maximum flood (PMF) analysis and then used it for a dam breach assessment of Ghost Dam and its impact to downstream. The challenge in downstream routing was the large basin and a long flood route downstream, covering more than 1,000 km of the Bow and South Saskatchewan rivers. The model, developed using the HEC-RAS software, was split in two sub-models: a 2D model and a 1D model. This was to better manage the computational cost of such a large domain. The 2D modeling covered about 140 km of the Bow River, including a large section of downtown Calgary. Two different approaches for modeling the effect of buildings on the flow conditions were compared: modeling the structure directly in the model terrain and adapting the mesh around the buildings' shape; and modifying the terrain roughness. The hydraulic model was calibrated using 2013 flood data in Calgary and they concluded that representing buildings using roughness values resulted in more realistic water levels. Although it was a water dam breach analysis (i.e., a Newtonian fluid), this is an important observation for tailings dam breach flood routing to urban areas.

2.2.1.3 Physically Based Models

Physically based models like DL Breach, EMBREA, and WinDAM takes into account the intricate structural, geotechnical, and hydraulic behaviour of an embankment dam and its upstream reservoir. Both breach and outflow are modelled simultaneously based on the dam material properties and the evolution of breach opening is predicted without the need to make assumptions of the breach dimensions (Lumbroso et al., 2021). Although these models are very time-consuming compared to parametric and semi-physical models, physically based models give results with higher accuracy (West et al., 2018). To know more about the available physically based models, refer to West et al. (2018).

Breach Outflow Model Hydrograph Comparisons

A breach outflow hydrograph is necessary to route the breach flood downstream and map the impacted area to be used in the ERP and EPP. As mentioned above, both physically based models and semi-physically based models can generate the breach hydrograph. In this section,

two sets of comparisons are made in breach outflow hydrograph generation.

Comparison 1: Two Semi-Physically Based Models vs One Parametric Model

A critical factor in choosing the appropriate software to develop a breach hydrograph is the downstream topography near the location of the breach, as it impacts the peak and shape of the hydrograph. Here the topography refers to the distance from the breach point to approximately 100 m (for a channel with a steep slope) to 300 m (for a channel with a gentle slope). In this region, the backwater effect can affect the characteristics of the breach hydrograph (Gildeh et al., 2020). To analyze the impact of the downstream conditions on the breach hydrograph, model runs were conducted (HEC-RAS 2D, FLDWAV, and HEC-HMS) by keeping parameters for the breach and topographic conditions the same (HEC-RAS 2D and FLDWAV are the models that include downstream topographic conditions). According to Gildeh et al. (2020), the breach hydrographs of the HEC-RAS 2D and FLDWAV, both semi-physically based models, were relatively the same, particularly its shape and peak. However, the HEC-HMS model generated a wider hydrograph with a lower peak when compared to the other two models. The computed volumes were similar in all three hydrographs. Nonetheless, different peaks and shapes of hydrographs can impact the flood arrival time and flood extent. HEC-HMS is very easy in terms of model setup and run, whereas FLDWAV model takes high computational time to set up and run.

Comparison 2: HEC-RAS 2D Newtonian vs Non-Newtonian Breach

In this second comparison, one of the most popular semi-physically based models (HEC-RAS 2D) was used to compare the difference between its Newtonian and non-Newtonian (recently added to the model) modules. The same stage-storage curve was used in both modules (see Fig. 5), and the breach parameters were estimated based on the same parametric method.

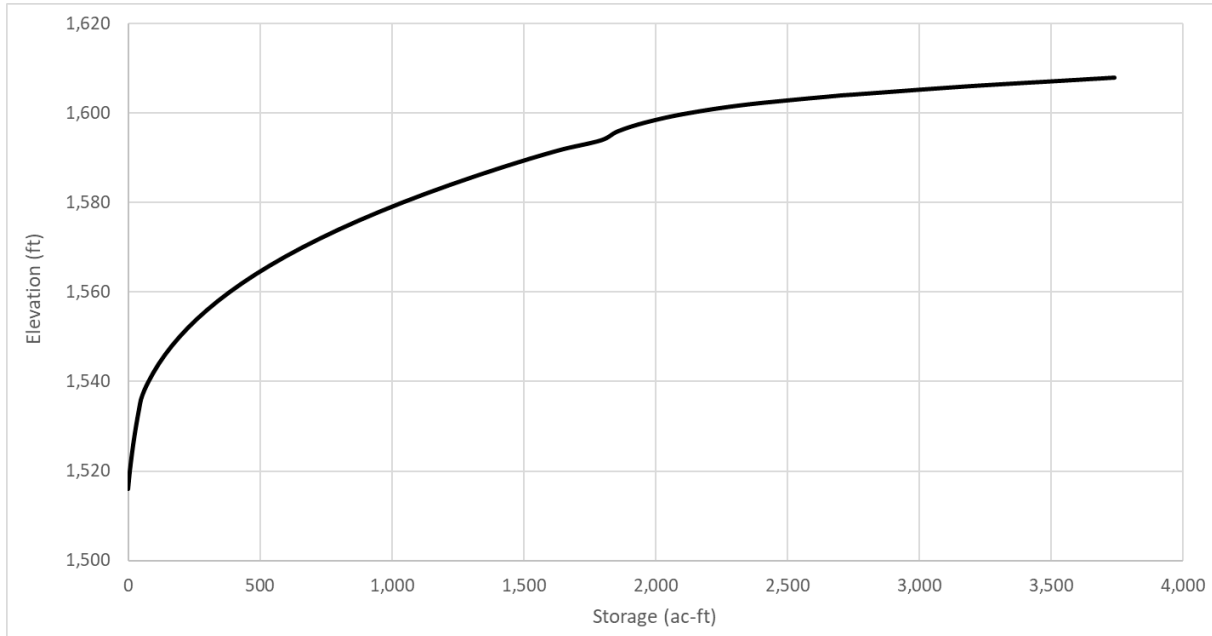


Figure 15: Stage-Storage Curve for Modelled Breach in HEC-RAS 2D

For non-Newtonian fluids, the model requires rheological parameters of the tailings. For this exercise, a typical concentration by volume (C_v) of 29% and yield stress of 4.12 Pa were selected for the released mixture of tailings and water. Two scenarios were tested for viscosity: 1) high viscosity (57.3 Pa-s) and 2) low viscosity (1.22 Pa-s). The results of the three models are shown in Fig. 6 where there seem to be no obvious difference between the models. This suggests that HEC-RAS model (version 6.4.1 at the time of this paper preparation), a semi-physically based model, is not capable of accounting for actual complex processes of tailings dam breach formation and release, as mentioned in the Section “Breach modelling”. Both models used the same topography and geometry details to ensure the results are comparable and they are not sensitive to the topographic and geometric conditions in the models.

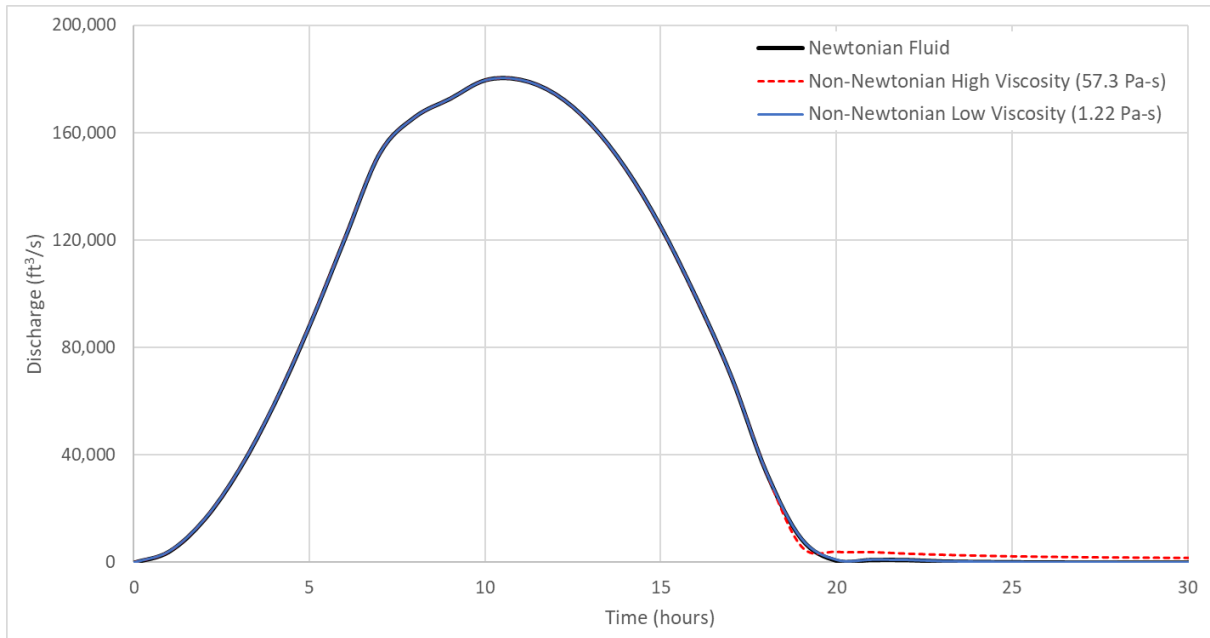


Figure 16: Comparison of Newtonian and Non-Newtonian Breach Modules in HEC-RAS 2D

2.3 Tailings Rheological Characterization

Tailings properties can vary greatly due to the gradation, ore type and extraction method, deposition method, and mineralogy of tailings. It can also vary over the TSF life cycle; for instance, the saturated tailings in the presence of a pond during the mine operation could behave differently than at the end of the operation and reclamation phase when the pond is small or non-existent (CDA, 2021). Tailings characteristics are often obtained from geotechnical investigations. These investigations can be in situ testing such as the cone penetration test (CPT) or laboratory testing and empirical correlations (e.g., Shuttle and Cunning, 2007; Idriss and Boulanger, 2008; Robertson, 2009; Jefferies and Been, 2015; Sadrekarimi, 2016).

For a TDBA, it is essential to understand the susceptibility of tailings to flow during liquefaction. Tailings release during the failure of a dam is a very complex phenomenon, as mentioned before, and the tailings behave like a non-Newtonian fluid that can be described using rheological parameters. The two main parameters for characterizing the tailings flowability are viscosity and yield stress. Viscosity is a measure of the flowability of a fluid, whereas yield stress is a measure of the stress required to cause the tailings to start moving. Viscosity is not often constant, and different equations are used to estimate the complex non-Newtonian behaviour of tailings (Fig. 7). For example, if a model uses Bingham stresses, ignoring inertial stresses, it is assumed that the flow is highly influenced by viscous stresses.

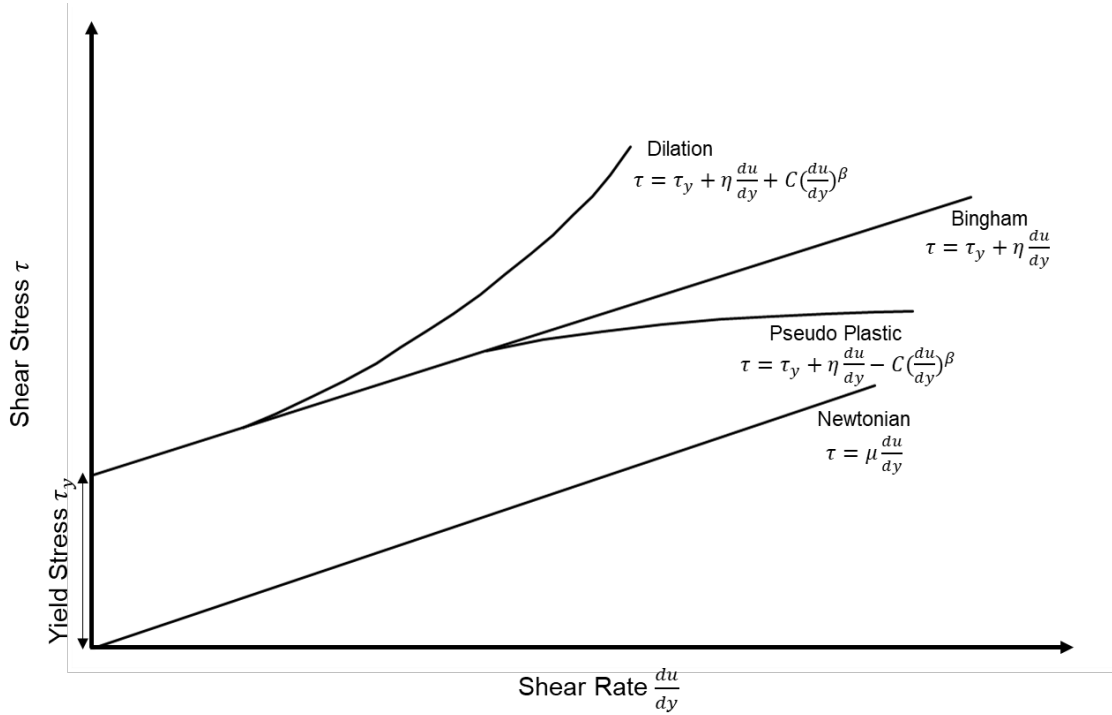


Figure 17: Shear Stress vs Shear Rate for Fluid Deformation Models (Source: FLO-2D)

The yield stress and viscosity can be measured in the laboratory based on samples collected from the field using a viscometer (see the “Discussion” Section for the caveats on using lab results in numerical models). The tests could be repeated under different water contents and temperatures to build an exponential relationship between the viscosity and C_v ($\eta = \alpha e^{\beta C_v}$) or yield stress and C_v ($\tau = \alpha e^{\beta C_v}$), where η is viscosity, C_v is concentration by volume, τ is the yield stress and α and β are the coefficient and exponent of the equations. Typical graphs of these parameters are shown in Fig. 8 and 9, adopted from the Flo-2D reference manual (2023). Note that the vertical axes in both plots are on a logarithmic scale. It is a good practice for engineers performing the TDBA to always plot their rheology parameters onto these graphs to provide an understanding of where the data sit and interpret them, knowing that the field data plotted in the Flo-2D manual are most likely different from type of materials they are dealing with.

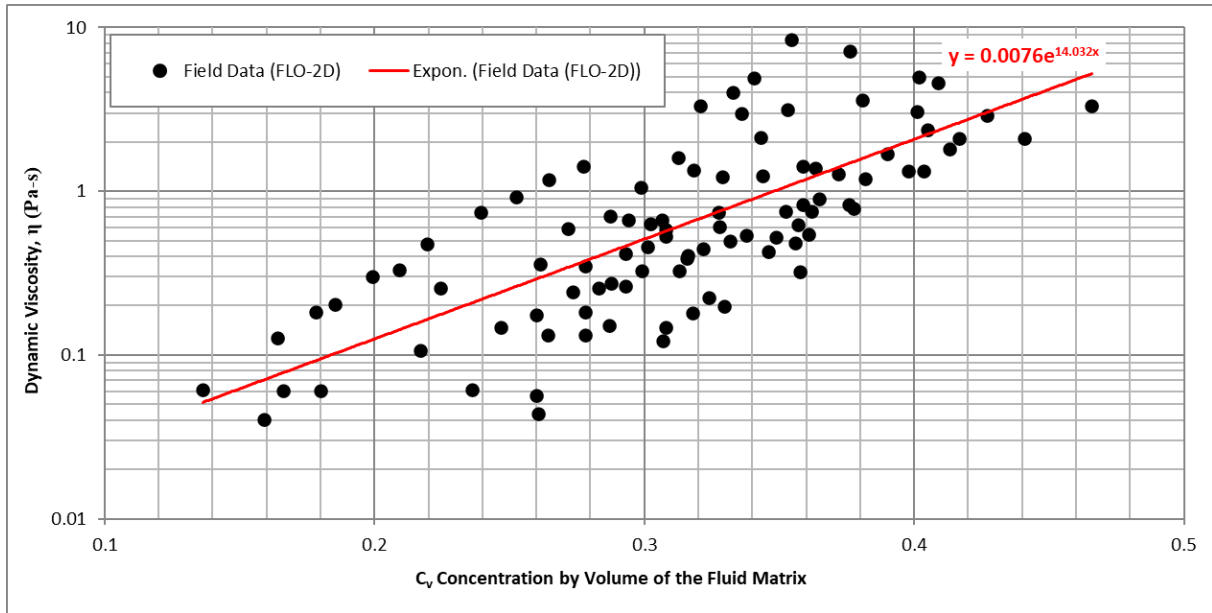


Figure 18: Dynamic Viscosity vs Concentration by Volume for Mud Flow of Various Sources as Described in FLO-2D Reference Manual (2023)

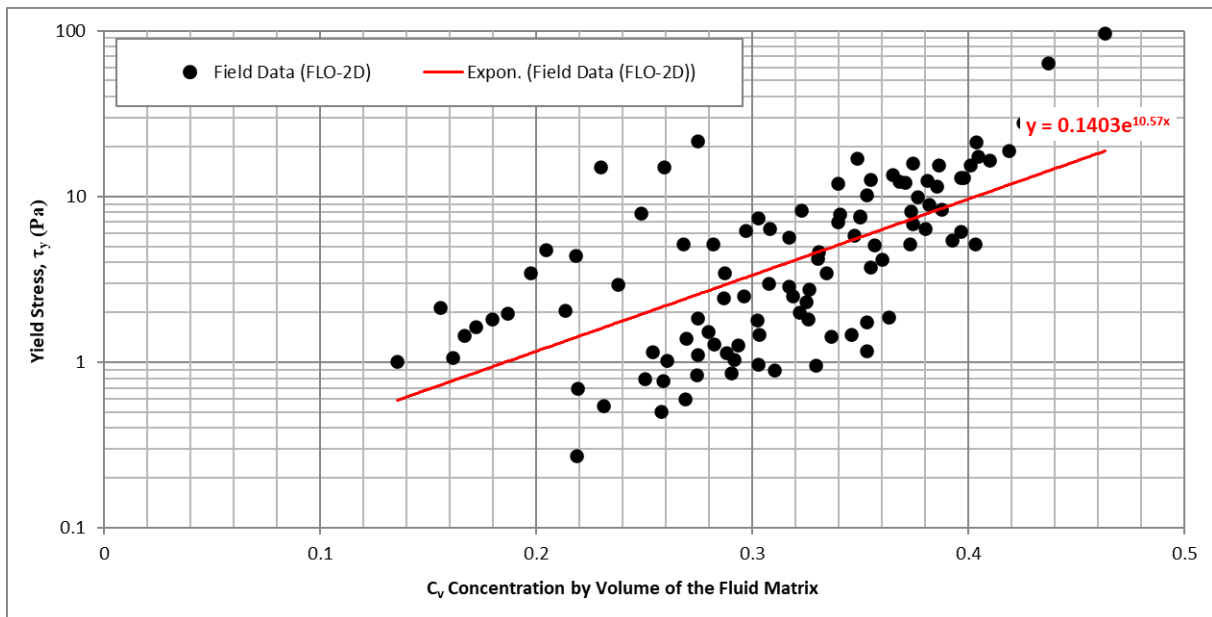


Figure 19: Yield Stress vs Concentration by Volume for Mud Flow of Various Sources as Described in FLO-2D Reference Manual (2023)

Roman et al. (2022) recently investigated the importance of tailings rheology in dam breach assessment and dam consequence classification of tailings storage facilities. To characterize the influence of rheological tests and their interpretation, or misinterpretation, in the TDBA results and the consequence classification, a hypothetical case of TDBA was modeled

considering both unsheared (static) and sheared (dynamic) rheology test results, comparing their effects regarding consequences downstream. Through inundation mapping of various scenarios modelled using FLO-2D (see below), the authors showed how important it is to choose reliable rheology parameters for TDBA. It also highlights the importance of sensitivity analyses on such parameters. Similarly, Sakano et al. (2021) emphasized the importance of rheology properties for a breach analysis. They focused on geotechnical protocols in testing the materials and interpreting the viscosity and yield stress for dam breach analysis, as it results in quite different inundation extents, as discussed in Roman et al. (2022).

2.4 Downstream routing analysis

2.4.1 Numerical modelling studies

Mudflows resemble debris flows but with less boulders and granular materials and can have very steep frontal wave (Pasculli et al. 2021). Many granular debris flow modelling studies have been conducted recently to have a clear understanding of the nature of landslides and debris flows. Since tailings are composed of water, sediments and contain high concentrations of heavy metals, they can be highly concentrated and, as such, mudflow models are widely used for tailings dam risk assessment (Ghahramani et al. 2020). In this section, single-phase, quasi-two-phase and two-phase modelling studies are evaluated.

2.4.1.1 Single phase approach (homogeneous mixture)

Several numerical modelling studies reported in the past used a single-phase approach, where it is assumed that mixture density remains the same both in space and time. The solid phase is assumed to be uniformly distributed and the debris flow density variation in mass and momentum conservation equations have been overlooked (Cesca and D'Agostino 2008; Hubl and Steinwendtner 2001; Chen et al. 2010; Aleotti and Polloni 2003; Juez et al. 2013; Peng and Lu 2013; Liu and Huang 2006; Mahdi et al. 2020; Sreekumar et al. 2022). Some studies like Mahdi et al. (2020), Ghahramani et al. (2020) and Sreekumar et al. (2022) used Flo-2D to simulate tailings dam breach outflow and for flood extent delineation. Wu et al. (2013) compared Flo-2D and Debris-2D, for modelling debris flow induced by landslides in Xinfan village, southern Taiwan. In Flo-2D, the governing flow equations (mass and momentum equations) are formulated in one dimension and applied independently in eight directions. The central difference and Newton-Raphson methods are used to solve the equations, and the non-

Newtonian nature is simulated using a quadratic rheological model. In the quadratic rheological formulation, yield stress and viscosity are expressed as a function of the solid concentration and a turbulence term that considers the surface roughness is included (O'Brien and Julien 1985). The inputs include sediment concentration, viscosity, yield stress, Manning's n values, Digital Elevation Model (DEM), and mudflow discharge hydrograph, which includes the water outflow hydrograph and temporal variation of solid volume concentration. Debris-2D uses mass and momentum conservation equations, and the first-order upwind method is used to discretize the convective term. The second-order central difference method is used for the remaining terms, and the third-order Adams-Bashforth method is employed for time advancement. The main model inputs are topography and initial debris source distribution. The only rheological parameter to be assigned is the yield stress. In the Flo-2D model, density remains constant in each flow direction, while in Debris-2D, yield stress and density are assumed to be constant. Debris-2D can model the commencement and stopping of debris flows, but Flo-2D simulations cannot be stopped until the user terminates the computation and that can impact the final inundated area. Flo-2D is more efficient in terms of the computation time of the Central Processing Unit (CPU) because it employs variable time steps compared to Debris-2D, which uses a fixed time step. Flo-2D employs user-defined mudflow discharge hydrographs for flood routing. Hence, the total volume released depends on the artificially determined hydrograph, which may not be the same as the actual outflow hydrograph. However, Debris-2D simulates using real source distributions estimated through field surveys or aerial image analysis; hence, landslide-triggered debris flow events are better simulated by Debris-2D (Wu et al. 2013).

2.4.1.2 Two-phase approach

Several two-phase debris flow modelling studies have been performed in the past (Pelanti et al. 2008; Pudasaini 2012; Pitman and Le, 2005; Meng and Wang, 2016; Pailha and Pouliquen 2009; Bouchut et al. 2016; Greco et al. 2019; Tai et al. 2019). In these models, solid and liquid phases are regarded individually in the mass and momentum conservation equations. Recently, Flo-2D has adopted a two-phase modelling approach to simulate the breach of a tailings dam with reservoir water storage. However, in a two-layer shallow water model, if the difference between the phase velocities of the solid and liquid layers is very high, complex eigenvalues may appear and there can be loss of hyperbolicity and numerical instability. This can make numerical modelling very challenging (Pelanti et al. 2008). Several ways to prevent the loss of

hyperbolicity have been proposed by Castro et al. (2011) and Sarno et al. (2017) but those techniques need iterative algorithms that are very computationally expensive. Another limitation of the two-phase modelling studies done to date is that they neglected the bed entrainment or the changes in the downstream channel morphology.

2.4.1.3 Quasi two-phase modelling studies

In quasi-two-phase modelling approach, the mass and momentum conservation of mixtures and mass conservation of solid phases are considered individually. This approach has been employed in studies like Iverson and George (2014), Rosatti and Begnudelli (2013), Kuo et al. (2013), Kowalski and McElwaine (2013), and Pasculli et al. (2021). According to this approach, the solid and fluid phase velocities are combined into the depth-averaged bulk mixture velocity and the effects of solid-fluid particle interactions in the mixture are considered. Even though this modelling approach is simplified when compared to the two-phase modelling approach, it offers better numerical stability. Hence, this approach is suitable for realistic large-scale mud flow events that need quick evacuation planning. Riverflow2D model uses this quasi-two-phase approach in simulating mudflow. Martínez-Aranda et al. (2022) used Riverflow 2D to simulate tailings dam failure that occurred in Brumadinho (Brazil) in 2019. In the study conducted by Sreekumar et al. (2023), Riverflow 2D was used to simulate bed entrainment during the Mount Polley tailings dam failure.

2.4.2 Numerical models

Commonly used numerical models for the analysis of hyperconcentrated flow or debris flow are discussed in this section. These software packages use various rheological models. Several of these rheological models and their formulations are listed in Table 1.

Table 1: Rheological flow resistance formulations

Formulation	Flow resistance equation
Pure turbulent	$ \tau_b = \tau_t = \rho C_f u^2$
Simplified Bingham	$ \tau_b = 1.5\tau_y + 3\tau_\mu$ where $\tau_\mu = \mu q/h^2$
Turbulent & Coulomb	$ \tau_b = \tau_t + \tau_f$
Turbulent and Yield	$ \tau_b = \tau_t + \tau_y$
Turbulent, Coulomb and Yield	$ \tau_b = \tau_t + \min(\tau_y, \tau_f)$
Full Bingham	$2 \tau_b ^3 - 3(\tau_y + 2\tau_\mu) \tau_b ^2 + \tau_y^3 = 0$
Quadratic	$ \tau_b = \tau_y + \tau_t + k/8 \tau_\mu$
Granular	$ \tau_b = \tau_f = g\rho h \cos \theta \tan \theta_b$
Herschel- Bulkley	$\tau = \tau_y + K \left(\frac{du}{dy} \right)^n$
Voellmy	$\tau_b = \tau_y + \frac{\rho_m g V ^2}{\xi}$
Mohr-Coulomb (Clastic)	$\tau_y = C + \sigma \tan \phi$

In Table 1, ρ is the sediment-water mixture density in kg/m^3 , u is the depth-averaged flow velocity in m/s , g is the acceleration due to gravity in m/s^2 , $|\tau_b|$ is the bed shear stress in Pa , τ_μ is the viscous stress in Pa , τ_y is the yield stress in Pa , τ_t is the turbulent shear stress in Pa , τ_f is the Coulomb-type frictional stress in Pa , q is the unit flux in m^2/s , θ is the bed slope, θ_b is the friction angle of the solid material in degrees, k is a resistance parameter equal to 24, C_f is the friction coefficient, h is the flow depth in m (Hydronia 2022), K is consistency index, n is the flow behaviour index, τ is the shear stress in Pa , $\frac{du}{dy}$ is the shear strain rate related to a local u velocity, $|V|$ is the avalanche velocity in m/s , ξ is the Voellmy coefficient (Kocyigit and Gurer 2007), C is the cohesion or cohesive strength in Pa , μ is the Coulomb friction coefficient, σ is the normal stress at the bottom of the mixture in Pa , ϕ is the internal friction angle, ρ_m is the mixture density, (HEC-RAS manual 2023).

2.4.2.1 Flow-3D

Flow-3D (Flow Science 2021) is a commercial computational fluid dynamic (CFD) software

that is used to analyze complex free surfaces as well as confined flow problems. The model is based on the Finite Volume method in the Eulerian reference frame and employs 3D structured grids of cubic cells for discretizing the model geometry. It solves non-hydrostatic Navier-Stokes equations with free surface. Various rheological models, such as the Herschel–Bulkley model and the Bingham rheological model, are included in this model. The Flow-3D hydro tailings model can be used to model the highly non-Newtonian behaviour of tailings and water mixtures. Fine and coarse tailing particles can be modelled separately or together. The model can consider varying tailings concentrations and the presence of a supernatant water layer above the coarse layers of tailings. Three-dimensional and 2D shallow water modelling methods are available. Tailings mixing and settling can be modelled in three dimensions and can be combined with shallow water meshes to accurately simulate the runout flow of tailings over large areas. Several turbulence models are available both in 2D and 3D modules. Examples of tailings dam breach studies using Flow 3D include Chen et al. (2022), Ghahramani et al. (2022), and Yao et al. (2020). Chen et al. (2022) investigated overtopping erosion in reinforced tailings dam by conducting physical model tests and numerical modelling was done using Flow 3D. Ghahramani et al. (2022) modelled two tailings dam breaches (1985 Stava and 1994 Merriespruit) using Flow 3D. Yao et al. (2020) investigated the influence of particle size on the tailings dam failure process by conducting physical tests and then numerical modelling was done using Flow 3D.

2.4.2.2 *Flo-2D*

Flo-2D software (Flo-2D 2022) was discussed in the Section “Single phase approach (homogeneous mixture)” of this paper. It has been widely used to simulate mudflows in industrial practices over the past few decades. This quasi-two-dimensional model uses a finite-volume numerical method in the Eulerian reference frame (Flo-2D 2022). To consider the inflow into the computational domain, the user inputs a breach outflow hydrograph at the breach location using the module Flo-2D Tailings Dam Failure Volume Estimate Tool. A new level of predictive analysis for tailings dam breach outflow was developed by adopting a two-phase modelling approach. This new approach can be used to simulate the breach of a tailings dam with reservoir water-storage. The model can simulate mudflow-fluid exchange along with erosion and deposition, mudflow cessation, and tributary inflow and mudflow into downstream lakes. As mentioned in the Section “Single phase approach (homogeneous mixture)”, examples

of tailings dam breach outflow modelling studies that used Flo-2D include Mahdi et al. (2020), Ghahramani et al. (2020) and Sreekumar et al. (2022).

2.4.2.3 RiverFlow2D

RiverFlow2D (Martínez-Aranda et al., 2020) is a two-dimensional hydraulic flexible-mesh model that offers a high-performance finite-volume engine for accurate and fast conservative volume computations. The model can be adapted to any terrain and boundary by using a triangular unstructured mesh. The mud and tailing flow module within Riverflow2D employs an upwind Roe-type Riemann solver and is solved on a Graphics Processing Unit (GPU). It can model the variable-density flow of tailings mixture over an erodible bed. It solves the hydrodynamic equations, rheological formulations, and sediment transport equations, and considers settling, re-suspension, and sediment transport in the fluid column. Two-phase rheological formulations account for different friction terms and represent various non-Newtonian fluids (Martínez-Aranda et al. 2020). The rheological models used in RiverFlow2D include pure turbulent model, simplified Bingham model, Full Bingham model, quadratic rheological model, Turbulent, Coulomb and Yield model, and Granular model. As mentioned in the Section “Quasi two-phase modelling studies”, examples of tailings dam breach outflow modelling studies that used Riverflow 2D include Martínez-Aranda et al. (2022) and Sreekumar et al. (2023).

2.4.2.4 DAN-3D

DAN-3D (Cheon 2020) is a semi-empirical numerical analysis method and quasi-three-dimensional extension of the DAN-W model. This Lagrangian numerical model is based on “smoothed particle hydrodynamics” (SPH) and is primarily developed for landslide runout analysis. Mud or debris flow is modelled as an equivalent fluid and the complex flow dynamics is simplified. A meshless Lagrangian frame of reference is used and the depth-averaged velocity and nonhydrostatic internal stress distribution based on the assumptions developed from the study conducted by Savage and Hutter (1989) is adopted (McDougall and Hungr 2004). The breach is modelled using a slope instability failure mechanism and the volume released is input as a source term. Five rheological models, namely Newtonian, Plastic, Bingham, Frictional, and Voellmy, can be used to simulate the complex dynamics of landslides and mud/debris flows (Cheon 2020). Ghahramani et al. (2022) modelled two tailings dam failures (1985 Stava and 1994 Merriespruit) using DAN 3D.

2.4.2.5 *MADflow*

MADflow (Chen et al. 2019) is a quasi-3D (depth-averaged) hydrostatic model that can be used for mobility analysis of gravity-driven flows of soils, tailings, rock, and water mixtures. The model uses a finite element numerical method and employs rheological models, such as Frictional, Bingham, Voellmy, Quadratic, Coulomb viscous, Herschel-Bulkley, Plastic, Sassa and Lava flow. The assumptions taken from the study conducted by Savage and Hutter (1989) were adopted to implement the stress in response to strain during movement for flows at a high solid concentration. The entrainment from the bed layer, hydrodynamic drag, and hydroplaning onset for submarine debris flows are also included. The user defines the location and geometry of the failure. Breach modelling can be done as a dam breach scenario or a slope instability scenario, and the volume released is calculated by inputting a hydrograph (Chen et al. 2019). Chen and Cuning (2021) conducted breach modelling and downstream routing using the MADflow model. The model was calibrated using historical dam breach events. They discussed application of critical state soil mechanics in TDBA. They also discussed how the breach hydrograph from an erosional breach could be different than non-erosional breach in terms of shape and timing. They used in-situ tailings properties for analysing the mobilization of eroded tailings using an interpreted cone penetration test. Finally, Ghahramani et al. (2022) modelled two tailings dam failures (1985 Stava and 1994 Merriespruit) by employing MADflow.

2.4.2.6 *DAMBRK*

DAMBRK is a dam-break flood forecasting model that constitutes a breach module that uses simple parameters to give a temporal and geometrical definition of the breach. This model can simulate tailings flow by specifying rheological parameters of the fluid like its dynamic viscosity, initial shear strength, unit weight and stress rate of strain (Kheirkhah Gildeh et al. 2020). This model estimates the breach outflow hydrograph through a broad-crested weir flow approximation that involves the corrections for approach velocities and the submergence from downstream tailwater depths. The fundamental component of the DAMBRK model is a dynamic routing approach for estimating the changes to the flood wave as it advances such as its velocity profile, travel time, and resulting flow depths. The dynamic routing technique is based on a non-linear weighted four-point finite-difference solution of the Saint-Venant equations in which variable time and distance steps can be used in the solution procedure. There are also provisions for routing subcritical flows, supercritical flows, or a mixture of each, and

combining the effects of downstream obstructions such as embankments or other dams, mud/debris flows, pressurized flow, landslide-generated reservoir waves, etc. (Dodson & Associates, Inc. 2009). Xin et al. (2011) used DAMBRK for the risk assessment of the Shouyun iron mine Heshangyu tailings dam break.

2.4.2.7 FLDWAV

FLDWAV, a 1D hydraulic routing model, can be used to model the breach, emptying of the dam, and flood wave propagation. FLDWAV is generalized for broad applicability to rivers of varying roughness, irregular geometry, flow diversions, lateral inflows, off-channel storage, and head losses. It can estimate the hydraulic characteristics like the lateral extent and depth of flooding at various times and distances. FLDWAV is widely used for computing the outflow hydrograph from a dam due to overtopping and dam-breach outflows. The obtained flood wave is routed through rivers, reservoirs, estuaries, and canals. One-dimensional unsteady flow equations coupled with internal boundary equations are the governing equations. Thereby, it represents a rapidly varying flow through hydraulic structures like dams and embankments which can result in a time-dependent breach. Suitable external boundary equations at the upstream and downstream ends of the routing are also used. An iterative, weighted four-point implicit finite-difference method is used for solving the system of equations. FLDWAV can also be used for generating accurate outputs like elevation, discharge, and velocity profiles when only limited data are available. The governing equations of the FLDWAV model involve average parameters like channel width, cross-sectional area, depth of flow, and discharge and thus simplifies the inputs required for modelling. Cross-sections along the river are denoted by a table of mean top widths vs. elevations. Along the channel reach, roughness coefficients are averaged as a function of discharge or elevation. FLDWAV interpolates between river reaches for getting additional roughness data and cross-sections and for satisfying computational requirements. Hydraulic structures are also given in the model input by using average parameters like the effective area of the breach instead of breach geometry (RiverMechanics.net, 2020).

2.4.2.8 HEC-RAS

The unsteady flow module of the HEC-RAS model is used for dam-break simulations. In this model, the shallow water equations (SWE) that include spatial and temporal acceleration with horizontal mixing are used. The breach of a tailings storage facility (TSF) has been observed to

result in high momentum waves travelling downstream and the SWE are very suited to this type of modelling. Two approaches can be followed in HEC-RAS for solving advection, namely an Eulerian Lagrangian approach (SWE-ELM) and an Eulerian approach (SWE-EM). Among these two, SWE-EM is more momentum conservative and can result in longer run times and this model is necessary only when detailed analysis is required. HEC-RAS allows the user to define the non-Newtonian nature of tailings and the non-Newtonian models include the Clastic Grain-Flow, O'Brien equations, and the generalized Herschel-Bulkley method. HEC-RAS does not have the capability to consider varying sediment concentration, which is a major limitation. HEC-RAS has the capability to refine the computational mesh around hydraulic structures and is helpful in detailed analysis of dam breaches (Scholtz and Chetty 2021). Melo and Eleutério (2023) conducted probabilistic analysis of floods from tailings dam failures and analyzed the impact of rheological parameters on the HEC-RAS Bingham and Herschel-Bulkley Models. In this study, the sensitivity analysis methodology was applied to the ICOLD (International Commission on Large Dams) case study, that involves a hypothetical dam presented by Zenz and Goldgruber 2013.

2.4.2.9 MIKE11 and MIKE21

MIKE FLOOD links two software packages namely, Mike HYDRO River (1D) and MIKE 21 (2D). Mike HYDRO River solves the 1D Saint-Venant equations by using a finite difference scheme and the breaches can be modelled by a dam-break structure. Breach initiation and formation can be defined by time series for crest level, breach width, and side slope. An erosion model formed from the Engelund-Hansen sediment transport equation is available. Breach outflow can be calculated by utilizing two sets of equations: one set of equations for flow via a generic structure (Borda losses) and the other set from the NWS DAMBRK model. MIKE 21 employs a rectangular grid and solves the 2D shallow water equations by using a finite difference scheme. This model can handle flooding, varying surface roughness, Coriolis forces, eddy viscosity, and wind friction (Vanderkimpfen et al.2009). MIKE 11 does not have the capability to model non- Newtonian nature of tailings flow. Therefore, MIKE 21/3 mud transport model has been developed: this model has the option to simulate non-Newtonian fluid flow by specifying properties such as density, fluid viscosity and yield stress. Fluid properties can change in space and time and can represent mixing of non-Newtonian fluids with water (Danish Hydraulic Institute (DHI), 2017). Lumbroso et al. (2021) modelled mudflow resulting

from Brumadinho tailings dam breach using MIKE 21.

2.4.2.10 TUFLOW

TUFLOW HPC allows modelling of non-Newtonian fluids in two dimensions (2D). In this model, turbulent eddy viscosity is not considered important in non-Newtonian fluids as they are highly viscous. The 2D viscosity is calculated using a viscosity model in case of shear thickening fluids. The flow regime can become turbulent in the case of shear thinning fluids. Those added turbulent shear stresses that are developed are depicted using the standard TUFLOW HPC Wu turbulence model. TUFLOW uses the Herschel-Bulkley model in which fluid shear stress is related to the shear rate in a non-linear manner. The Herschel-Bulkley model combines elements from power law and Bingham Plastic models and thus corrects some of the deficiencies seen in those models. This model is more comprehensive and allows the modelling of shear thinning behaviour of tailing slurries. In case of Newtonian fluids, a turbulent boundary layer is present, and the velocity profile follows the ‘law of the wall’ and is commonly determined using Manning’s equation. In case of non-Newtonian fluids, the turbulent velocity profile is different. If the flow is in the laminar regime, a power law viscosity model is used to compute bed friction and the depth-averaged flow velocity. The Manning's bed friction becomes more applicable as the fluid flow becomes more turbulent and begins to dominate over the non-Newtonian bed friction. Another assumption in this model is that effects of acceleration are negligible, and the shear stress of the fluid is linear with depth (TufLOW 2021).

2.4.2.11 TELEMAC

TELEMAC-2D solves the Saint-Venant equations using the finite-volume or finite-element method and adopts a computation mesh of triangular elements. The breach outflow volume depends on the breach development rate and the resistive forces like the non-Newtonian nature and bottom friction. In TELEMAC-2D, a “widening” breach option is available and using this, the nodes on each side of the breach opening are instantaneously lowered from crest to bottom. This triggers a sudden discontinuity in the breach geometry and an increase in outflow volume. This software also has the capability to simulate the cascade failures of downstream dams or levees. Within this software, a “pseudo-biphasic model” is available, and this can be used to model the mixing between Newtonian and non-Newtonian fluids. The volumetric sediment concentration (C_v) is represented by a passive tracer and can be given as an initial condition or boundary condition. The fluid rheological properties are then calculated as a function of C_v .

Non-Newtonian rheological models treat the fluid mixture as a continuous medium and they are not combined with sediment transport models. Therefore, morphological changes linked to erosion processes cannot be modelled when conducting tailings run out analysis (Ligier et al. 2022). Ligier (2020) modelled Brumadinho tailings dam breach outflow and studied the application of non-Newtonian rheological models in TELEMAC-2D. The rheological models available in each software are summarized in Fig 20.

Models	Type	Case 1A	Case 1B	Case 2A	Case 2B	Newtonian	Non-Newtonian	Rheological options	Morphological changes	Computing Cost
DAMBRK	1D	Yes	Yes	-	-	Yes	-	-	No	Medium
FLDWAV	1D	Yes	Yes	Yes	-	Yes	Yes	Bingham; Quadratic model	No	Medium
HEC-RAS	1D/2D	Yes	Yes	Yes	-	Yes	Yes	Bingham; Classic Grain-Flow; Herschel-Bulkley ; Quadratic	Yes	Medium
FLO-2D	2D	Yes	Yes	Yes	-	Yes	Yes	Quadratic model	Yes	Medium
MIKE 11 and MIKE 21	1D/2D	Yes	Yes	Yes	-	Yes	Yes	Bingham, Turbulent, Hindered Settling	Yes	High
RiverFlow2D	2D	Yes	Yes	Yes	Yes	Yes	Yes	Pure Turbulent; Simplified Bingham; Full Bingham; Quadratic; Turbulent and Coulomb; Turbulent and Yield; Turbulent and Coulomb Yield; Granular model	Yes	Medium to High
TUFLOW	2D	Yes	Yes	Yes	-	Yes	Yes	Herschel-Bulkley	No	Medium to High
Telemac	2D/3D	Yes	Yes	Yes	-	Yes	Yes	Bingham; Pure Bingham	No	Medium to High
FLOW-3D	2D/3D	Yes	Yes	Yes	Yes	Yes	Yes	Herschel-Bulkley	Yes	High
DAN3D	Quasi-3D	-	-	Yes	Yes	-	Yes	Frictional, Voellmy, Bingham, Turbulent	No	NA
MADFLOW	Quasi-2D/3D	Yes	Yes	Yes	Yes	Yes	Yes	Frictional, Voellmy, Quadratic, Bingham Herschel-Bulkley ; Coulomb viscous, Plastic, Lava flow; Sassa model	No	NA

Figure 20: Available Software Packages for Application to Tailings Dam Breach and Runout Modelling (Source: CDA, 2021)

2.5 Discussion

2.5.1 Uncertainties

Several uncertainties exist in the tailings dam breach runout analysis, and the technical challenges discussed below need to be addressed when conducting a risk assessment of tailings dams.

2.5.1.1 Selection of rheological model

One of the major challenges when conducting runout analysis is the selection of suitable rheological models for different tailings materials. Since the rheological properties and sediment concentration of tailings vary among sites, the selection of a rheological model a priori can be difficult. However, the development of a physical model using fluid mud with properties similar to those of site tailings could be useful for addressing this issue. Numerical model simulations using different rheological models can be performed, and the model that best agrees with the observed (experimental) data can be selected. Based on the study conducted by Ghahramani et al. (2022), who used the Bingham and Quadratic models for the back analysis of a historical event, different viscosity values had to be assigned in each model. This emphasizes the need to study each rheological model individually to calibrate more historical events and obtain a better understanding of the selection of the numerical model in each case.

2.5.1.2 Rheometric analysis

Rheometric analysis of tailings samples are not performed in most of the studies and published values are used to input the rheology parameters (Mahdi et al. 2020, Sreekumar et al. 2022, Sreekumar et al. 2023). Based on a study conducted by Ghahramani et al. (2022), there is a lack of published viscosity measurements for tailings with solid concentrations more than 45-50%. In addition, most published measurement values are not applicable to tailings that have settled or consolidated over time. The values of yield stress and viscosity depend on many site-specific factors, such as particle size, shape, solids concentration, and shear rate. Hence, a lack of field studies and geotechnical laboratory testing can cause uncertainty in the actual values of the rheological parameters and their relationship with different numerical models. Based on Ghahramani et al. (2022), multiple sets of rheological parameter values can produce similar outputs, and selecting the most appropriate set of values requires an adequate understanding of the rheology of the tailings material. In this study, it was also noted that the

input rheological parameters are not transferable between the rheological models. Thus, it is necessary to develop a stepwise technical approach to calibrate the yield stress and dynamic viscosity values. For this, a comprehensive literature review, assessment of available laboratory and field data, and sorting of these data based on tailings materials are essential.

2.5.1.3 Estimation of breach outflow hydrograph

One of the key challenges in tailings dam breach runout analysis is the proper estimation of the outflow hydrograph. The outflow rate is critical in the runout analysis and downstream risk assessment. There are many uncertainties in calculating breach release volume. The current industry practice is to use historic tailings dam breach shapes and slopes, or empirical formulations derived from historical datasets (Kheirkhah Gildeh et al. 2020). The breach release volume is highly dependent on the storage volume and where the supernatant pond is located. If the supernatant pond volume is larger, there can be excessive breach release. In addition, when a tailings dam with stored water collapses, at the start a flood wave containing mainly water may propagate downstream, and, subsequently, concentrated tailings may mobilize through the breach. The water may advance at a higher velocity, and dense mud may propagate only a relatively short distance (Martin et al. 2015). This two-phase mudflow characteristic has not been included in most studies and is a major limitation. In most models, the breach development time used in estimating the hydrograph is taken from data mainly adopted from previous water dam breach studies (Mahdi et al. 2020, Sreekumar et al. 2023). It is necessary to verify this approach as the peak of the breach outflow hydrograph estimated by software is also based on historical data and this can have significant impact when conducting risk assessments. The tailings release volume also depends on the type of failure mechanism and slope of the breach and hence a thorough site-specific failure mode analysis should be performed. Sensitivity analysis should be conducted by taking into account different breach slopes, and a range of breach release volumes should be developed when performing a risk assessment.

2.5.1.4 Consideration of downstream erosion and deposition

Water retention dam failures and their impact on downstream channel morphology due to erosion and sediment deposition have been analyzed extensively in the studies like Acker et al. (2008), Chen et al. (2015), Jiang et al. (2021), Baynes et al. (2015), Lane et al. (2007), Marchi et al. (2009), Carrivick et al. (2010). Geomorphic processes can cause increased discharge,

morphological channel evolution, and immense destruction (Eagle et al. 2021, Guan et al. 2016, Rickenmann and Koschni 2010). Likewise, the tailings flow after a tailings dam breach is not limited to the flow of hyper-concentrated fluids, but there is extensive morphodynamic impact. Sediments can be entrained from the bed or get deposited on the bed resulting in a change in the sediment supply and ultimately change in the channel morphology. As a result, there can be significant variations in fluid properties, such as viscosity, density, and yield stress, with space and time. Most modelling studies conducted in the past considered mudflow over a fixed bed, which is a simplified approach. In the case of Mount Polley tailings dam failure, the influence of the tailings flow on the downstream channel morphology was considerable and similar to the changes resulting from severe debris flow and flooding events (Cuervo et al. 2017). Hence, a mobile bed modelling approach may be needed when conducting risk assessments.

Based on the experimental study conducted by Iverson et al. (2011), it was found that the fluid velocity of mudflow can either rise or fall with sediment transport and it depends on the bed material water content. Likewise, in the study conducted by Pudasaini and Krautblatter (2021) on landslide dynamics, it was found that erosive landslides can increase or decrease mobility, and this trend depends on the site as well as the tailings material. Sreekumar et al. (2023) studied the effects of sediment exchange on the dynamics of tailings flow and compared the flow over mobile and fixed beds. From the model results it was concluded that when sediment transport is considered, maximum mudflow depth of the flood wave is higher, and when it is neglected, downstream flood arrival time is underestimated. Thus, to predict the immediate physical impacts following a failure, such as channel avulsion, erosion, and deposition zones, a mudflow mobile bed model that accounts for variable density and multiple sediment classes is necessary. There was a large difference in velocity between the mobile and fixed bed models and it produced completely different flood arrival time (Sreekumar et al. 2023). However, in this 2D modelling study, velocities of both solids and fluids were combined into the bulk mixture velocity. When a tailings dam with supernatant pond breaches, a water flood wave initially travels downstream which is followed by a dense mudflow. This two-phase mudflow characteristic was not considered in the modelling study of Sreekumar et al. (2023) and is a major drawback. The vertical variability of properties such as density, viscosity, and yield stress may have significant influence in modelling results and thus may result in serious consequences when conducting risk assessments and while planning for evacuation. A flow chart showing

different uncertainties in tailings dam breach studies is shown in Fig. 11.

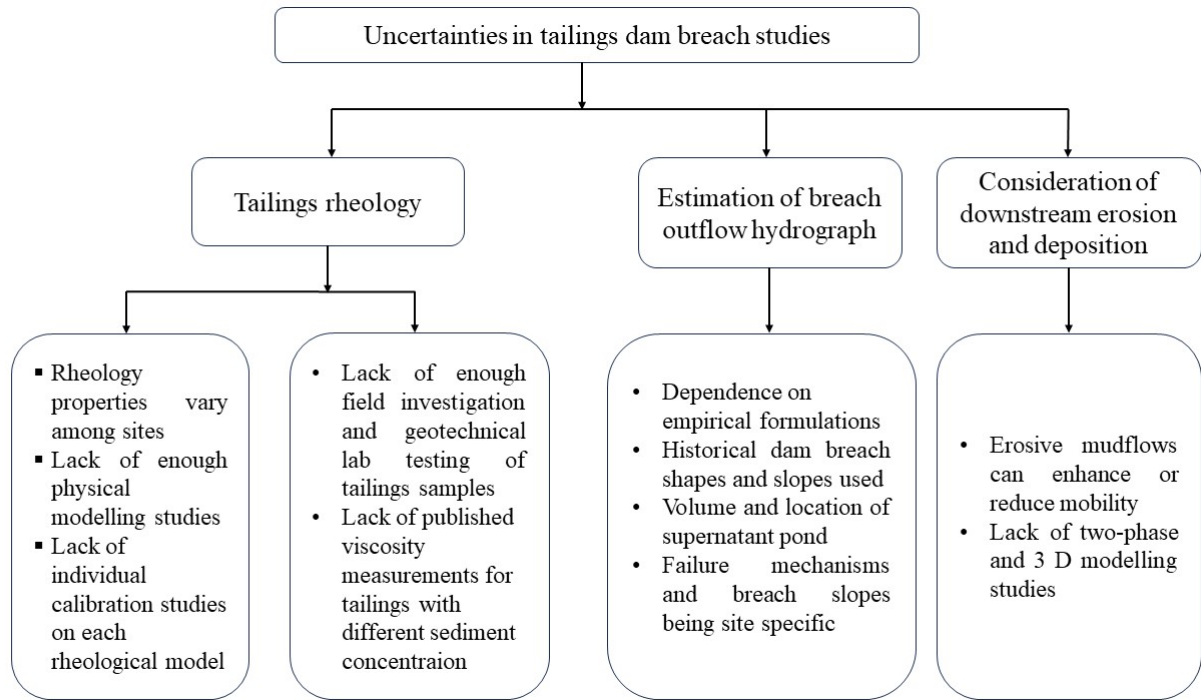


Figure 21: Flow chart showing different uncertainties in tailings dam breach studies.

2.6 Application of GIS and remote sensing in tailings dam breach analysis

Remote sensing and geographic information systems (GIS) have become mainstream technologies for the study, identification, and monitoring of natural hazards. This technology provides tools for the collection and analysis of spatial data for pre-disaster preparedness and post-disaster restoration (Luscombe and Hassan 1993). Earth observation satellite images have large-scale scientific applications such as environmental monitoring, weather prediction, and archaeological surveys. These images are significant data sources for rebuilding historical records and monitoring the performance of different hydraulic structures, such as dams (Schumann et al. 2018). Using GIS techniques integrated with hydraulic modelling software, potential dam-break flood hazards can be forecasted, and an early warning system can be set up. A 3D visualization of the spatiotemporal variations of dam-break floods, risk assessment of dam-breaks, flood disaster management, and land use planning downstream can also be implemented (Derdous et al. 2015). Geometric data can be prepared and directly imported into hydraulic models. Moreover, the data generated by the hydraulic model can be moved to a GIS,

and inundation maps can be prepared for further analysis. (Pandya and Jitaji 2013).

2.6.1 Pre-event and post-event elevation data

According to Rotta et al. (2019), satellite-driven soil moisture index, Interferometric Synthetic Aperture Radar (InSAR), and multispectral high-resolution imagery can be used to evaluate pre-disaster scenarios and the reasons of tailings dam failure. Rotta et al. (2019) examined the case study of Brumadinho tailings dam collapse in Brazil and their study showed a declining trend in the moisture content at the surface; hence, it could be concluded that seepage erosion was the reason for the tailings dam collapse. The volume of the tailings dam can be verified against the mining company's declared volume given in the environmental licenses' processes using remote sensing data. Geoprocessing tools can be used to measure the volume of the tailings. The Digital Terrain Model (DTM) before building the dam can be subtracted from the DTM during the study year to obtain this measurement. The results could be used to check if the dam is in compliance with environmental legislation, and this methodology could be used for the precise monitoring of tailings dams (Camargos et al. 2019). During the tailings flow following a dam breach, there can be entrainment and considerable morphological changes in the downstream channels. Pre-event and post-event DEM of the study site can be used to quantify these changes caused during the event. Nearest neighbor technique can be used to resample the pre-event and post-event DEMs to the same resolution and when subtracted a difference DEM can be computed (Sreekumar et al. 2022). This DEM can be used to analyze the event in detail, know the changes in the downstream area, and estimate the volumes of final erosion and deposition. Using this difference raster, the spatial variation in erosion and deposition patterns and the site features, such as the inundated area, erosion depth, and deposition depth, can be obtained.

2.6.2 Estimation of runoff coefficient

Tailings dams are commonly located in valleys, and the surrounding terrain can pose a threat to the stability of tailings dams. In some cases, the runoff from the watershed can enter the tailings pond and can be a reason for the failure. In different study areas with the same soil type and rainfall conditions, surface slopes directly impact the generated runoff, and the runoff coefficient increases with increasing slope. In short, the slope is one of the crucial elements influencing runoff generation. The topography parameters, including ridges, river courses, and

mountain peaks can be calculated from the elevation models. Another factor is vegetation coverage, which plays a key role in eliminating storms and soil consolidation. Moreover, the rainfall interception and blockage functionalities of different vegetation vary, which can have a significant impact on the runoff coefficient. The soil consolidation and rainfall retention capacity of different vegetation types are different. Fractional Vegetation Coverage (FVC) is an important indicator of the distribution of surface vegetation and ecological environment. FVC is the ratio of the vertically projected vegetation area to the total surface extent and is mostly expressed in relation to the unit area (Evans et al. 2006). Remote sensing has many efficient methods for retrieving FVC at local and global scales (Wanjuan et al., 2017). The pixel dichotomy model based on Normalized Difference Vegetation Index (NDVI) is widely used to estimate FVC. The pixel dichotomy model is a remote sensing estimation model in which it is assumed that a pixel consists of vegetated and non-vegetated areas (Gutman and Ignatov 1998). In this model, the spectral data captured by the remote sensing sensor are linearly weighted on the basis of the component. The pixel dichotomy model is given by Equation (1):

$$FVC = \frac{(NDVI - NDVI_{min})}{(NDVI_{max} - NDVI_{min})} \quad (1)$$

where $NDVI_{min}$ and $NDVI_{max}$ are the minimum and maximum NDVI values, respectively, in the region. $NDVI_{min}$ and $NDVI_{max}$ values may be within a confidence level range due to the inevitable noise, and the real situation of the remotely sensed image determines the confidence level (Che et al. 2018). Remote sensing images can be used to derive vegetation information, and vegetation classification can be performed using the support vector machine (SVM) method (a machine learning method based on statistical learning theory) (Shi and Yang 2015). Slope, vegetation type and vegetation coverage can be used to estimate the runoff coefficient of the area using the Analytic Hierarchy Process model (AHP – a multiple criteria decision-making method based on weight assignment) (Oliva et al. 2017). Apart from the runoff coefficient, the catchment area size contributes significantly to the determination of the surface runoff. Both the average runoff coefficient and catchment area are determining factors for the risk assessment of tailings ponds. The risk index is obtained as the product of the catchment area and runoff coefficient and can be used to assess the risk of tailings ponds. This could be used to identify low-risk, moderate-risk and high-risk tailings ponds, and to provide focused safety monitoring during the rainy season (Che et al. 2018). These steps are summarized in the flow

chart shown in Fig. 12.

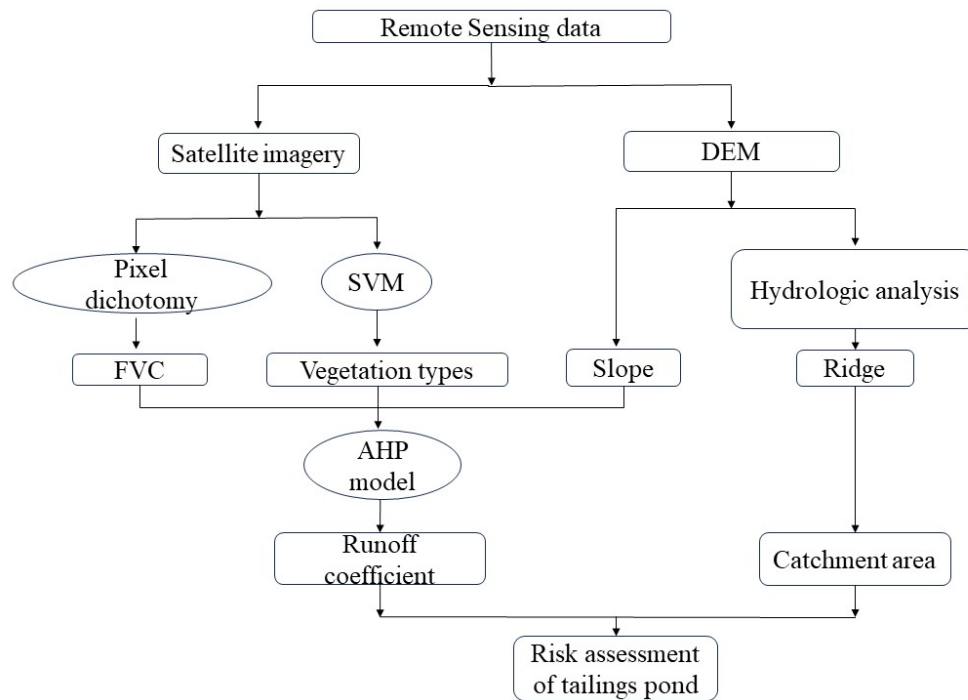


Figure 22: The flow chart of the risk assessment for tailings pond due to flow contribution from the watershed. (Che et al. 2018)

2.6.3 Spatial Resolution, Pixel Size, and Scale of images

Tailings slurry runout can submerge communities located downstream and other important facilities. Microtopography can occur in the form of bridges, buildings, and levees, which can obstruct and resist dam-break flows. The smallest building dimension should be used as the critical length scale of downstream areas. If the model resolution is insufficient, such features may not be captured, and the performance of the model may deteriorate. Hence, it is appropriate to choose scales finer than the size of the elements to enhance the modelling outcomes. For example, the scale chosen must be finer than the mean river width to properly delineate those channels and ensure flow connectivity between the channel and the floodplain.

Bank elevation is a critical factor in characterizing overbank flooding. An overbank flow happens when the channel water elevation reaches the floodplain elevation. As the grid size increases, the crest of the floodplain adjacent to the main channel is averaged and smoothed out and the elevation of bank is lowered. This can induce more overbank flooding in the simulation results (Jung and Jasinski 2015). The vertical accuracy of DEMs is important

because it provides local differences among adjacent elevation values and defines the intricacies of channel geometry, such as slope and aspect. If the river gradients are too low, only data with high vertical accuracy can capture small variations in the height differences. In most previous studies, remote sensing data with large vertical inaccuracies were used, which affected the modelling of the water depth and inundation patterns (Mahdi et al., 2020). The chosen scale was also larger than the channel dimensions (width), and the results overestimated the extent of flooding. If Light Detection and Ranging (LiDAR) data with high horizontal and vertical resolutions are available, they can be used to model narrow creeks. Low-resolution satellite images are recommended only for large rivers. Hence, such scale issues need to be considered in modelling, but currently, there are limitations to the available data products.

Relatively low resolution GeoBase DEMs or global DEMs are used for back analysis of historical events in most tailings dam breach studies (Sreekumar et al. 2022). According to Sreekumar et al. (2022), a physically meaningful set of values cannot be given to fluid properties such as the yield stress and viscosity during the calibration process if low-resolution DEMs are used. The main reason for the reduced accuracy of the low-resolution DEM results is the resolution being coarser than the channel dimensions and hence, the downstream channel will not be properly delineated. The limited vertical accuracy could lead to more fluid flow from channel cells to floodplain cells and could result in an increased flood extent. Thus, when conducting a detailed risk assessment, use of a low-resolution DEM to generate the model grid can reduce accuracy. Detailed assessment of the unreliability of using a low-resolution DEM should be performed prior to making risk analysis decisions. Multiple data products can be used concurrently until a high-resolution global DEM is available (Sreekumar et al. 2022). It is also necessary to ensure that parts of the DEM with different resolutions are stitched together using a proper merging procedure and that the fine details at the boundary are preserved.

2.7 Future Research Directions

As discussed in this paper, TDBA and modelling are complex and uncertain tasks. However, the importance of such analyses is increasingly recognized by the public, mine owners, consulting engineers, emergency planners and has attracted the attention and focus of academia. For example, journal and conference publications on TDBA have increased over the past decade and are still growing. The following are a few future research directions to consider:

2.7.1 Breach Parameters for Tailings Dam

Almost all empirical models (parametric models) developed for breach parameters are based on water retaining dams and not tailings dams. Given the tailings data based on breaches with known TSF characteristics and released volumes, the same regression relationships can be developed for tailings dam breaches. It is suggested that this analysis be completed based on tailings types and not combining all data together, so that each category represents the same ore type, materials, rheology, etc.

2.7.2 Physically Based Breach Models

More complex breach modelling is a major requirement. Physically based breach models will have to be employed by both academics and practicing engineers for breach modelling, as such models should better characterize the complex geotechnical behaviour of earthen embankment breaches by simulating the complex geotechnical characteristics of the embankment during the breach. HEC-RAS 2D developers recently implemented a Dam/Levee (DL) breach module in their model that can be further explored and tested for breach hydrograph modelling. Coupling the breach modelling and downstream flood routing in the HEC-RAS 2D model by applying a non-Newtonian solver should also be further investigated.

2.7.3 Data Base for Tailings Rheology

The tailings industry has created a database for historical dam breaches (e.g., WISE-URANIUM, 2024) to catalogue tailings dam failures worldwide. However, to the best of the authors' knowledge, a comprehensive database of rheology does not exist. The authors encourage mine owners to be open to sharing the tailings rheology information of their TSFs and contribute to a shared effort. A template could be prepared and shared on a sharing platform site accessible to mine owners worldwide to catalogue the rheology of tailings and embankment materials, at different stages of TSF development. This database will be of great help to practicing engineers and researchers to better model tailings dam breach and routing.

2.7.4 Downstream Routing Models

The CDA (2021) guidelines summarize the industry-accepted software packages for tailings dam breach and routing modelling. However, engineers must always be knowledgeable about the state-of-the-art modelling tools that best estimate the complex breaching processes. For

example, a tailings flood wave has a much higher potential of eroding the flow path and streams downstream than a water flood wave. However, most two-dimensional (depth-averaged) hydraulic models either do not have this capability or are not used as coupled models of hydrodynamics and sediment transport. With the advancement of computational fluid dynamics (CFD) models, the use of three-dimensional models should also be explored for TDBA.

2.7.5 Climate change impacts

Climate change impacts have also not been considered explicitly in most tailings dam breach studies. There has been increasing uncertainty with respect to climate change and hence while designing tailings dams it is necessary to factor in the associated risks. For developing a life cycle plan for current and future mining operations, it is essential to incorporate climate change adaptation and for that reliable data are required. The models must be updated based on the effect of climate change on risk components and new modelling scenarios must be developed by considering climate projections.

2.8 Conclusions

The conclusions drawn from this study are summarized below:

- It is necessary to assess the suitability of the empirical regression relationships for breach hydrographs developed from water retention dam failures for application to tailings dam breaches. New analyses should be conducted specifically for tailings dam failures. The analysis should be completed based on tailing types and not by combining all data so that each category indicates the same ore type, materials, and rheology.
- More physically based breach models should be employed for breach modelling, as they better characterize the complex geotechnical behaviour of earthen embankment breaches.
- There are different rheological models, such as the Herschel-Bulkley, frictional, Voellmy, Bingham, and turbulent models. There is a pressing need to study each rheological model individually to assess suitability for modelling historical failure events and to obtain a better understanding of the preferred rheological model to be selected for TDBA risk assessments.
- The lack of field investigation and geotechnical laboratory testing causes uncertainty in the actual values of the rheological parameters and their relationship with different

numerical models. To resolve this, assessment of available laboratory and field data and sorting of these data based on tailings materials are essential. Further laboratory tests are also recommended to estimate the rheological parameters of tailings materials.

- The multi-layer flow of saturated tailings and water for dams where the tailings are capped by supernatant water is not modelled in most tailings dam failure risk assessment studies. There is a need to consider the presence of a supernatant water layer above the coarse layers of tailings, and it is necessary to model mixing and settling while predicting the inundation extent.
- Two-phase mudflow modeling should be further investigated against available data.
- The entrainment of additional solids from the bed layer during the tailings flow can result in a dramatic increase in the sediment supply and considerable changes in the channel morphology. Only a limited number of two-dimensional morphodynamic modeling studies have evaluated such scenarios. With the advancement of computational fluid dynamics (CFD) models, the use of non-hydrostatic three-dimensional models can also be explored to consider downstream erosion and deposition during TDBA and flood wave routing.
- Sensitivity analysis with respect to various parameters such as grid, choice of rheological model, fluid properties, sediment properties, and failure mechanisms needs to be conducted. Also, advanced uncertainty analysis methods should be developed to analyze the range of uncertainty in the final results linked to the uncertainties in estimating the breach development time and outflow volume.
- Remotely sensed satellite imageries (e.g., SPOT) and elevation data (e.g., GeoBase DEM, Lidar) have large-scale scientific applications and play a key role in the identification and monitoring of natural hazards. Advanced remote sensing and GIS methods can be used in the risk assessment of tailings ponds.

3. Modelling the transport of tailings after Mount Polley tailings dam failure using multi-source geospatial data

3.1 Abstract

Tailings dams (TD) are usually located in valleys that are not easily accessible and hence one global digital elevation model (DEM) is used in most of the TD breach outflow modelling studies but the challenges this impose when calibrating visco-plastic rheological models has not been fully investigated. Implications of using GeoBase DEMs for model calibration is studied by comparing it with a model that is calibrated using a merged DEM generated from multiple products. The influence of rheological parameters, roughness coefficient and sediment concentration (C_v) on simulated variables is studied. It was concluded that when GeoBase DEM was used for back analysis of the event, physically meaningful set of rheology values could not be assigned. Flow behaviour was strongly influenced by C_v and least influenced by Manning's values. Runout distance was more sensitive to viscosity than yield stress. Mudflow depth and arrival time increased with increase in viscosity and C_v .

3.2 Introduction

Tailings dams (TD) are mining storage facilities constructed from waste rock to impound waste solids and water generated in a mine processing plant (Wang et al. 2014). A tailings dam accident can cause detrimental impacts on public safety and environment in the downstream areas (Mao et al. 2017). There has been a recent surge in the number of tailings dam failures, and it can be due to several factors like improper dam management, slope instability, foundation failure, natural hazards, extreme meteorological events (Zongjie et al. 2019). Based on magnitude-frequency statistics, tailings dam breaches with more than 1Mm³ outflow volume took place at an average recurrence interval of 2 to 3 years over the period of 1965–2020 (Rana et al. 2021). For ensuring the safety of downstream environment and human settlements, numerical risk analysis needs to be performed which involves understanding flow characteristics such as velocity and depth and identifying the possible extent of the downstream impact area (Derdous et al. 2015).

Conventional flood routing models are not dependable for predicting tailings dam breach outflows as they do not consider the non-Newtonian visco-plastic nature of tailings (O'Brien

and Julien, 2000). Some of the tailings dam breach outflow studies (e.g., Raman and Liu 2019, Dibike et al. 2018, Knight Piesold Consulting 2017) used a Newtonian hydrodynamic approach to model discharge mechanisms thus the non-Newtonian nature of tailings was overlooked. This caused the predicted results to deviate largely from actual tailings breach outflows because the rheological parameters viscosity (η) and yield stress (τ_y) were neglected, and the flood wave was modelled like a water dam-break. In previous studies like Raman and Liu (2019), only qualitative validation of the simulation was conducted based on the flood extent in the post-event satellite imagery and depth validation was not conducted. Here, only the lateral expansion of water was considered and, according to Lim and Brandt (2019b), it will be advantageous to perform water surface elevation analysis in addition to flood extent analysis. If only the flooding extent is analyzed, it may erroneously be concluded that lower resolution digital elevation models (DEMs) can produce results equal to higher resolution DEMs. It is important to perform depth validation along with flood extent validation to assess the performance of the model.

Studies like Mahdi et al. (2019) used Flo-2D model to study the consequences of a hypothetical breach of Alberta oil sands TD and Dutto et al. (2017) used Smooth Particle Hydrodynamics (SPH) depth-integrated Biot–Zienkiewicz model for back analysing the Gypsum tailings impoundment flowslide and the Aberfan flowslide in 1966. Pirulli et al. (2017) used RASH3D to model the failure of the Stava Valley TD (Northern Italy). Wang, K. et al. (2018) used SPH method to model the 2015 Brazilian Fundao TD breach and to predict the runout distance following the potential failure of an operating tailings pond in Northern China. Pasculli et al. (2021) used Riverflow 2D model to assess an early warning system for Alpine debris flow. Ghahramani et al. (2022) used rheological models like MADflow, DAN 3D, Flo-2D, FLOW 3D for back analysing 1985 Stava and 1994 Merriespruit TD failures. Since tailings dams are usually located in valleys which are not easily accessible, one global DEM is used in most of the studies but their accuracy and impacts when calibrating visco-plastic rheological models has not been fully investigated. The use of Unmanned Aerial Vehicles (UAV) offers new potentialities with high level details even when the study zone is not accessible for traditional terrestrial survey techniques (Sammartano and Spanò 2016). Several assumptions and simplifications may be involved when modelling tailings flow. For example, there can be uncertainties in rheology parameters, inflow sediment concentration, surface roughness along

with uncertainties in underlying topography. The relative importance of these parameters on simulated variables like flood extent, flow depth and flood arrival time is not well-understood.

In this study, implications of using global DEMs for the calibration of a model is studied by comparing it with a model that is calibrated using a merged DEM generated from multiple sources like UAV photogrammetry data. Data pertaining to the catastrophic breach of the Mount Polley mine tailings impoundment that occurred on August 4th, 2014, will be used to assess the model performance and to identify the challenges associated with the selected elevation models during calibration. The viability of open-source tools such as Raster Mosaic tool in ArcGIS Pro software (ESRI 2020) and a blending process developed by Gallant (2019) for merging elevation data from multiple sources will be evaluated and compared. Flow depth validation along with flood extent validation will be performed for comprehensive understanding of the model performance. The influence of other input parameters like rheological parameters, Manning's n values and inflow sediment concentration on simulated variables flood extent, flow depth and flood arrival time will be also investigated.

3.3 Methodology

3.3.1 Study site

The Mount Polley gold and copper mine tailings pond, located in British Columbia, Canada is the study site for this research. The tailings dam disaster took place on 4th August 2014, when the dam failed on a sunny day due to a weak foundation constructed on a glacial layer. The dam embankment collapsed progressively, i.e., a sequence of localized failures developed initially in the dam foundation and then advanced through the core in the upstream direction (Zabolotnii et al. 2022). As a result of the breach, a slurry mixture of mining waste tailings and water travelled as debris flow into Polley Lake (PL) as well as down Hazeltine Creek (HC) into Quesnel Lake (QL) and eventually into Cariboo River (Figure 23). Prior to the dam breach, HC located downstream of the dam was about 5 m in width and 0.3 m in depth. However, the breach outflow eroded the floodplain and channel of HC, and the impacted zone was about 136 hectares in area (Golder Associates Ltd., 2015). The model domain in this study included the tailings dam, PL, HC, and it extended until the measurement station located north of the QL at Likely.

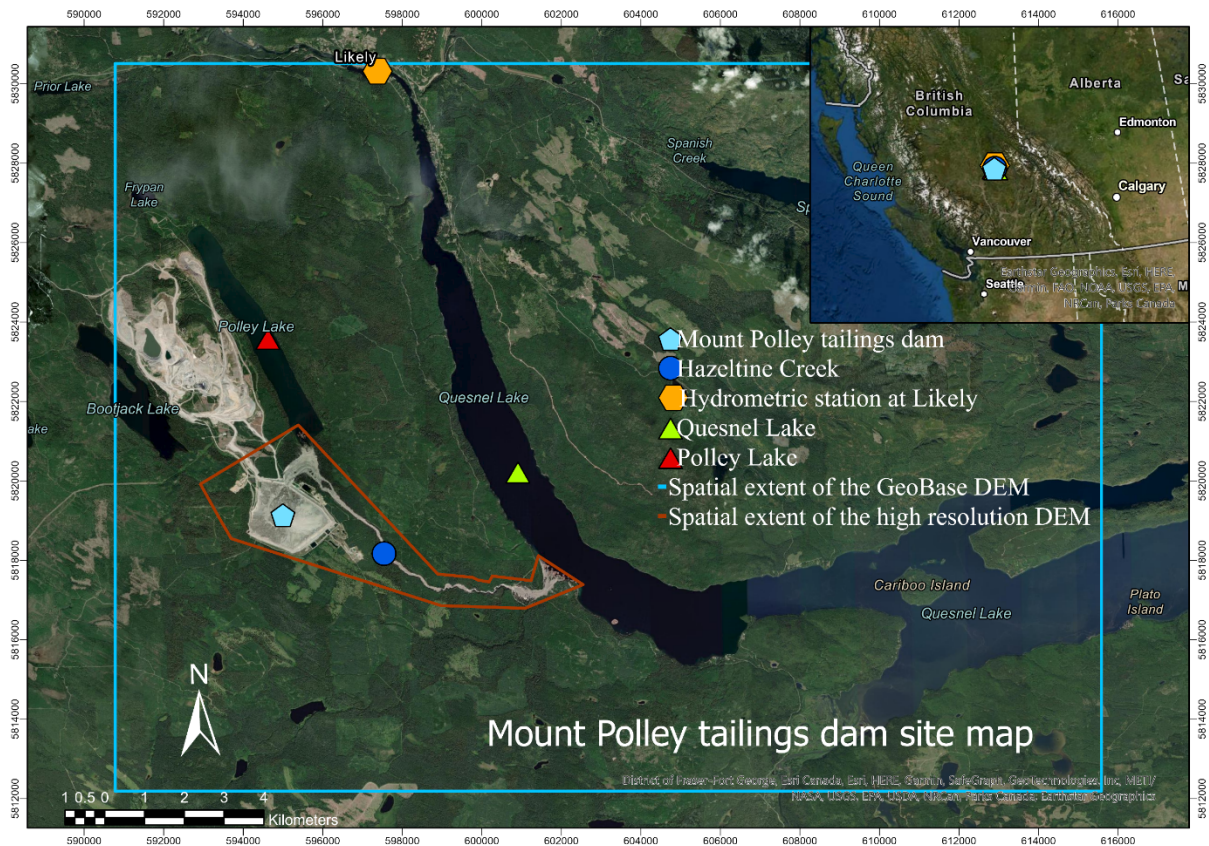


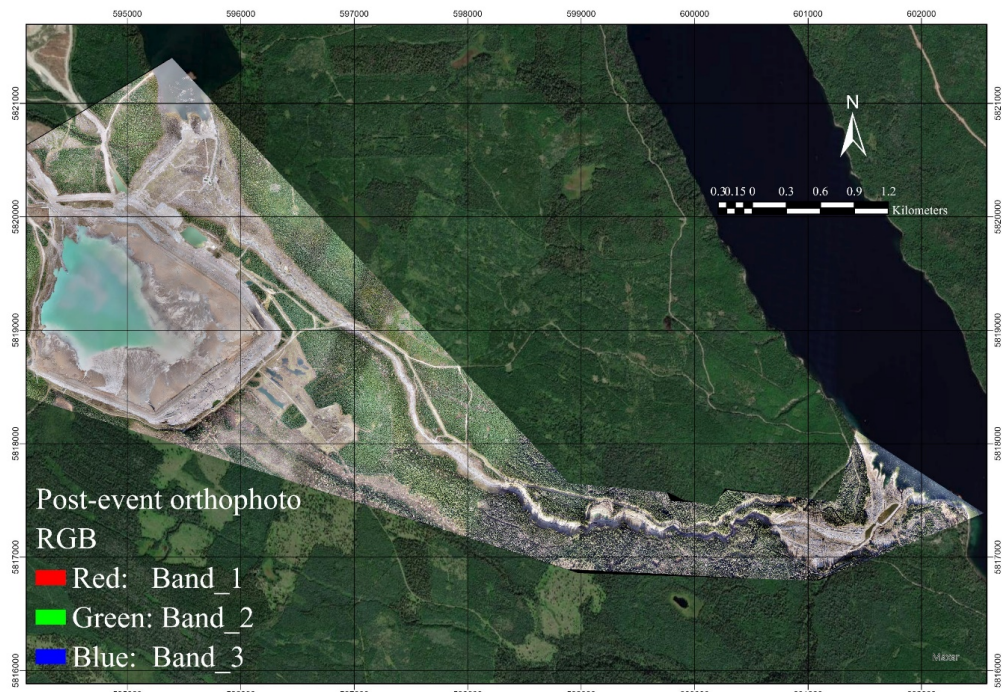
Figure 23: Study site map including the spatial extent of the available pre-event dataset.

3.3.2 Data Sources

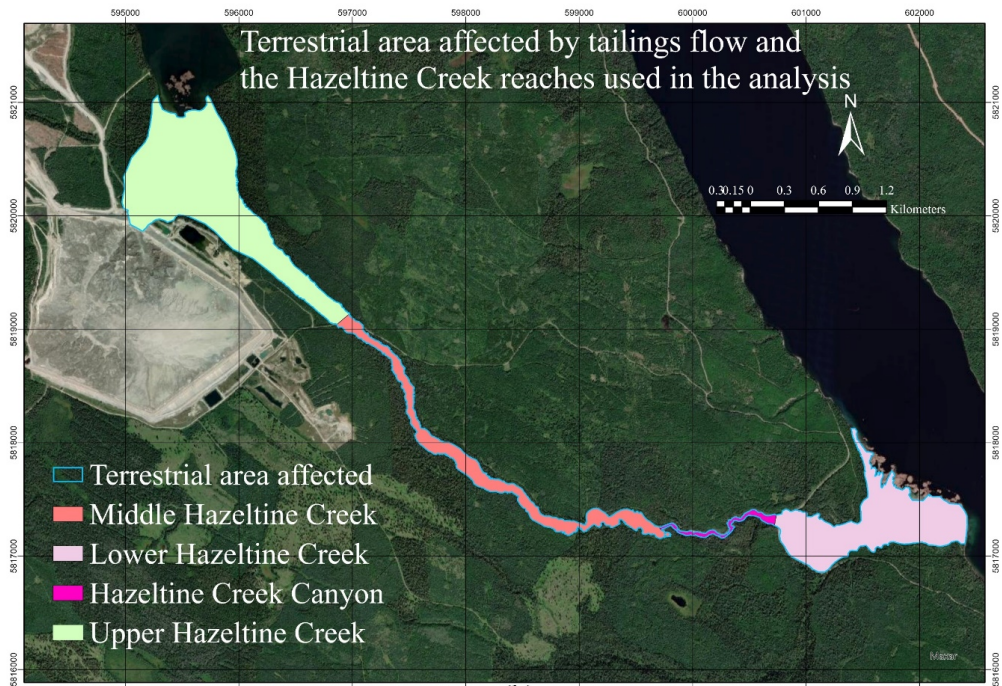
Remote sensing data used in this model development were:

- High resolution (2.5m) 2013 Digital Surface Model (DSM) derived from PRISM-ALOS image by AW3D (aw3d.jp), which covers the HC floodplain and the tailings dam location.
- Open-source Canadian DEM, 2013 or GeoBase DEM (global DEM) of 18m resolution that covered the whole study area (i.e., the tailings dam, HC, PL, and QL). This elevation model was extracted from the Geospatial Database (GDB), hypsographic and hydrographic elements of the National Topographic Data Base (NTDB), 2005 at the scale of 1:50 000, different scaled positional data acquired by various provinces or remotely sensed imagery resolution (Canadian Digital Elevation Model 2013).

- DSM of resolution 13 cm from Unmanned Aerial Vehicle (UAV) dataset acquired in 2019 by Natural Resources Canada which was used to generate bare earth elevation.
- Water depth contours of PL (Scale 1: 12000) and QL (Scale 1: 24000) (Canada marine charts 2021).
- SPOT6 PAN-sharpened multispectral image of resolution 1.5m which was used to generate the pre-event Land cover (LC) map.
- Post – event orthophoto of resolution 10cm provided by the Mount Polley Environmental Team of the Imperial Metals, Bing satellite imagery of resolution 50 cm (ESRI 2020), and a map of terrestrial area affected by debris flow (Golder Associates Ltd., 2015). These post-event data provided a guide to determine the flood extent in the HC. Post-event orthophoto and the extent of terrestrial area affected by the event are shown in Figure 24.



(a)



(b)

Figure 24: (a) post-event orthophoto b) Terrestrial map of the affected area.

3.3.3 Model setup

The modelling of the transport of tailings after the Mount Polley tailings dam failure was done using FLO-2D, a non-Newtonian numerical model that uses a visco-plastic rheological

relationship. Flood routing is accomplished through numerical integration of the equations of motion and the conservation of fluid volume. In this model, eight potential flow directions are defined i.e., four compass directions and four diagonal directions. The constitutive fluid motion equations include the continuity equation and the momentum equation:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = i_s \quad (5)$$

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial h}{\partial x} + (S_f - S_o) g = 0 \quad (6)$$

where i_s is the source/sink term, h is the flow depth, S_f is the friction slope, g is gravitational acceleration, S_o is bed slope, and u is the depth averaged velocity in one of the eight flow directions, x . This equation represents the one-dimensional depth averaged flow, and the equations of motion are applied by computing the average flow velocity across a grid element boundary one direction at a time. Each velocity computation is one-dimensional and is solved independently of the other seven directions.

Central difference and Newton-Raphson methods are used to solve the depth averaged velocity in each flow direction. The discharge in each direction across the boundary of the grid element is calculated by multiplying velocity and cross-sectional area. The net discharge is the summation of the discharges in 8 directions.

$$\Delta Q_i^{t+1} = \sum_{j=1}^8 Q_j^{t+1} \quad (7)$$

where i, j indicate the number of flow directions, $t+1$ represents the next time step. The flow depth at the next time step is:

$$\Delta h_i^{t+1} = \frac{\Delta Q_i^{t+1} \Delta t}{A_s} \quad (8)$$

where Δt and A_s are the time step and surface grid area respectively (FLO- 2D Software Inc. 2019).

The main steps for tailings dam-break and run-out analysis include: (i) Selection of the failure mechanism, estimation of the total volume of tailings released, breach development time, outflow hydrograph, tailings' characteristics like sediment concentration and rheology parameters (ii) input of the downstream terrain (elevation data and flow resistance) (iii) routing

of the outflow hydrograph through the downstream valley (iv) estimation of flood levels and (v) sensitivity analysis to determine the robustness of the results (Llano et al. 2017).

3.3.3.1 Developing breach hydrographs.

The parameters used for the tailings dam breach modelling included size of the impoundment, volume released, release flow rate, duration of the event and the sediment concentration in the tailings. After Mount Polley tailings dam breach, about 25 Mm³ of tailings along with water i.e., about 10.6 Mm³ supernatant water, 7.3 Mm³ tailings solids, 0.6 Mm³ construction materials and 6.5 Mm³ interstitial water were released. The average sediment concentration in the outflow was about 30% and the mean particle size was 50 µm (Petticrew et al. 2015). According to the Report on Mount Polley tailings storage facility breach (2015), the flow abated after almost 14 hours.

In a tailings dam breach failure, only a portion of the tailings get released, depending on the type and volume of stored tailings, volume of the stored water, the dam height and construction method, the failure trigger, etc. (Martin and Akkerman 2017). Empirical approaches are often employed to estimate tailings release volume (O'Brien et al. 2015). For the Mount Polley case study, the total volume of the breach outflow (25Mm³) was readily available from literature, thus the “Tailing’s Dam failure Volume Estimate Tool (TDVET)” developed by O'Brien et al. (2015) was used only to distribute the release volume over the known duration of the entire event. Similarly, the hyper concentrated sediment flow flood wave progression was simulated by distributing the concentration by volume over the duration of the hydrograph. For this, several model runs were performed using different values of maximum volumetric sediment concentration and the maximum value (0.5) was calibrated to ensure total solids outflow matched the observed data. The generated outflow hydrograph and sediment concentration time series (Figure 25) were used as inflow boundary conditions in the model. The distribution of tailings constituents is assumed to be homogeneous i.e., there is full mixing of the water with tailings solids.

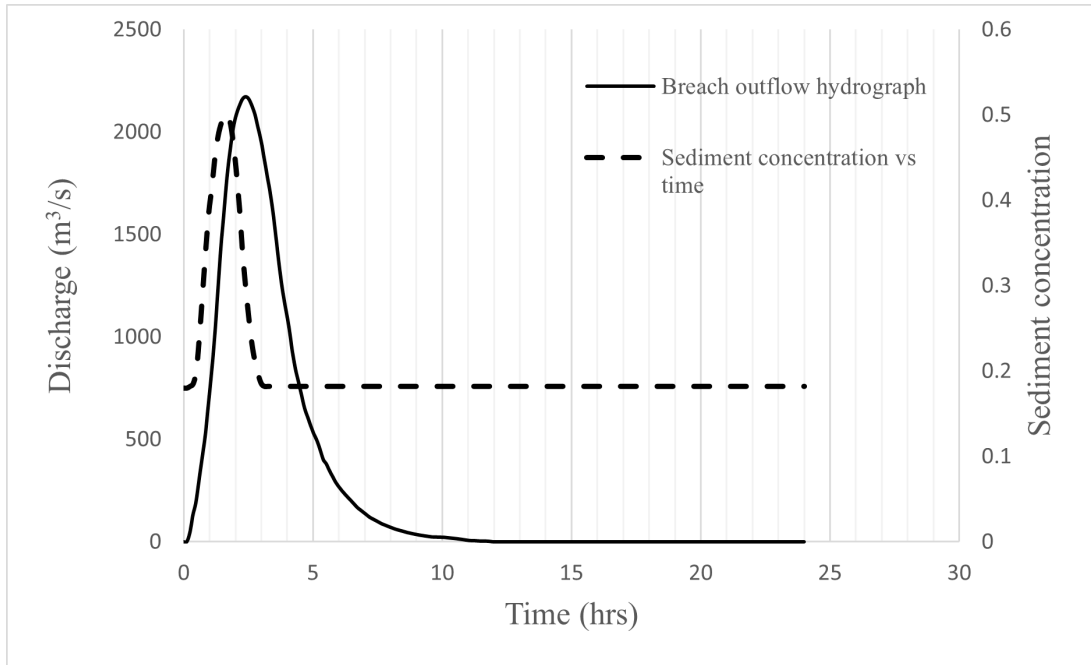


Figure 25: Tailings dam breach outflow hydrograph and breach sediment concentration time series data developed using Tailing's Dam failure Volume Estimate Tool (TDVET).

3.3.3.2 Topography and flow resistance

In this study, highly resolved elevation data were required to delineate properly the tailings dam breach location and HC, which was the steepest and narrowest area out of the entire domain. Many topographic undulations could be found in the hill shade layer from the 2013 DSM (Figure 26 a1) due to the presence of vegetation downstream of the tailings dam as indicated in the 2013 SPOT satellite image (Figure 27a). 2019 DSM of resolution 13cm from UAV was chosen to get the above ground level heights of the vegetation along the HC. The UAV dense point cloud data were classified as ground and non-ground points in CloudCompare software (CloudCompare 2.7, 2020) and the canopy height model was extracted. Along the HC floodplain, computed canopy heights were used to remove the surface features. The site close to the tailings dam failure was not covered in the 2019 DSM generated from UAV photogrammetry. Hence, to remove the surface features, the bare earth and sparsely vegetated areas were identified from the LC map (Figure 27 b) and the elevation of these classes were used to perform surface interpolation.

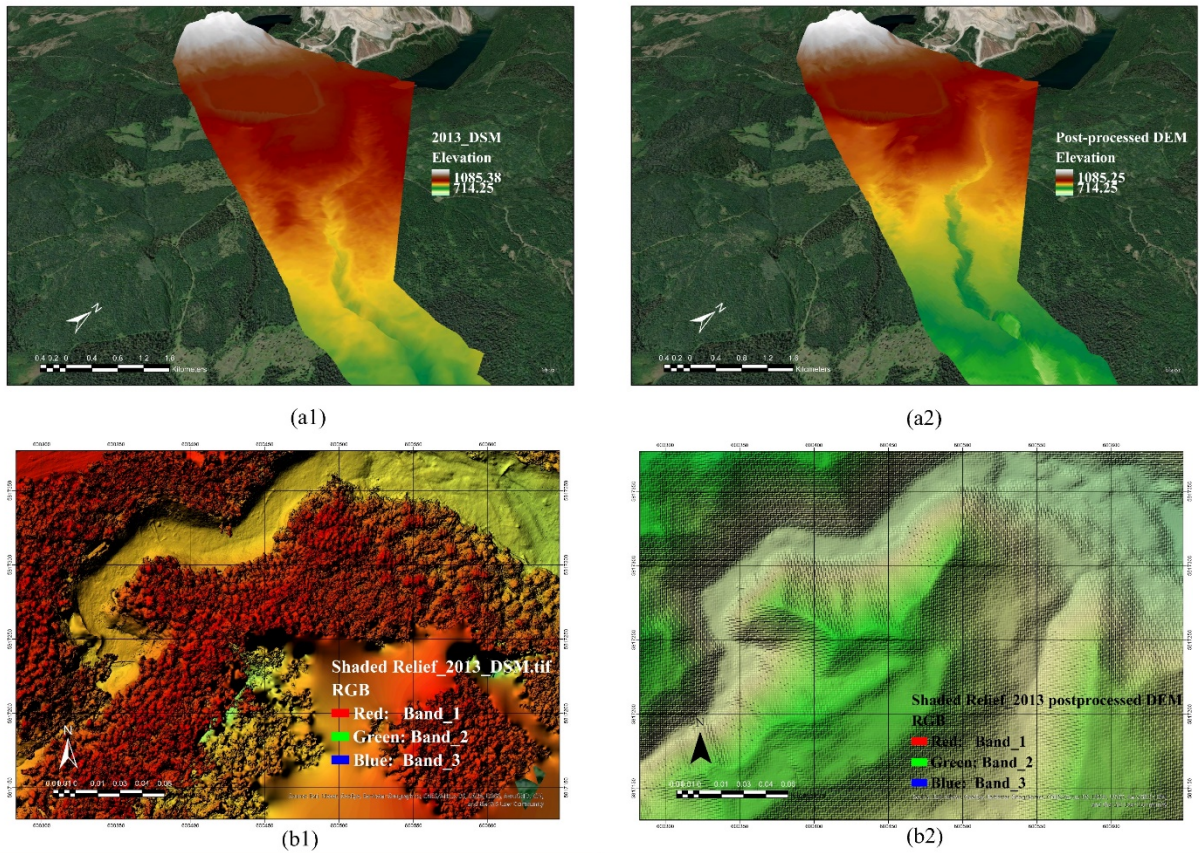


Figure 26: Comparison between hill shade layers from (a1) 2013 digital surface model (DSM) (a2) post-processed digital elevation model (DEM) in 3D; (b1) DSM and (b2) DEM at the steep gorge entrance point to the Lower Hazeltine Creek.

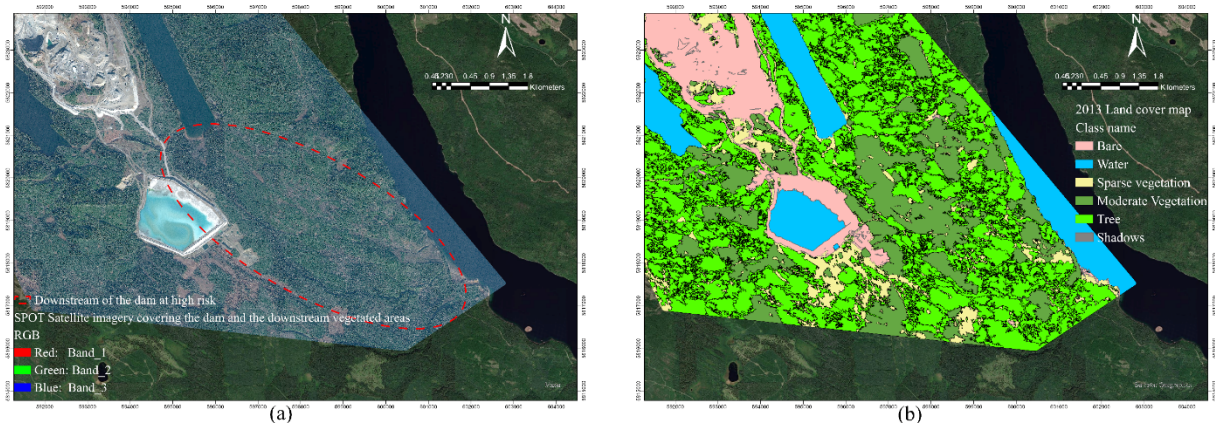


Figure 27: (a) 2013 SPOT satellite imagery showing the downstream vegetated area at high risk and (b) the land cover map derived from it.

Following this, the hydrology tools in ArcGIS Pro were used to model the movement of water across the surface. The sinks in the generated DEM were filled and any imperfections in data were removed. To understand the flow direction from each cell to its steepest downslope neighbor, flow direction arrays were generated from the filled DEM and this raster was used to generate flow accumulation raster for highlighting the total accumulated flow from higher elevation cells to lower elevation cells. This flow accumulation raster plays a key role in flood hazard mapping, dam failures and landslides (Atif et al. 2020). This raster was used to ensure that there is hydrologic connectivity in the generated DEM without any break lines.

In flood modelling studies, high resolution terrain models are often used to represent the area of real interest, and low resolution or global digital elevation models are used beyond the focus area. The generated high-resolution DEM provided detailed elevation data in the vicinity of HC, but less detailed and open-source GeoBase DEM data had to be used elsewhere, and these two DEMs had to be merged. Both the high-resolution DEM and the GeoBase DEM used NAD_1983_UTM_Zone_10N projection and Canadian Geodetic Vertical Datum 1928 (CGVD28). The resolution of GeoBase DEM was 18 m and that of high-resolution DEM was 2.5 m. In the confluence of the HC and the QL, the elevation of the GeoBase DEM was 7 m lower than the high-resolution DEM, hence 7 m was added to the GeoBase DEM elevations to align them. However, significant discrepancies were still present at the boundary of the high-resolution DEM and the GeoBase DEM due to less accurate details in the coarser DEM or broader scale variations. For merging rasters, open-source GIS tools such as Raster Mosaic tool in ArcGIS Pro software (ESRI 2020) proved insufficient, so the blending process developed by Gallant (2019) was used to avoid sudden changes in slope or height at the merging location. The first step for smoothing the transition was to calculate the difference between the two rasters where they overlap and to generate a difference raster. Since the high-resolution DEM is more precise, it was left untouched, and all the changes were applied to the GeoBase DEM. Two filters were used for this purpose namely uniform filter and Gaussian filter. Uniform filter (`scipy.ndimage.uniform_filter`) is generally used for reducing the noise in an image by replacing the value of a pixel by the mean value of an area centered at the pixel. Gaussian filter (`scipy.ndimage.gaussian_filter`) is similar to the uniform filter but weighted in favour of the pixels closer to the center (Dror 2015). In this case, to generate the difference raster, uniform filter was used to calculate the mean difference in a 3x3-cell square neighbourhood and the no

data values beyond the overlap area were replaced with the mean values. This extends the difference value by one cell beyond the overlap area where GeoBase DEM is the only source. This filter was applied once more to extend the difference values by 2 cells beyond the overlap area. The uniform filter ensures that fine details are preserved adjacent to the boundary (Gallant 2019). Following this, two further extrapolation steps were performed using Gaussian filter and this helped to extend the difference values to farther distance beyond the transition area. It was noted that some abrupt transitions from non-zero to zero values were still present at the edges and hence, weighting values were computed that changed smoothly from one at the original boundary to zero at the edge of the extended difference. These weighting values were then multiplied with the extended difference to produce the desired smooth transition to zero differences at the outer edge. This difference surface was then added to the GeoBase DEM to create a coarse resolution DEM that had the same elevations as the high-resolution DEM at the boundary. This coarse resolution DEM was then resampled to 2.5m resolution and then merged with the high-resolution DEM to create a 2.5m resolution merged DEM.

When cross sections were drawn across the lakes and elevation profiles were plotted, it was evident that the GeoBase DEM failed to model the submerged lakebed effectively. The elevation values in the GeoBase DEM represented the water surface elevation and not the bare earth elevation. Hence surveyed bathymetric data were required for the complete representation of the lake bathymetry. Water depth contours of PL (Scale 1: 12000) and QL (Scale 1: 24000) were subtracted from the merged DEM to obtain the final bare earth elevation model.

The FLO-2D model routes surface water through the floodplain using the Manning's equation and the Manning's n friction factors are selected based on land-use features. Satellite imagery of resolution 1.5m was used for the classification of the land cover types. Six classes determined were bare earth, moderate vegetation, shadows, sparse vegetation, trees, and water, where elevation of sparse vegetation = <1m, moderate vegetation = 1-3m, trees = >3m.

3.3.3.3 Flood wave routing

Mudflows resulting from a tailings dam breach are hyper-concentrated non-Newtonian flows thus the equations of motion depend on sediment concentration which is tracked dynamically within the model. The shear stress in hyper-concentrated sediment flows is the sum of five shear stress components (FLO- 2D Software Inc. 2019).

$$\tau = \tau_c + \tau_{mc} + \tau_v + \tau_t + \tau_d \quad (9)$$

where τ_c is cohesive yield stress;

τ_{mc} is Mohr-Coulomb shear;

τ_v is viscous shear stress;

τ_t is turbulent shear stress;

τ_d is dispersive shear stress.

When written in terms of the shear rate $(\frac{\partial u}{\partial y})$ the following quadratic rheological model can be

defined (O'Brien and Julien, 1985):

$$\tau = \tau_y + \eta \frac{\partial u}{\partial y} + C \left(\frac{\partial u}{\partial y} \right)^2 \quad (10)$$

where $\tau_y = \tau_c + \tau_{mc}$

and C is the turbulent- dispersion given as:

$$C = \rho_m l^2 + \frac{\pi}{12} \left(\frac{6}{\pi} \right)^{1/3} \sin^2(\alpha_1) \rho_s (1 - e_n^2) C_v^{1/3} \quad (11)$$

where ρ_s is the density of debris,

ρ_m is density of mixture,

l is the Prandtl mixing length,

e_n is energy restitution coefficient,

C_v is volumetric sediment concentration,

α_1 is averaged impact angle of solid.

Due to increased particle interactions in mudflows, dispersive stress increases, and it leads to the increase in the flow resistance (n_{td}). This increased flow resistance is calculated by modifying the turbulent flow resistance n value (n_t) with an exponential function that includes C_v .

$$n_{td} = n_t b e^{m C_v} \quad (12)$$

where n_{td} is the modified flow resistance, m is an exponent (6.0896), b is a coefficient (0.0538). In the estimation of the turbulent-dispersive slope (S_{td}) which is approximated from the Manning's equation, this modified n value replaces the typical n value as:

$$S_{td} = \frac{n_{td}^2}{H^{4/3}} \quad (13)$$

where H is the hydraulic radius.

Total friction slope is determined as the summation of yield stress slope S_y , viscous slope S_v , and turbulence slope S_{td} .

$$S_f = S_y + S_v + S_{td} \quad (14)$$

In the expanded form, total friction slope is given as:

$$S_f = \frac{\tau_y}{\gamma_m H} + \frac{K\eta u}{8\gamma_m H^2} + \frac{n^2 u^2}{H^{4/3}} \quad (15)$$

where γ_m is specific weight of the fluid and K is a resistance parameter (FLO- 2D Software Inc. 2019).

The sediment concentration-dependent parameters defining the non-Newtonian fluid properties are τ_y and the Bingham η . Based on the laboratory analysis of the rheological properties of mudflow deposits carried out by O'Brien' and Julien (1988), τ_y and η are exponential functions of C_v and the empirical relationship derived is given as:

$$\eta = \alpha_1 \exp(\beta_1 C_v) \quad (16)$$

$$\tau_y = \alpha_2 \exp(\beta_2 C_v) \quad (17)$$

Regression analysis was done to obtain the values of the four empirical coefficients α_1 , β_1 , α_2 , β_2 and these empirical coefficients are considered as calibration factors. Equations 15-17 are used for the prediction of the non-Newtonian behaviour of the tailings flow.

For routing the deep-water slow velocity movement in the PL and QL, the reservoir routing method described in the FLO-2D documentation (FLO- 2D Software Inc. 2019) was used. This method computes the slow velocities in reservoirs using a friction slope equation in the form of Manning's equation but with a variable flow depth exponent that is a function of both depth and slope. Based on this routing method, a high n value of 0.2 was assigned to each reservoir grid element.

3.3.3.4 Validation and model sensitivity analysis

The model was calibrated using the high resolution (2.5 m) and GeoBase (18 m) elevation models by systematically varying other model parameters like tailings' characteristics like τ_y , η , sediment concentration and Manning's coefficients. Flood depth measurements together with post-event flood extent data were used to assess the accuracy of each simulation.

Measured water level and recorded flood outlines.

Time-history of the water level recorded at Water Survey of Canada hydrometric station 08KH011 located near Likely (see Figure 23) on August 4, 2014, was used for the validation of the model (Golder Associates Ltd. 2015). The extent of terrestrial area affected by the event (Figure 24 b) was used for the validation of the simulated inundation extent. In this study the tailings spill path is classified into four reaches:

- 1) Upper HC region closest to the tailings dam failure site where the slope varied from 0.7% to 1.2%
- 2) Middle HC region which consisted of several steep sections and nearly 3% channel gradient.
- 3) HC Canyon where the HC channel narrows and steepens, and the slope gradient was nearly 7.3%.
- 4) Lower HC region downstream of the HC Canyon until the river mouth at QL, where the mean slope decreased to almost 0.8%.

Critical Success Index (CSI) is a commonly used verification statistic for evaluating flood extent accuracy (Lim and Brandt 2019a).

$$CSI = \frac{A}{A+B+C} \quad (18)$$

where A is the number of cells correctly predicted by the model (hits)

B is the number of cells overestimated (false alarm)

C is the number of cells underpredicted (misses).

CSI and floodplain width Root Mean Square Percentage Error (RMSPE) were calculated in each of the four reaches to identify regions where differences in performance between the models are more prominent. To calculate the floodplain width RMSPE, 32 cross sections were drawn across the tailings spill path and error in the flood extent width was computed.

Model sensitivity analysis

To ensure appropriate calibration, and to explore the relative importance of input parameters and their contributions to final model outputs, sensitivities to DEM, Manning's coefficient values, inflow sediment concentration and rheology parameters were conducted. Systematic sensitivity analysis was performed by changing each of the selected input variables by + 5 %. When the full study area covering a region of about 429 km² was considered for comparison, the percentage difference in model outputs was not quite discernible. According to Lim and Brandt (2019a), when comparing the modelled flood area and the reference flood area, even a poor model can achieve strong statistics if the flooded area is large. This is because the modelled

flood area may overlap the reference flood area to a large extent compared with the areas that are either underestimated or over estimated. Therefore, for statistical measure (for calculating CSI and RMSPE), only the model domain covering the tailings dam and the HC region is considered.

3.4 Results

3.4.1 Generation of bare earth elevation model

The original raw 2013 DSM and the bare earth DEM obtained after canopy removal are compared in Figure 26. Figure 26 (a1) and (a2) shows the entire domain of the high-resolution DEM in 3D, while Figures 26 (b1) and (b2) focus on the steep gorge entrance point to the lower HC, an area of concern during the filtering process. The raster created by filling the sinks in the filtered DEM and the flow direction and flow accumulation rasters are shown in Appendix B Figure B44. The stream network is clearly defined in the flow accumulation raster and hence it is ensured that there is hydrologic connectivity in the generated DEM without any break lines.

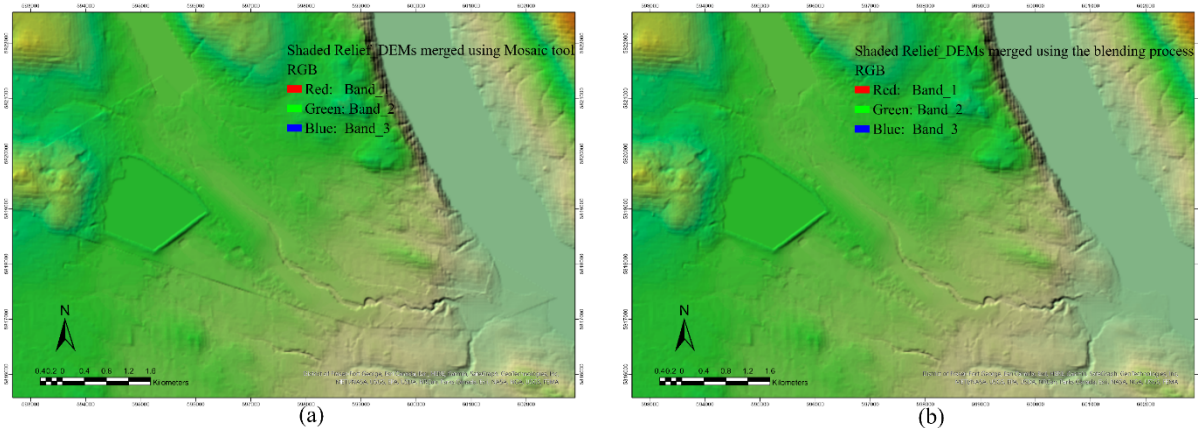
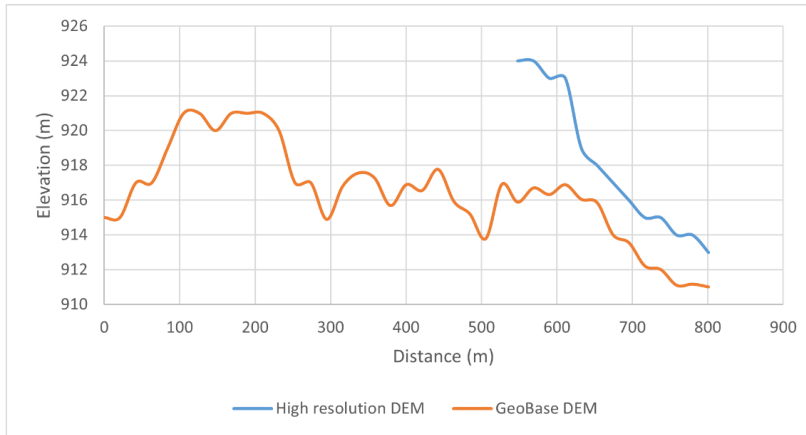


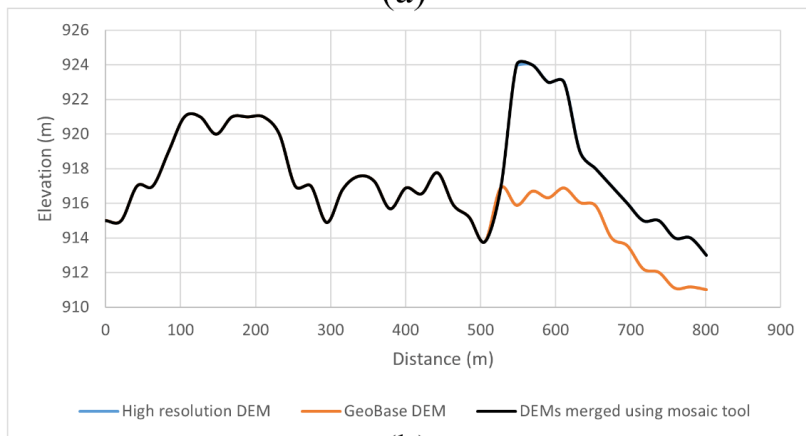
Figure 28: High resolution (2.5 m) digital elevation model (DEM) and GeoBase (18 m) DEM merged using (a) the Mosaic tool (b) using the blending process.

The two DEMs (2.5 m resolution DEM and GeoBase DEM) merged using the Mosaic tool and using the blending process are shown in Figures 28 (a) and 6 (b), respectively. An obvious discontinuity remains when using the Mosaic tool (Figure 28 a), but after the blending process the exact location of the boundary is no longer obvious, and the discrepancies have been eliminated. To demonstrate this, profile graphs were drawn at a cross section (encircled in Figure 28 a) where there is height discontinuity between the 2.5 m resolution and the GeoBase

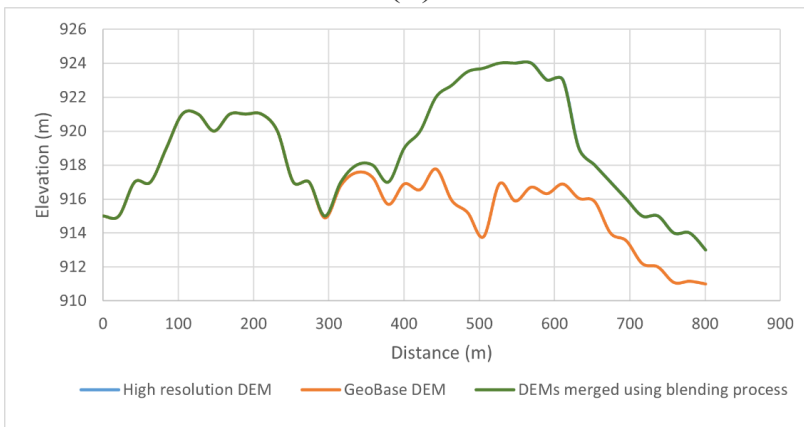
DEMs (Figure 29). In the merged DEM, terrain profile graphs were plotted at cross sections drawn across PL and QL and as noted above the elevation remained constant across the lakes i.e., 921m across the PL and 729 m across the QL. This implies that the elevation represented is water surface elevation and not lakebed elevation. Hence, water depth contours were subtracted from the merged DEM to get the final bare earth elevation model of resolution 2.5m shown in Figure B45. Terrain profile graphs plotted at cross sections drawn across PL and QL are shown and compared with water surface elevation plot in Figure B46.



(a)



(b)



(c)

Figure 29: Terrain profile graph at a cross section in (a) 2.5m resolution digital elevation model (DEM) and GeoBase DEM b) 2.5m resolution DEM, GeoBase (18 m) DEM and DEM merged using open-source tool c) 2.5m resolution DEM, GeoBase (18 m) DEM and DEM merged after treatment of the edge offsets using the blending process.

3.4.2 Calibration of the model using the merged DEM and GeoBase DEM

The high-resolution topographic data were interpolated on a mesh system with 10m x 10m grid resolution. The model was simulated for a duration of 24 hrs starting from the breach initiation. The input data included the breach outflow hydrograph and sediment concentration time series mentioned in Section 3.3.3.1. Grid sensitivity analysis was performed by running identical failure scenarios on a mesh system with 7m x 7m grid resolution. The water level variation at the measurement station as a function of grid size is shown in Figure B47 which demonstrates that the arrival time at the measurement station remained the same and the water level variation differed only by few centimeters. Hence, to reduce the computational time, 10 m grid resolution was chosen for the calibration of the model. Similarly, identical failure scenarios were run on a mesh system with 2.5m x 2.5m grid resolution over a smaller domain (HC floodplain and a part of PL and QL). Comparison of water level variation at the confluence of the HC and the QL in the case of simulation using a) 10m grid resolution and b) 2.5m grid resolution is also shown in Figure B47. It was noted that there are only very small discrepancies between the simulations. To obtain a highly resolved flood extent in the downstream area of the tailings dam and to conduct statistical analysis, 2.5m resolution grid size was used. Total number of grid elements were 1,547,864 and the total computational time was 1.5 days. A computer with 8 cores and 8 logical processors was used for conducting model runs.

Model calibration was achieved by heuristic trial-and-error variation of rheological parameters and roughness coefficients. The calibrated optimum values of τ_y and η were 8.7 Pa and 0.135 Pa.s. These values were validated based on the experimental study conducted by Wang, X. et al. (2018), who examined the effect of tailings particle size on τ_y and η for a series of sediment concentrations. The average sediment concentration in Mount Polley tailings outflow was around 30% and tailings particle size was about 50 μ m. The calibrated values of τ_y and η closely matched the experimental values which were around 10 Pa for τ_y and 0.15 Pa. s for η . Calibrated Manning's coefficients for each land-use class are given in Table 2.

Table 2: Calibrated Manning's n coefficients assigned to different land cover classes for 2.5m resolution model and GeoBase (18 m) DEM based model.

Land cover type	2.5m resolution model - Manning's n coefficients	GeoBase (18 m) DEM based model- Manning's n coefficients
Bare earth	0.025	0.03
Moderate Vegetation	0.08	0.15
Shadows	0.025	0.03
Sparse Vegetation	0.06	0.085
Trees	0.15	0.2

The reservoir routing method mentioned in Section 3.3.3.3 was used to simulate slow velocity movement in PL and QL, with Manning's $n=0.2$.

The time evolution of the modelled tailings dam breach outflow and flood extent using the calibrated model with the high-resolution DEM is shown in Figure 30.

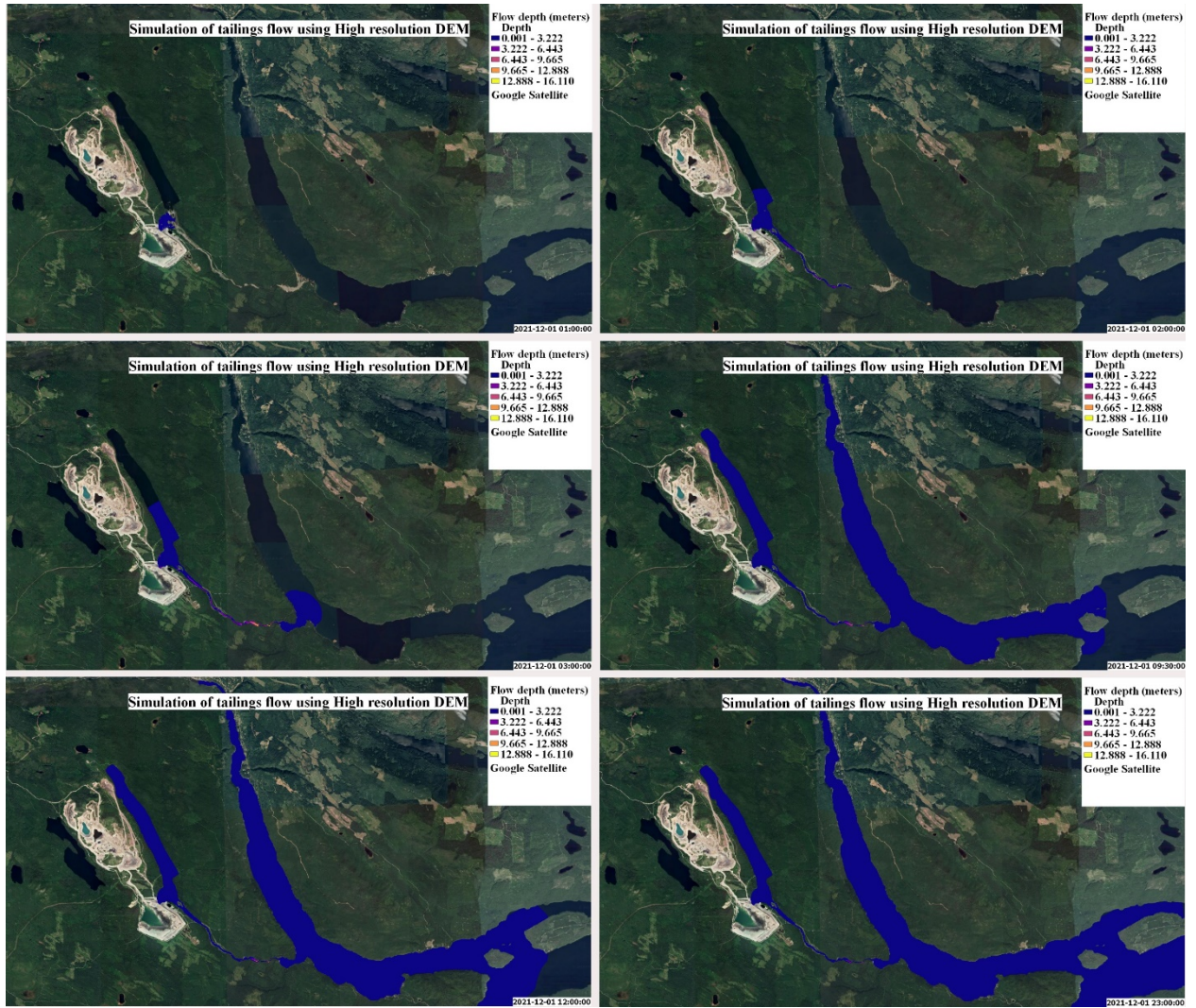


Figure 30: Time evolution of simulated tailings transport after the breach using 2.5 m resolution digital elevation model (Flow depth above initial water level in the case of lakes)

The comparison of the observed and the simulated water level variation at the hydrometric station near Likely is shown in Figure 31.

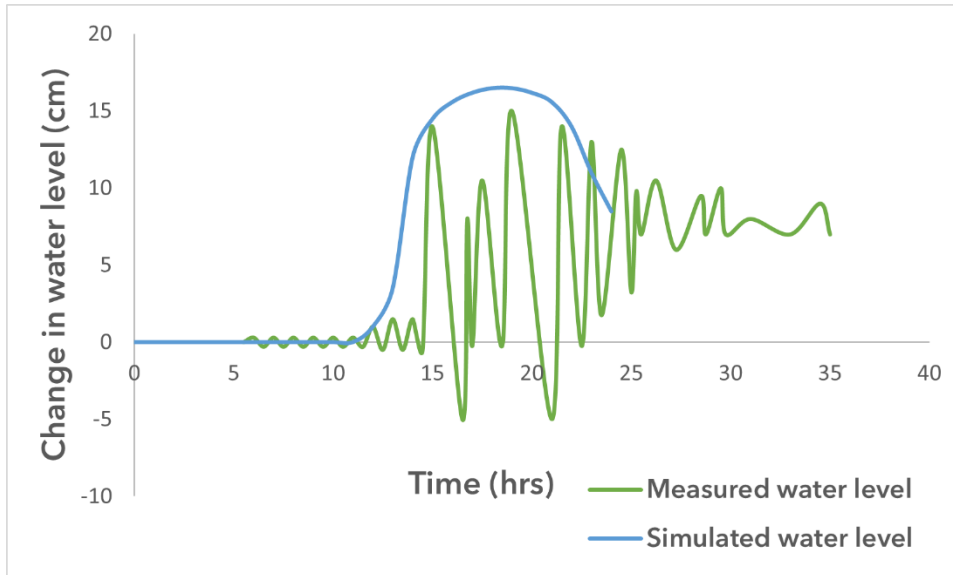
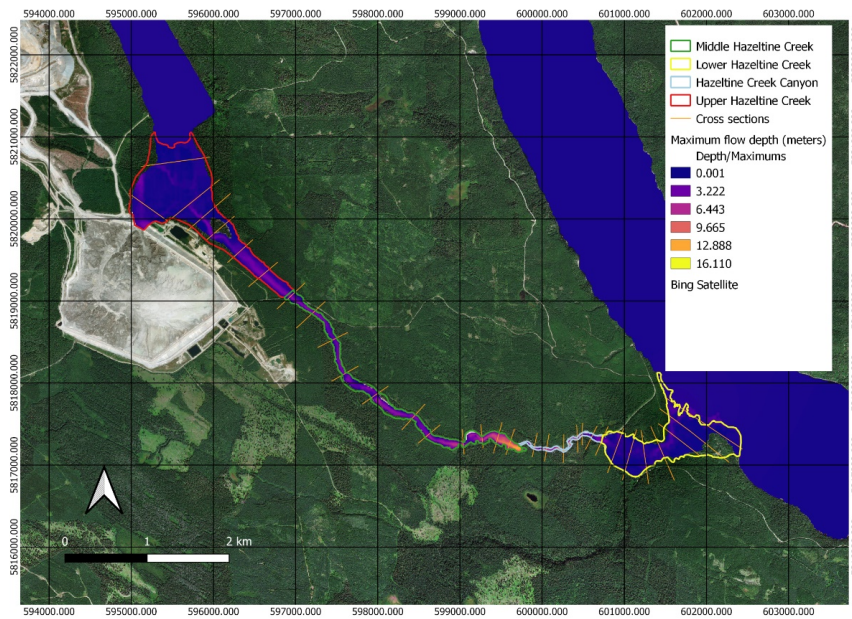
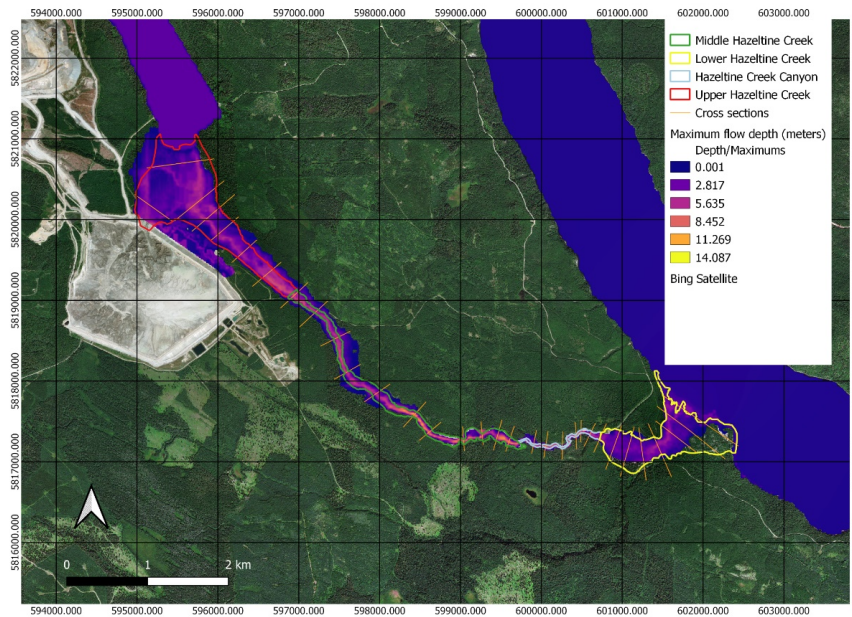


Figure 31: Comparison between the Water Survey of Canada data measured at hydrometric station number 08KH011 showing rise in water level on August 4, 2014 (Source: Golder Associates Ltd. 2015) and the simulated water level variation at the hydrometric station using 10m x 10m grid size in the case of high-resolution digital elevation model (DEM) based simulation.

From the simulated results it was clear that the flood wave from the tailings breach reaches the confluence of the HC and the QL in less than 3 hrs. The arrival time of the flood at the measurement station is 12hrs and the peak increase in water level is 16 cm at the end of 20 hrs. Eventually the water level at Likely dampens resulting in water level variation of about 8 cm. After the calibration of the model using 2.5 m resolution DEM, the same boundary conditions were inputted for a second simulation that was run on a mesh system with 2.5m x 2.5m grid resolution over a smaller domain (HC floodplain and a part of PL and QL), to obtain highly resolved flood extent shown in Figure 32 (a).



(a)



(b)

Figure 32: Comparison of the simulated flood extent with the observed flood extent map (a) in the case of high-resolution digital elevation model-based simulation (b) in the case of GeoBase (18 m) digital elevation model-based simulation (Flow depth above initial water level in the case of lakes).

A similar procedure was conducted for a second calibration using GeoBase DEM. The calibrated values of τ_y and η were 15.7 Pa and 0.31 Pa. s respectively. Calibrated Manning's coefficients for the model are given in Table 2. The time evolution of the modelled tailings dam breach outflow and flood extent using the GeoBase DEM is shown in Figure B48. When compared to the high-resolution DEM, the flood wave was faster when GeoBase DEM was used since the tailings just flowed on top of the water surface without mixing with the water in the lakes. Hence, to calibrate and make the arrival time at the measurement station correct, higher Manning's coefficient value and higher rheology parameters had to be assigned. The optimum values of τ_y (15.7 Pa) and η (0.31 Pa. s) assigned corresponded to more than 40% sediment concentration according to the experimental research conducted by Wang, X. et al. (2018), which is not the sediment concentration in Mount Polley tailings outflow based on literature. This implies that if the open source GeoBase DEM is used for the calibration of the model, the accuracy of the other parameters used would have to be compromised.

Following this, the same boundary conditions were given for a second simulation that was run on a mesh system with 2.5m x 2.5m grid resolution over a smaller domain to obtain the flood extent shown in Figure 32 (b). CSI and RMSPE calculated for the four reaches shown in Figure 24(b) are summarized in the Table 3. From the two model results it is evident that even when individually calibrated, the model based on the low resolution GeoBase DEM has greater error. The shift in model performance between the 2.5 m resolution and the GeoBase DEM was most prominent in the Upper HC.

Table 3: Statistical measure of the flood extent accuracy for each model.

DEM used to calibrate	2.5 m resolution DEM		Low resolution (18 m) GeoBase DEM	
Creek Sections	CSI	Floodplain width RMSPE (%)	CSI	Floodplain width RMSPE (%)
Upper HC	0.88	10.8	0.502	52
Middle HC	0.917	9.75	0.663	32.2
HC Canyon	0.958	4.8	0.74	24.1
Lower HC	0.856	14.1	0.62	41.7

3.4.3 Model Sensitivity to DEM

The sensitivity of the model results to the elevation data was performed by running identical failure scenarios over 2.5 m resolution DEM and GeoBase (18 m) DEM. The parameters (outflow volume, rheological properties, sediment concentration, roughness values) used in the calibrated high-resolution model are used for both the simulations. In the model results using the high-resolution DEM, the HC was more distinguished, and achieved a good CSI score of 0.9. The model was also able to replicate a treed island within the tailings outflow path that resisted the tailings flow due to either high ground or high roughness value. The simulated tailings dam breach overland flow using the GeoBase DEM with this model parameterization is shown in Figure B49. The comparison of the observed and the simulated water level variation at the hydrometric station near Likely is shown in Figure B50. From the simulated results it was clear the flood wave from the tailings breach reached the confluence of the HC and the QL in a travel time of about 2 hrs. The arrival time of the flood at the measurement station is 9.5 hrs and the maximum water level is around 25 cm at the end of 15 hrs and eventually it dampens resulting in water level variation of about 10 cm.

3.4.4 Model Sensitivity to inflow sediment concentrations

To evaluate the sensitivity of model results to sediment concentration, three model runs (A, C D) were conducted identical in all aspects but different inflow sediment concentrations. In these model runs all parameters used in the calibrated high-resolution model were used except that in the model run C, lower inflow sediment concentration value of 0.21 was applied and in the model run D higher inflow sediment concentration value of 0.39 was applied. The flow depth contours in the case of model runs C and D are shown in Figures 33 (a) and (b) respectively.

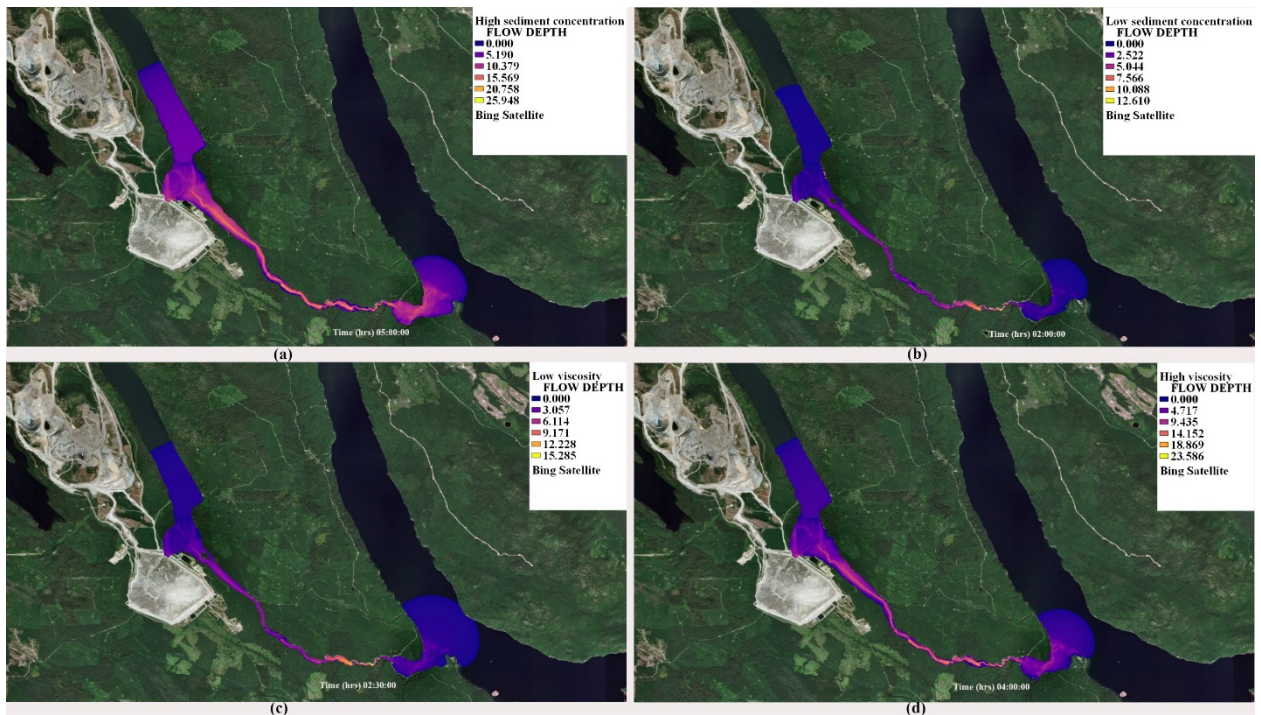


Figure 33: Maximum flow depth contours at the time the peak of the hydrograph reaches the confluence of the Hazeltine Creek and the Quesnel Lake (a) when inflow sediment concentration = 0.39 (b) when inflow sediment concentration = 0.21 and (c) when viscosity = 0.176 Pas.

In the case of model run C, the flood wave travelled faster, and both arrival time and maximum flow depth at the station was lesser compared to the observed data. In the model run D, the flood wave travelled slower, and did not reach the station within the simulation time of 24 hours. It was also noted that the output parameters are highly sensitive to inflow sediment concentration.

3.4.5 Model Sensitivity to rheology parameters

To evaluate the sensitivity of model results to viscosity, three model runs (A, E, F) were conducted identical in all aspects but different η values. In these model runs all parameters used in the calibrated high-resolution model were used except that in the model run E, lower η value of 0.095 Pa.s was applied and in the model run F higher η value of 0.176 Pa s was applied. The flow depth contours in the case of the model runs E and F are shown in Figures 33 (c) and (d) respectively. To evaluate the sensitivity of model results to yield stress, three model runs (A, G, H) were conducted identical in all aspects but different τ_y values. In these model runs all parameters used in the calibrated high-resolution model were used except that in the model run G, lower τ_y value of 6.09 Pa was applied and, in the model run H run higher τ_y value of 11.31 Pa was applied. In the case of model run E and G, the flood wave travelled faster, and both arrival time and maximum flow depth at the station were lesser compared to the observed data. In the model runs F and H, the flood wave travelled slower, and both arrival time and maximum flow depth at the station were higher compared to the observed data. It was also noted that the flow characteristics are more sensitive to viscosity (particularly the coefficient β_1) than yield stress.

3.4.6 Model Sensitivity to Manning's coefficient, n

To evaluate the sensitivity of model results to Manning's n value, three model runs (A, I, J) were conducted identical in all aspects but with different Manning's n values. In all the model runs, all parameters' values were the same as those used in the calibrated high-resolution model except that in the model runs I and J, a uniform Manning's n value of 0.105 and 0.195 were applied respectively for the entire vegetation in the downstream area. It was concluded that Manning's values had comparatively less influence on simulated flow characteristics. Key statistics and results of model sensitivity analysis are summarized in Table 4.

Table 4: Summary of the results from model sensitivity analysis.

Model run	Sensitivity analysis	Arrival time at station (hr)	Error (%)	Maximum flow depth at station (cm)	Error (%)	CSI
A	2.5m resolution DEM; Viscosity (0.135 Pa s); Sediment concentration (0.3); Yield stress (8.7 Pa); Manning's n (0.15)	12	0	16	6.66	0.9
Model run	Sensitivity analysis	Arrival time at station (hr)	Error (%)	Maximum flow depth at station (cm)	Error (%)	CSI
B	GeoBase (18 m) DEM	9.5	20.83	25	66.66	0.63
C	Sediment concentration (0.21)	7	41.66	10.11	32.6	0.85
D	Sediment concentration (0.39)	More than 24 hrs	> 100	-	-	0.84
E	Viscosity (0.095 Pa s)	10.5	12.5	13.78	8.13	0.81

F	Viscosity (0.176 Pa s)	14	16.66	19.82	32.133	0.85
G	Yield stress (6.09 Pa)	11.5	4.16	15.1	7.33	0.84
H	Yield stress (11.31 Pa)	12.5	4.16	17.2	14.66	0.8
I	Manning's n (0.105)	12	0	16	6.66	0.88
J	Manning's n (0.195)	12.5	4.16	16	6.66	0.86

3.5 Discussion

The use of high-resolution canopy height information from UAV photogrammetry data was effective in generating 2.5 m resolution bare earth elevation model of the pre-event DEM. The blending process was able to produce a seamless transition between the high-resolution DEM and GeoBase DEM. The water depth contours of PL and QL were useful in getting a complete representation of lake bathymetry. Hydrologic connectivity of the generated DEM was verified, and it was concluded that the integration of different source geospatial data was successful in generating a model bathymetry suitable for hydrodynamic modelling. Calibration of the model using the high-resolution DEM was performed and the simulated inundation extent matched almost 90% with the terrestrial affected area plotted based on post-event orthophotograph and satellite imagery. The simulated flow depth variation at the measurement station was in reasonable agreement with the actual hydrometric data collected immediately after the event. Typical Manning's n values were assigned, and the rheology parameters assigned were within the range recommended by previous experimental studies. Thus, it was concluded that data filtering and merging techniques adopted for generating bare earth elevation model had positive effect on flood extent accuracy.

Calibration of the model using the GeoBase (18 m) DEM was also performed, and it was noted that higher values had to be assigned to the rheology parameters compared to the values recommended by previous experimental studies to calibrate the model based on flow depth variation at the hydrometric station. This implies that if open-source elevation data is used for the calibration of the model, then the accuracy of other parameters will have to be compromised. Moreover, the simulated flood extent matched only 63% with the terrestrial affected area map. Wider flow path was observed near the breach location, across the middle HC and the HC Canyon compared to the high- resolution DEM flood extent. The flow expanded over a large flood extent due to the vertical inaccuracy of GeoBase DEM. However, in the lower HC close to the confluence of the HC and the QL, the flood extent seems to be narrower than the actual flood extent. This inconsistency can be because of the GeoBase DEM representing reflective surface elevations at certain regions and bare earth elevations at other regions as specified in the metadata of GeoBase DEM. From the analysis of model sensitivity to DEM, it was concluded that the flood wave travelled faster when the GeoBase DEM was used and resulted in an over estimation of the flood extent. However, in the case of GeoBase DEMs, these trends in travel time or flow depth could not be generalized as it is uncertain if the sensors have partially or fully penetrated the vegetation and other surface features. Among the other parameters, model results were most sensitive to inflow sediment concentration followed by viscosity. The flow depth and the travel time to reach the measurement station increased as higher sediment concentration and viscosity values were assigned.

A comparison has also been made to the calibrated values of other case studies. Ghahramani et al. (2022) calibrated the input rheological parameters for the 1994 Merriespruit tailings flow and the 1985 Stava tailings flow using different rheological models and concluded that the best-fit input parameter sets cannot be exchanged between rheological models. After back-analyzing the Mount Polley event using different model runs, it was concluded that the best-fit input parameter sets cannot be exchanged not only between rheological models but also between different elevation models. It was also noted that the same rheological values used in the study conducted by Ghahramani et al. (2022) could not be assigned to the present study. When the input parameters given for back analysing 1985 Stava TD failure are used in the present study, the flood wave travels faster and arrives at the hydrometric station in 8.5 hours i.e., there is 29% error in flood arrival time. When the input parameters given for back analysing

1994 Merriespruit TD failure are used, the flood wave does not arrive at the hydrometric station within 24 hours. Therefore, it is important to use values within the range of calibrated rheological parameters obtained from back analyses of similar historical events and not from other case studies even if calibrated by the same rheological model.

During the calibration procedure, the measured water level at the gauging station and the simulated water level was in reasonable agreement since the arrival time and the maximum water level were almost the same. However, the model was not able to capture dynamics of the flood wave at the measurement station. Specifically, the gauge measurements show the flood wave had a steep wave front followed by a series of water surface oscillations, whereas the numerical model produced a more diffusive wave. The error in water level variation may have been due to the lack of consideration of the advection and diffusion of the subaqueous sediment density flow (Kostaschuk et al. 2021). An immediate full mixing was assumed, and this may have affected the results. A non-Newtonian model capable of simulating the advection and diffusion of the plume and the continuous observations recorded at the gauging stations would be useful for better impact analysis. Model results were sensitive to η and τ_y but sampling and rheometric analysis of Mount Polley tailings have not been conducted. Rheological properties of tailings are site specific and hence experimental research of material rheology would be useful before being given as model input. Small discrepancies between the simulated inundation extent using 2.5 m resolution DEM and the terrestrial affected area map may be attributed to possible errors in the delineation of the boundaries using the post- event orthophotographs as the dense forest cover might have obscured the actual affected area boundary. Another possible reason could be because of not considering geomorphological impacts from the event during modelling. Further research is suggested to model the downstream morphological changes after the tailings dam breach as it can also contribute to the flood extent.

3.6 Conclusions

Using the research approach adopted in this study, the most accurate (to date) prediction of the Mount Polley tailings dam breach outflow flood extent, flood depth and arrival time was achieved. The merged DEM (2.5 m resolution) was exceptionally suitable for calibration both in terms of magnitude and spatial extent. When GeoBase DEM (18 m resolution) was used for

back analysis of the event, a physically meaningful set of values could not be assigned when trying to minimize the error between observed and modelled data. It was also found that one set of input parameters could not be used for calibrating the model with two types of DEMs with acceptable accuracy. The fundamental reason for the reduced performance of GeoBase DEM is that the resolution was less than the channel width and hence there was lack of definition of the downstream channel. The reduced channel bed depth led to more mud being propagated from channel cells to surrounding cells and caused increased flood extent. Simulation results clearly indicated that when conducting detailed tailings dam risk analysis, GeoBase DEM should not be seen as an appropriate replacement. A correct merging procedure is required to stitch together 2.5 m resolution and low-resolution portions of the DEM and to preserve fine details at the boundary. The sensitivity analysis showed that the model output flood extent was highly influenced by DEMs, while other model outputs such as arrival time and maximum mudflow depth were sensitive to DEMs, inflow sediment concentration and rheological properties (viscosity and yield stress). Runout distance was more sensitive to viscosity η (especially coefficient β_1) than yield stress. It was noted that with increasing sediment concentration and viscosity, both flood depth and flood arrival time increased. Manning's n values had comparatively less influence on flow behaviour. Accurate quantification of the uncertainties of using GeoBase DEM should be done and communicated before making flood risk analysis decisions as they are likely to overpredict or underestimate risks. Until a high resolution, accurate, global DEM is available, multiple products should be used concurrently for better decision making.

4. Numerical modelling of downstream morphological evolution during Mount Polley tailings dam failure

4.1 Abstract

In this study, a robust non-Newtonian numerical model that can simulate coupled mudflow and sediment transport processes is used to model downstream geomorphic changes during a tailings dam failure. The catastrophic breach of the Mount Polley tailings dam is studied to assess the model performance. Spatial and temporal variation of flow properties like density, viscosity, yield stress, sediment size fractions, and friction are considered in the model. Flexible triangular mesh is adopted, and this helps reduce the computational time significantly compared with structured grid with the same average resolution. High resolution multi-temporal Digital Elevation Models (DEMs) are used for the detection of geomorphic changes and estimation of erosion and deposition volumes. The results indicate that the final distribution of tailings deposits obtained from the model results is in good agreement with that obtained from topographic analysis. The model predicted the total volume of erosion and deposition with almost 93% accuracy. The tailings characteristics followed the full Bingham model during the propagation. Different runout scenarios obtained from the mudflow-morphodynamic model, and a mudflow-fixed bed model are analyzed, and it was concluded that maximum mudflow depth of the flood wave is higher when bed entrainment is considered. Sediment concentration is higher in the wavefront and middle regions and lesser in the tail zone. The mudflow fixed bed model could underestimate the downstream flood arrival time. The results also confirm that the adopted approach can efficiently model the sediment budget in the study site and the volume of tailings and bed materials released to the downstream lake.

4.2 Introduction

Tailings dams are essential storage facilities being built globally for containing waste solids, muddy slurries, and other by-products of mining operations. Advances in mining technology and rapid growth of mining activities have increased waste production and put more pressure on tailings facilities. Many tailings dams have collapsed in the past few years due to slope

instability, foundation failure, natural hazards, and extreme meteorological events. Examples of tailings dam failures include Los Frailes in Spain, Mount Polley in Canada, Samarco and Brumadinho in Brazil etc. (Armstrong et al. 2019). The released mining waste and slurries have caused massive damage to the downstream communities and the local environment (Grangeia et al. 2011, Sun et al. 2012, Luo et al. 2012, Martin et al. 2015, Ishihara et al. 2015, Wang and Kang 2017). A clear understanding of the potential risks is required to enable proper risk management by adopting mitigation measures, emergency plans, exclusion zones, and flood protection structures (Moon et al. 2019).

Tailings and muddy slurries are highly concentrated, and the fluidized material can consist of a mixture of water and several solid phases. Mud flow can be considered as a slope movement in which the collapsing mass behaves as a viscous fluid. The bulk flow properties of viscous fluids are very complex and when analyzing their hydrodynamic behaviour, it is important to consider the effects of parameters like solid volumetric concentration, particle size and shape, nature of the interstitial fluid, etc. (Pellegrino and Schippa 2018). Conventional flood routing models are not dependable for predicting tailings dam breach inundation extent as they do not consider the non-Newtonian visco-plastic nature of tailings. Several studies like Raman and Liu (2019) and Knight Piesold Consulting (2017) adopted a Newtonian hydrodynamic approach to model tailings' discharge mechanisms. Dibike et al. (2018) investigated the potential effects of tailings pond breach on water and sediment quality of a downstream river, but the study neglected the rheological properties of tailings, and the flood was modelled like a water-dam break. It was also generalized that the breach hydrograph remains unchanged while routing through the drainage course.

Dam failures can immensely impact the downstream channel geomorphology by altering its natural flow pattern and these changes can profoundly impact the aquatic and riparian ecosystem. (Acker et al. 2008, Chen et al. 2015, Jiang et al. 2021). Water flood events and associated geomorphic processes like bed and lateral erosion, and deposition of sediments have been discussed extensively in the literature (Baynes et al. 2015, Carrivick et al. 2010, Lane et al. 2007, Marchi et al. 2009). The influence on flood levels of morphodynamic bed geometry change during the flood has been rarely considered in practice, although researchers are beginning to develop such models (e.g., Wong et al. 2015; Guan et al. 2016; Ahilan et al. 2018). Geomorphic processes during flooding events can cause elevated discharges, river

morphological evolution and extensive damage (Guan et al. 2016, Rickenmann and Koschni 2010, Eagle et al. 2021). Similarly, tailing's transport and floods following a tailings dam failure are also not just confined to the hyper-concentrated fluidized material released but there is broader morphodynamic influence. During tailings flow, entrainment of additional solids can cause dramatic surge in sediment supply and significant changes in the morphology of channels. There can be entrainment of materials from the bed layer and deposition of sediments and as a result the fluid properties like density, viscosity, and yield stress will vary in space and time. In the tailings dam breach studies conducted by Mahdi et al. (2020) and Wang, Yang, et al. (2018), the erosion of the downstream terrain along the tailings spill path and transport of eroded materials were neglected. These conservative approaches could significantly impact the volume and concentration of sediments reaching a downstream river or lake. Palu and Julien (2019) modelled the sediment load of Doce River following the Fundao tailings dam failure. One-dimensional advection-dispersion equation with settling was solved and calibrated to fit the observed sediment concentration. Palu and Julien (2020) proposed an improved one-dimensional flood routing approach by reformulating hydraulic diffusion coefficient and flood wave celerity. In these studies, the rheological properties of tailings and bed elevation change caused by the hyper-concentrated mudflow were not considered. Han and Wang (1996) modelled Anhui debris flow using Bingham rheological model. The two-dimensional depth-averaged debris flow equations obtained by integrating equations of continuity and momentum are discretized and solved using the method of characteristics. In this study as well sediment transport and bed elevation change during debris flow were not considered.

Mudflows appear as waves with a steep front and a shape that resembles debris flows but consist of muddy slurries with less boulders and less granular materials (Pasculli et al. 2021). Several granular debris flow modelling studies were reported in the last years to understand the dynamics of landslides and debris flows. For example, Wu et al. (2013) used two numerical models Flo-2D and Debris-2D for the assessment of debris flow hazard. In the Flo-2D model, constant density was assumed in each flow direction whereas in Debris-2D, both debris-flow yield stress and density are assumed to be constant. In these single-phase models, it is assumed that the solid phase is distributed uniformly over the fluid column and there is no mixture density variation in space and time. Most of the numerical models used in the previous studies used single phase approach by neglecting spatial and temporal variation of debris flow density

in mass and momentum conservation equations (Hubl and Steinwendtner 2001; Aleotti and Polloni 2003; Liu and Huang 2006; Cesca and D'Agostino 2008; Chen et al. 2010; Juez et al. 2013; Peng and Lu 2013). Two-phase debris flow models have also been proposed in several studies (Pitman and Le 2005; Pailha and Pouliquen 2009; Pelanti et al. 2008; Pudasaini 2012; Meng and Wang 2016; Bouchut et al. 2016; Tai et al. 2019; Greco et al. 2019) in which solid and liquid phases are considered separately in the mass and momentum conservation equation. But according to the studies conducted by Pelanti et al. (2008) in a two-layer shallow water model if the difference in phase velocities of the solid and liquid layers are too large, there can be the appearance of complex eigenvalues and loss of hyperbolicity which makes numerical modeling more challenging. Castro-Díaz et al. (2011) and Sarno et al. (2017) propose different approaches to avoid the loss of hyperbolicity, but those techniques require computationally expensive iterative algorithms. Another drawback of most of the previous two-dimensional two-phase modelling studies is that they did not consider entrainment of the bed and morphological evolution.

Quasi two-phase models that consider mass and momentum conservation of fluid-solid mixture and mass conservation of solid phases separately have been used in studies like Rosatti and Begnudelli (2013), Kowalski and McElwaine (2013); Kuo et al., (2013); Iverson and George (2014); Pasculli et al. (2021) etc. In these models, solid and fluid phase velocities are incorporated into the depth-averaged bulk velocity of the mixture and accounts for the fluid-solid particle interactions within the mixture. Although this model has simplifications when compared to the two-phase models, relatively better numerical stability makes it suitable when dealing with large scale unsteady mud flood events that require rapid evacuation planning. Martínez-Aranda et al. (2022) modelled mudflow over non-uniform erodible bed but the morphological evolution of downstream channel during a tailings dam failure has not been investigated. Studies like Rosatti and Begnudelli (2013) and Ouyang et al. (2015) considered bed entrainment, the entrainment of different solid classes into the fluid-solid mixture was not considered separately. This is a major limitation of these studies since sediment particles of different particle size and properties can be present on the landscape and each solid phase has its own entrainment and settling properties and it is important to include them while modelling. Furthermore, these studies focused on debris flow modelling and have not yet been applied to conduct simulation of tailings dam failures and to model morphological evolution of channels.

Also, large-scale unsteady flows like tailings dam breach outflow often occur along steep terrain and require a highly refined mesh to capture the irregular terrain characteristics. Most of the mud/ debris flow models use structured meshes and this can typically increase the computational time due to the lack of local mesh refinement and can be problematic during real-time flood forecasting.

In this study, a two-dimensional quasi-two-phase mudflow model was used to simulate tailings dam breach outflow over non-uniform erodible bed. To the best of the authors' knowledge, this is the first non-Newtonian tailings outflow numerical modelling study to simulate morphological evolution of the downstream channel. Furthermore, the model considers multiple sediment size fractions, variable density, viscosity, yield stress and friction angle in space and time and is applied to a real accident. A Graphical-Processing-Unit (GPU) approach and non-structured mesh were adopted which can significantly reduce the computational time and help perform several simulations simultaneously for early flood warning. The feasibility of the selected numerical approach in simulating large-scale mud flow was discussed by comparing the model results with field data. Based on the field investigation conducted by Cuervo et al. (2017), the geomorphic impacts of the flow created by the failure of Mount Polley tailings dam was significant and comparable to those resulting from extreme debris flow and outburst flood events in mountains. Hence, in this study, data pertaining to the breach of the Mount Polley mine tailings dam were used to assess the model performance and to examine the dynamic characteristics of the tailings from initiation to deposition. High resolution multi-temporal DEMs (Digital Elevation Models) were used for the detection of geomorphic changes caused by the event and the model was validated based on this data. Erosion and deposition volumes estimated from pre- and post- event DEMs were compared with that obtained from the numerical model. Furthermore, the time-resolved numerical results were analyzed to understand the sequence of erosion and deposition during the event. Finally, the variable properties mudflow-morphodynamic model was compared with a constant properties' mudflow-fixed bed model. A sediment budget study was also conducted to evaluate the magnitude of downstream geomorphic response including sediment supply, transfer, and deposition. To summarize, the objectives of the study are:

- 1) To model downstream geomorphic changes during a tailings dam failure using a non-Newtonian numerical model that can simulate coupled mudflow and sediment transport processes.
- 2) To compare variable properties mudflow-morphodynamic model with a constant properties' mudflow-fixed bed model
- 3) To evaluate the magnitude of downstream geomorphic response by conducting a sediment budget study. (The catastrophic breach of the Mount Polley tailings dam will be studied to assess the model performance and to examine the dynamic characteristics of the tailings from initiation to deposition).

4.3 Methodology

4.3.1 Study site

The Mount Polley gold and copper mine tailings dam, located in British Columbia, Canada was the study site for this research. On August 4th, 2014, the dam suffered a catastrophic failure and the embankment collapsed because of a weak foundation constructed on a glacial layer. Following the failure, 25 Mm³ of mining waste travelled as a debris flow into Polley Lake (PL), Hazeltine Creek (HC) and into Quesnel Lake (QL) (shown in Figure 34 (a)).

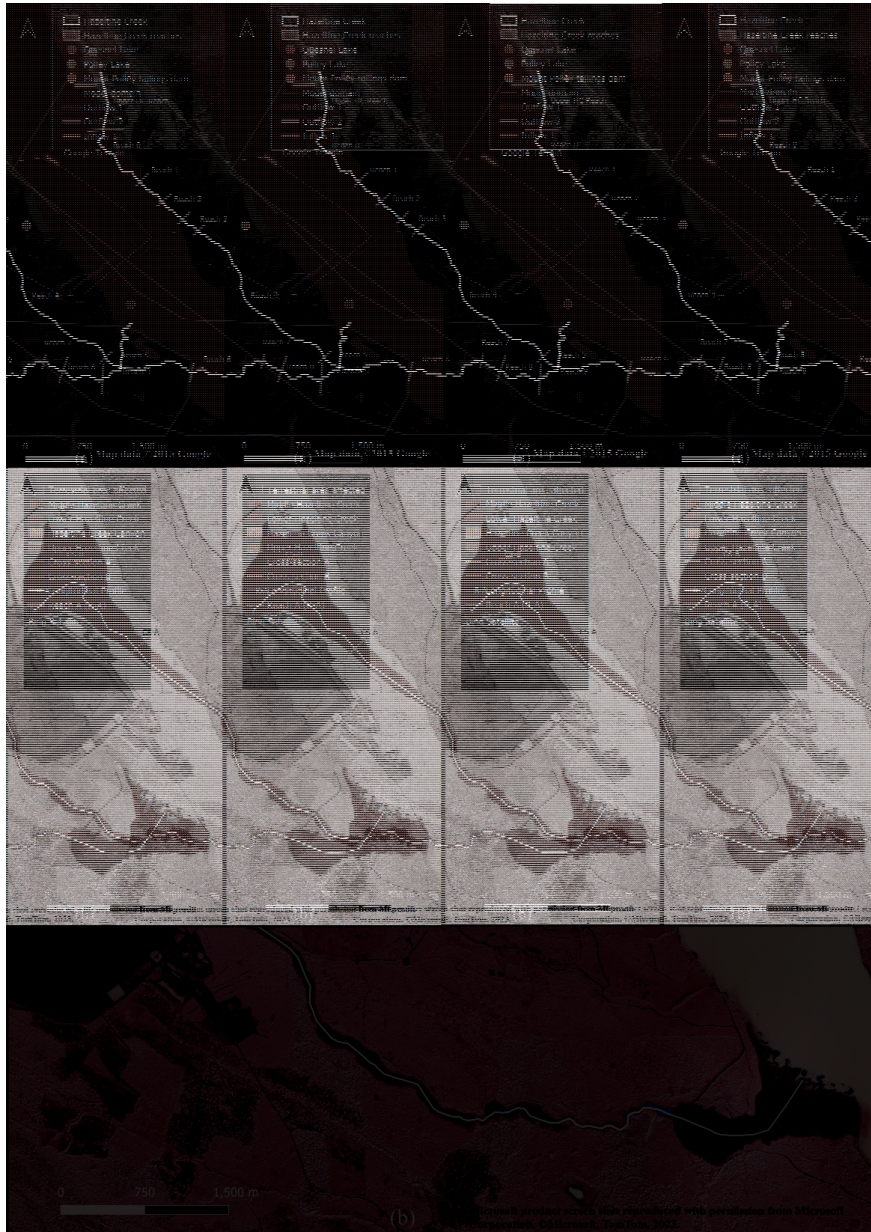


Figure 34: (a) Study site map (Google Terrain source: Map data ©2015 Google) (b) Map showing terrestrial affected area after the breach and longitudinal profile and cross-sections used in the analysis (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023).

Prior to the dam breach, HC located downstream of the dam flowed through a densely vegetated valley from PL to QL. Hazeltine Creek (HC) was 5 m wide and 0.3 m deep and the channel bed was mainly gravel and cobbles. The slope of the HC channel increased in the downstream direction reaching maximum within the HC Canyon, and then decreasing in the HC delta

located at the interface of the creek with QL. The HC canyon was the steepest and narrowest section, and the bed and banks were generally stable. Following the dam failure, the debris flow eroded the channel and the floodplain of HC, widened the creek valley, and impacted about 237 hectares of area. Thick tailings blocked the outlet of Polley Lake, and tailings deposits measured more than 3.5m at some areas. A steep quickly eroding zone was developed in the middle HC. The channel bed was scoured to bed rock within the HC canyon. In the lower HC, native materials got deposited to depths ranging from 0.15m to 1.5m. The entire creek valley became wider, and the vegetation and organic layer of soil were removed. The Quesnel Lake (QL) shoreline also re-shaped because of deposition and erosion of the material in QL. A large volume of tailings and eroded overburden entered QL, and this surge generated an extensive lake bottom deposit (Golder Associates Ltd., 2015). In this study, the model domain included the tailings dam, Polley Lake outlet, HC, and it extended until the outlet of HC at QL. The width of the study area ranged from 23m within the Canyon to 1km in Lower HC.

4.3.2 Model setup

The main steps for tailings dam-break and run-out analysis in this study include: (i) Selection of the failure mechanism, estimation of the total volume of tailings released, breach development time, outflow hydrograph, tailings' characteristics like sediment concentration and rheology parameters and sediment properties (ii) input of the downstream terrain (elevation data and flow resistance) (iii) routing of the outflow hydrograph through the downstream valley (iv) calculation of channel morphodynamics, including erosion, deposition, and bed elevation change (v) estimation of flood levels, flood extent, sediment budget and (vi) sensitivity analysis to determine the robustness of the results.

4.3.3 Developing breach hydrographs.

During the breach of tailings, only a portion of the tailings get released compared to the total release of water in the case of water retention dams. The release volume depends on the volume and viscous nature of stored tailings, volume of the stored water, dam height and construction method, failure trigger, etc. (Martin and Akkerman 2017). To estimate tailings release volume, empirical approaches are often employed (O'Brien et al. 2015). For example, Rico et al. (2008) used the data from historic tailings dam failures to establish relationships between geometric properties of tailings ponds and hydraulic characteristics like outflow volume. For the Mount

Polley case study, about 25 Mm³ of tailings along with water i.e., about 10.6 Mm³ supernatant water, 7.3 Mm³ tailings solids, 0.6 Mm³ construction materials and 6.5 Mm³ interstitial water were released. The average sediment concentration in the outflow was about 30% and the mean particle size was 50 μ m (Petticrew et al. 2015). According to the Report on Mount Polley tailings storage facility breach (2015), the flow abated after almost 14 hours. In this study, the “Tailing’s Dam failure Volume Estimate Tool (TDVET)” developed by O’Brien et al. (2015) based on empirical formulations derived from studies like Azam and Li (2010); Rico et al. (2008) and Strachan (2001) was used to distribute the 25 Mm³ of tailings outflow over time and to generate outflow hydrograph and volumetric sediment concentration time series.

4.3.4 Topography and flow resistance

The pre-event 2013 DSM (Digital Surface Model) derived from PRISM-ALOS image by AW3D (aw3d.jp), was used as the underlying terrain dataset in this model and it covered the HC floodplain and the tailings dam. The quality of the bathymetry used influences the accuracy of the model results to a large extent and since the HC was a narrow creek prior to the event, highly resolved elevation data (2.5 m) were used for proper delineation. The influence of DEM resolution was evaluated in detail in Sreekumar et al. (2022) (using a different fixed bed model), and it has been confirmed for the present model that use of a high-resolution DEM is required for accurate representation of the flood extent. Further details are discussed in the Supplemental Materials under the section “Topography”. To account for the effects of bed roughness, the Manning’s n friction factors were selected based on land-use features. SPOT satellite imagery of resolution 1.5m was used for the classification of land cover types and for delineating the HC. Six classes determined were bare earth, moderate vegetation, shadows, sparse vegetation, trees, and water, where elevation of sparse vegetation = <1m, moderate vegetation = 1-3m, trees = >3m.

4.3.5 Sediment characteristics

Prior to the breach event, physical characterization of the HC was conducted by Minnow Environmental Inc (2007). The site evaluations were conducted by dividing the Creek into 9 reaches based on gradient and geomorphological characteristics (shown in Figure 34(a)). At each reach, channel dimensions, channel bed and bank materials, bank stability etc. were recorded. The physical characteristics of the channel and banks are summarized in Table 5

where R1 to R9 represent the 9 reaches. This field investigation was used to identify the main sediment classes in the site and assign different bed fractions.

Table 5: Summary of bed fractions of different sediment classes along the 9 Hazeltine Creek (HC) reaches (R1 to R9). Source: Data from Minnow Environmental Inc (2007).

Channel Bed and bank features	Sediment Classes (%)	HC R1	HC R2	HC R3	HC R4	HC R5	HC R6	HC R7	HC R8	HC R9
In-stream Substrate	Bedrock	-	-	-	-	-	10	-	-	-
	Boulder	-	-	-	-	3	20	10	-	-
	Cobble	-	-	-	43	78	53	80	33	43
	Gravel	60	60	40	47	11	13	10	53	33
	Sand	40	40	60	8	8	4	-	14	17
	Silt and finer	-	-	-	2	-	-	-	-	7
Left Bank material	Bedrock	-	-	-	-	-	37	-	-	-
	Boulder	-	-	-	-	-	20	7	-	-
	Cobble	-	-	-	3	3	3	40	2	-
	Gravel	10	10	5	2	5	10	13	13	-
	Sand	20	20	25	30	47	15	23	43	60
	Silt and finer	70	70	70	65	45	15	17	42	40
Right bank material	Bedrock	-	-	-	-	-	2	-	-	-
	Boulder	-	-	-	-	5	30	3	-	-
	Cobble	-	-	-	5	15	25	60	7	5
	Gravel	10	10	5	5	10	2	2	17	20
	Sand	20	20	25	33	42	16	25	40	38
	Silt and finer	70	70	70	57	28	25	10	36	37

4.3.6 Governing equations

In this study, an upwind Roe-type Riemann solver, implemented with the RiverFlow2D code and solved in parallel on a GPU was employed to model the variable-density multi-grain

mixture flow of tailings over non-uniform erodible bed. This two-dimensional mudflow and sediment transport model is developed based on Finite Volume Method (FVM). The model solves the hydrodynamic equations, sediment transport equations and rheological formulations by considering sedimentation, re-suspension, and transport of sediments within the fluid column. The quasi-two-phase system of equations that includes 2D mass and momentum conservation equations for the mixture, the mass conservation equation for the N different solid phases carried in the flow and the non-uniform bed elevation change equation is discussed in this section. The source term in the mass conservation equation accounts for the exchange of materials between the bed and the fluid and the non-Newtonian rheological nature of tailings is incorporated in the momentum conservation equations (Martínez-Aranda et al. 2020). The mass and momentum conservation equations for the mixture are given by:

$$\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho h u)}{\partial x} + \frac{\partial (\rho h v)}{\partial y} = - \sum_{p=1}^N \rho_{b,p} \xi_p (D_p - E_p) \quad (19)$$

$$\frac{\partial (\rho h u)}{\partial t} + \frac{\partial (\rho h u^2 + \frac{1}{2} g_\psi \rho h^2)}{\partial x} + \frac{\partial (\rho h u v)}{\partial y} = - g_\psi \rho h \frac{\partial z_b}{\partial x} - \tau_{b,x} \quad (20)$$

$$\frac{\partial (\rho h v)}{\partial t} + \frac{\partial (\rho h u v)}{\partial x} + \frac{\partial (\rho h v^2 + \frac{1}{2} g_\psi \rho h^2)}{\partial y} = - g_\psi \rho h \frac{\partial z_b}{\partial y} - \tau_{b,y} \quad (21)$$

The mass conservation equations for sediment classes present in the mixture are given by:

$$\frac{\partial (h E_p)}{\partial t} + \frac{\partial (h u E_p)}{\partial x} + \frac{\partial (h v E_p)}{\partial y} = - (D_p - E_p) \text{ where } p = 1 \dots N \quad (22)$$

The assumption in this system of equations is that porosity will directly impact bed change, but the change in water-sediment column concentration is not directly affected by porosity. Rather, porosity will indirectly affect total sediment concentration via its impact on the bed. This assumption has been used in numerous studies such as Benkhaldoun et al. (2012), Jelti and Boulterhcha (2022), Simpson and Castelltort (2006) and Yue et al. (2008).

The Exner equation for the erodible bed is given by:

$$\frac{\partial z_b}{\partial t} = \sum_{p=1}^N \xi_p (D_p - E_p) \quad (23)$$

where ρ is the sediment-water mixture density; h is the flow depth; (u, v) are the components of the depth-averaged flow velocity along x and y directions respectively; z_b is the bed elevation; E_p is the depth averaged volumetric concentration of p^{th} sediment size-class, with $p = 1, \dots, N$ and N the number of sediment size-classes transported; $\rho_{b,p}$ is the density of solid class p ; $\tau_{b,x}$, $\tau_{b,y}$ are bed shear stress components in x and y directions which constitute the depth-averaged basal resistance vector τ along x and y directions and $g_\psi = g \cos^2 \psi$ is the bed-normal projection of the gravity (g is the acceleration due to gravity and $\cos \psi$ the cosine of the bed normal to the vertical axis); D_p is the deposition flux of p class; E_p is the erosion flux of p class; $\xi_p = 1/(1-P_p)$, P_p is porosity;

$$D_p = \alpha_p \omega_{s,p} (1 - E_p)^{m_p} E_p \quad (24)$$

$$E_p = F_{b,p} \alpha_p \omega_{s,p} E_p^* \quad (25)$$

where $\omega_{s,p}$ is settling velocity for class p ; m_p is hindering effect constant = 4; $F_{b,p}$ is the fraction of sediment class p in the bed layer; E_p , E_p^* are the equilibrium sediment concentrations for class p and averaged volumetric concentration of class p . α_p is an empirical parameter representing the ratio between the near-bed sediment concentration and the depth-averaged sediment concentration for the p^{th} sediment class. Water and sediment are assumed to be well mixed along the flow column in this model and bulk mixture density is considered. This is a very fast and highly turbulent flow and hence it is assumed that the water-sediment is “fully mixed”. Hence α_p was given a value of 1.

Equation 25 is based on a hypothesis explained as follows. As described by Li et al. (2018), sediment entrainment flux can be specified based on the assumption that entrainment occurs at the same rate as it does under capacity regime. The entrainment flux is equal to the deposition flux in capacity conditions and hence, bed sediment entrainment flux can be determined by using near-bed sediment concentration at capacity and settling velocity. This hypothesis has been successfully employed in several studies such as Li et al. (2018), Martínez-Aranda et al. (2022), Spasojevic and Holly (1990), Wu (2007), Xia et al. (2018). Equation 26 is an empirical relationship that presents the dimensionless equilibrium sediment transport capacity in terms of various parameters. The notable parameters are 1) the ratio of bed shear stress to critical

shear stress, 2) the ratio of turbulent shear stress to critical shear stress (calculated from friction slope) and 3) velocity magnitude non-dimensionalized by settling velocity. As expected, increase in bed shear stress, turbulent shear stress and velocity magnitude will increase the equilibrium sediment transport capacity, while an increase in the settling velocity will decrease the equilibrium sediment transport capacity. The link between equations 24, 25, and 26, as mentioned, is via the use of the equilibrium sediment transport capacity concept in equations 24 and 25 in calculating deposition and entrainment.

The formula for equilibrium concentration is (Wu 2008):

$$\frac{q_{s,p}^*}{\beta_p \sqrt{X_p g d_{s,p}^3}} = 0.0053 \left[\left(\frac{n}{n_p} \right)^{1.5} \frac{|\tau_b|}{\tau_{c,p}} - 1 \right]^{2.2} + 0.0000262 \left[\left(\frac{\tau}{\tau_{c,p}} - 1 \right) \frac{|\mathbf{u}|}{\omega_{s,p}} \right]^{1.74} \quad (26)$$

where $|\mathbf{u}|$ is the flow velocity vector; $\mathbf{E}_p^* = q_{s,p}^* / (h|\mathbf{u}|)$ is the equilibrium solid transport rate by volume per unit time and width for the p th sediment size-class, $d_{s,p}$ is the corresponding medium diameter, β_p is the equilibrium formula factor for class p ; n and $n_p = d_{s,p}^{1/6} / 21.1$ are the global and size-specific Manning's roughness parameters respectively; $|\tau_b|$ is the bed shear stress; X_p is the relative buoyant density of the p^{th} sediment class; $\tau = \rho g h S_f$ is the turbulent shear stress of the flow with S_f being the friction slope; $\tau_{c,p}$ is the size-specific critical shear stress for incipient motion of the solid material. When yield stress becomes zero, the flow will revert to Newtonian nature and keep flowing. The finite volume numerical solution for the hyper-concentrated flow model is obtained by using modified Roe's Riemann solver and upwind discretization.

The global resistance behavior of the tailings flow depends on the relative importance of the shear stresses arising from different sources that include viscous stress (τ_μ), yield stress (τ_y), turbulent shear stress (τ_t), dispersive stress (τ_d), and Coulomb-type frictional stress (τ_f) (O'Brien et al. 1993, Naef et al. 2006). These stresses act concurrently along the flow column since the model is depth averaged and are formulated in different ways to determine the bulk rheological properties of the mixture. For example, the Bingham fluids do not begin to flow until the stress exceeds a threshold yield stress τ_y . Eight different basal resistance formulations that will be tested to incorporate the rheological nature of the multi-grain mixture into the momentum conservation equations are shown in Table 6 where q is the unit flux $= hu$, k is a

resistance parameter set equal to 24, θ is the bed slope, θ_b is the friction angle of the solid material (typically 35° for sand) and the friction coefficient, $C_f = n^2 h^{-4/3}$.

Table 6: Rheological flow resistance formulations.

Formulation	Flow resistance equation
Pure turbulent	$ \tau_b = \tau_t = \rho C_f u^2$
Turbulent & Coulomb	$ \tau_b = \tau_t + \tau_f$
Simplified Bingham	$ \tau_b = 1.5\tau_y + 3\tau_\mu$ where $\tau_\mu = \mu q/h^2$
Full Bingham	$2 \tau_b ^3 - 3(\tau_y + 2\tau_\mu) \tau_b ^2 + \tau_y^3 = 0$
Quadratic	$ \tau_b = \tau_y + \tau_t + k/8 \tau_\mu$
Turbulent and Yield	$ \tau_b = \tau_t + \tau_y$
Turbulent, Coulomb and Yield	$ \tau_b = \tau_t + \min(\tau_y, \tau_f)$
Granular	$ \tau_b = \tau_f = g\rho h \cos \theta \tan \theta_b$

In this model, the viscosity and yield stress are represented as a function of the volumetric concentration at each cell. The following equations are used to calculate the local viscosity and local yield stress respectively:

$$\mu = \alpha_1 \exp(\beta_1 C_v) \quad (27)$$

$$\tau_y = \alpha_2 \exp(\beta_2 C_v) \quad (28)$$

where C_v is the mixture volumetric concentration and α_1 , β_1 , α_2 , and β_2 , are empirical coefficients that can be estimated based on rheometric analysis of the fluid being modelled or from observations reported in literature such as Julien and Lan (1991) and Wan and Wang (1994). The fluid density ρ is also calculated as a function of C_v and water density ρ_w using the formula:

$$\rho = \rho_w [(1 + (1.65)C_v)] \quad (29)$$

The model is second order accurate and uses an upwind Roe-type Riemann formulation where the bed slope and basal resistance source terms are projected on the eigenvectors and included in the numerical fluxes (augmented approach), ensuring a well-balanced flux formulation in

wet-dry fronts in unstructured meshes. The upwind discretization of the source terms avoids additional time step reductions to ensure the stability of the solution regardless of the basal resistance formulation. Also, this two-dimensional mudflow model does not consider the vertical variability of fluid properties. The quasi-two-phase system of equations considers the depth-averaged bulk density of the water-sediment mixture and does not take into account sediment and fluid density separately. α_p is an empirical parameter representing the difference between the near-bed sediment concentration and the depth-averaged sediment concentration for the p th sediment class. Water and sediment are generally well mixed along the flow column in highly hyperconcentrated flows, and hence it is assumed that $\alpha_p = 1$. Sediment particle size changes during the simulation and associated effects have been neglected. An unchangeable default value of the resistance parameter $k = 24$ is implemented in RiverFlow2D in the quadratic rheological formulation. This value is suitable for laminar flow in smooth, rectangular, wide channels, but k is known to increase with roughness and irregular channel geometry. Consequently, in the present simulations, the authors instead calibrated the Full Bingham rheological model.

4.3.7 Numerical model setup

The 2013 DEM of resolution 2.5m was interpolated on an unstructured triangular mesh with around 5,300,000 cells. Triangular cells of resolution 2.5m were used to resolve the flow field around the HC (shown in Figure 35) and 10m grid resolution elsewhere.

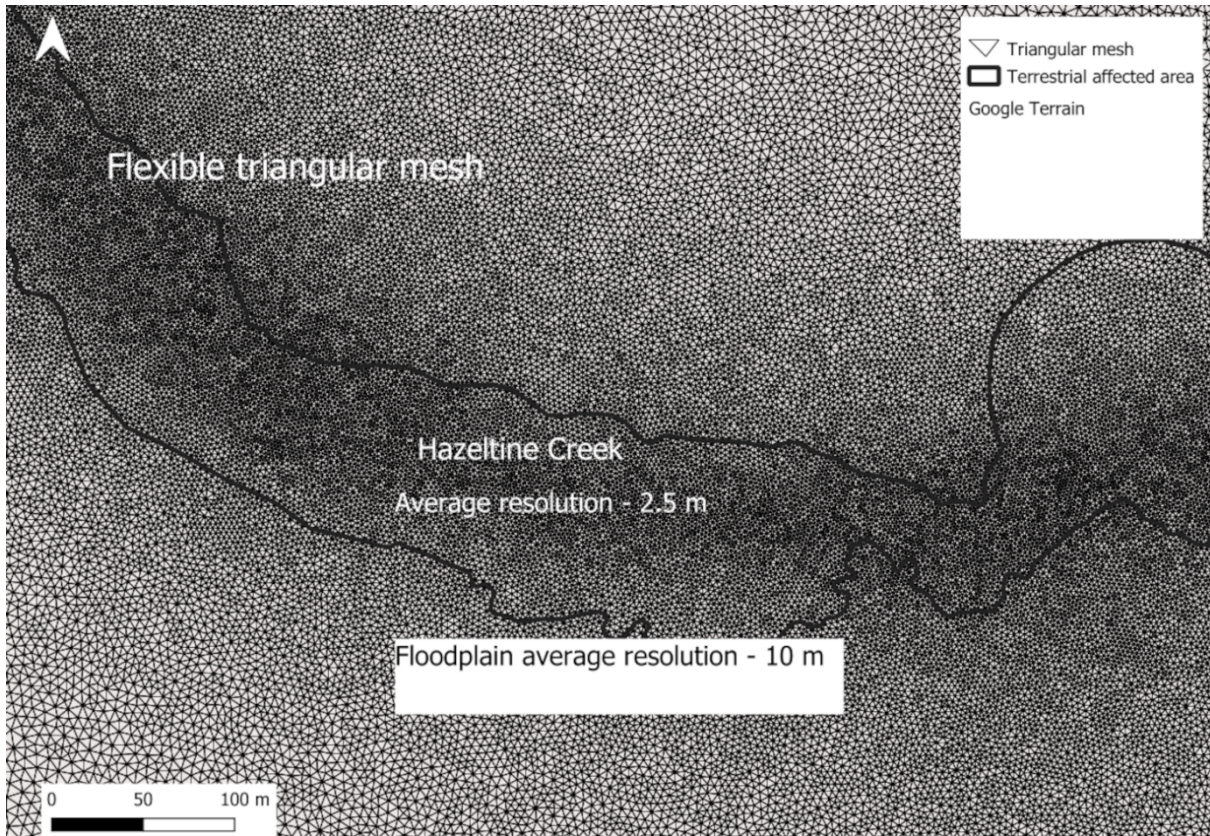


Figure 35: Triangular mesh used to refine the narrow Hazeltine Creek (Black line outlines the post-flood extent of Hazeltine Creek).

The hydrodynamic boundary conditions for the model included the time series of flow rates and sediment concentration at the inflow boundary and water levels at the outflow boundaries (marked in Figure 34(a)). Two cross-sections were placed across the Middle HC (Cross-section A) and at the outlet of Polley Lake (Cross-section B) both marked in Figure 34(b) to understand the vertical variation of bed elevation and fluid surface elevation during the simulation. The input parameters that govern the tailings flow over erodible bed were systematically calibrated until the error in the final modelled bed elevation is minimum. The main calibration parameters for the model were bed roughness, viscosity, and yield stress and typical values for these specific conditions were assigned to them. The size distribution of tailings consisted of a sand fraction (25%) and a silt fraction (75%). The outflow hydrograph and volumetric sediment concentration time series generated from TDVET (shown in Figure 36) were used as inflow boundary conditions.

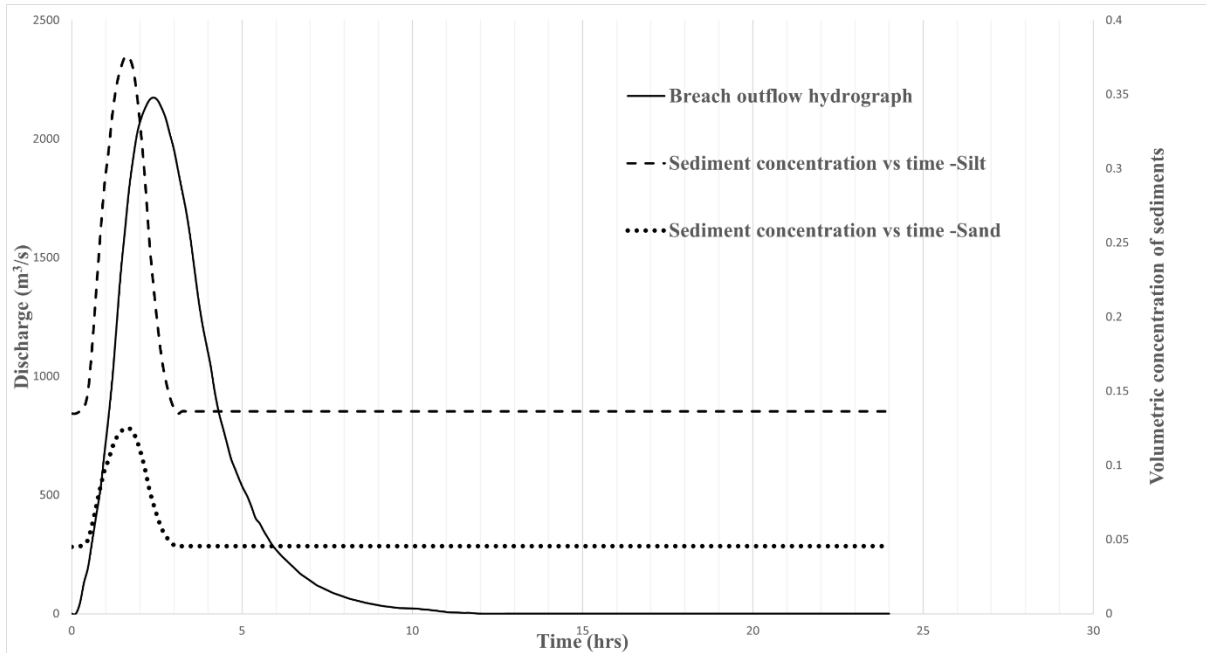


Figure 36: Tailings dam breach outflow hydrograph and breach volumetric sediment concentration time series data developed using Tailing's Dam failure Volume Estimate Tool (TDVET).

The optimal Manning's coefficients adopted for the five land cover classes were Trees: 0.15; Moderate vegetation: 0.08; Sparse vegetation: 0.06; Bare earth: 0.025. Yield stress and viscosity of the tailings released were 10 Pa and 0.15 Pa.s and were assigned based on the experimental research conducted by Wang, Wei, et al. (2018). The optimal sediment properties assigned to six different sediment classes are summarized in Table 7.

Table 7: Sediment properties

Sediment properties	Bedrock	Boulders	Cobble	Gravel	Sand	Silt
Density of solid class (kg/m ³)	2850	2800	2750	2700	2675	2650
Class diameter (m)	0.128	0.12	0.09	0.0226	0.0000625	0.000046
Bed material porosity	0.01	0.3	0.3	0.3	0.35	0.4
Shields critical stress parameter	0.06	0.06	0.06	0.06	0.1	0.1
Dimensional critical shear stress (N/m ²)	128	117	85	21	0.10	0.075

The sediment class diameter was assigned based on the Wentworth grain size classification chart given in Church et al. (1987). The porosity values assigned for each solid phase were adopted from Das (2008). Critical Shields stress parameter values for each of the sediment classes were assigned based on Shields diagram presented in Van Rijn (1993). Please note that some bedrock (10%) was present in Reach 6, and this bedrock was observed to erode during the event. Thus, a coarse particle diameter and appropriate critical Shields stress were assigned to the bedrock class to enable this observed erosion in the field. Based on Peticrew et al. (2015), the mean particle size of Mount Polley tailings was 50 μm . Hence, minimum sand size was used as it better represents the tailings. In the Mount Polley case, neither the tailings nor the downstream riverbed sediments displayed cohesion (Amec 2011), thus we applied critical Shields parameter values of 0.1, with corresponding dimensional critical shear stress values of 0.075 N/m² (silt) and 0.10 N/m² (sand), to be more representative of the entrainability of fine materials for this case.

Many simulations were performed to calibrate the parameter values characterizing rheology. The Full Bingham rheological formulation was set for estimating the flow basal resistance since it provided a satisfactory estimate of the wave arrival time and geomorphic changes. The model was simulated for a duration of 14 hrs starting from the breach initiation and the CFL was set

to 0.95. The computational time for the RiverFlow-2D model run was 2 days. To determine an appropriate mesh resolution, results of initial simulations were analysed by comparing water surface elevations. Mesh independence was analysed by running identical failure scenarios on a mesh domain with 7m, 10m and 15 m grid resolutions. The water level variation at two observation points (shown in Figure 37 (a)) as a function of grid size are shown in Figures 37 (b) and (c).

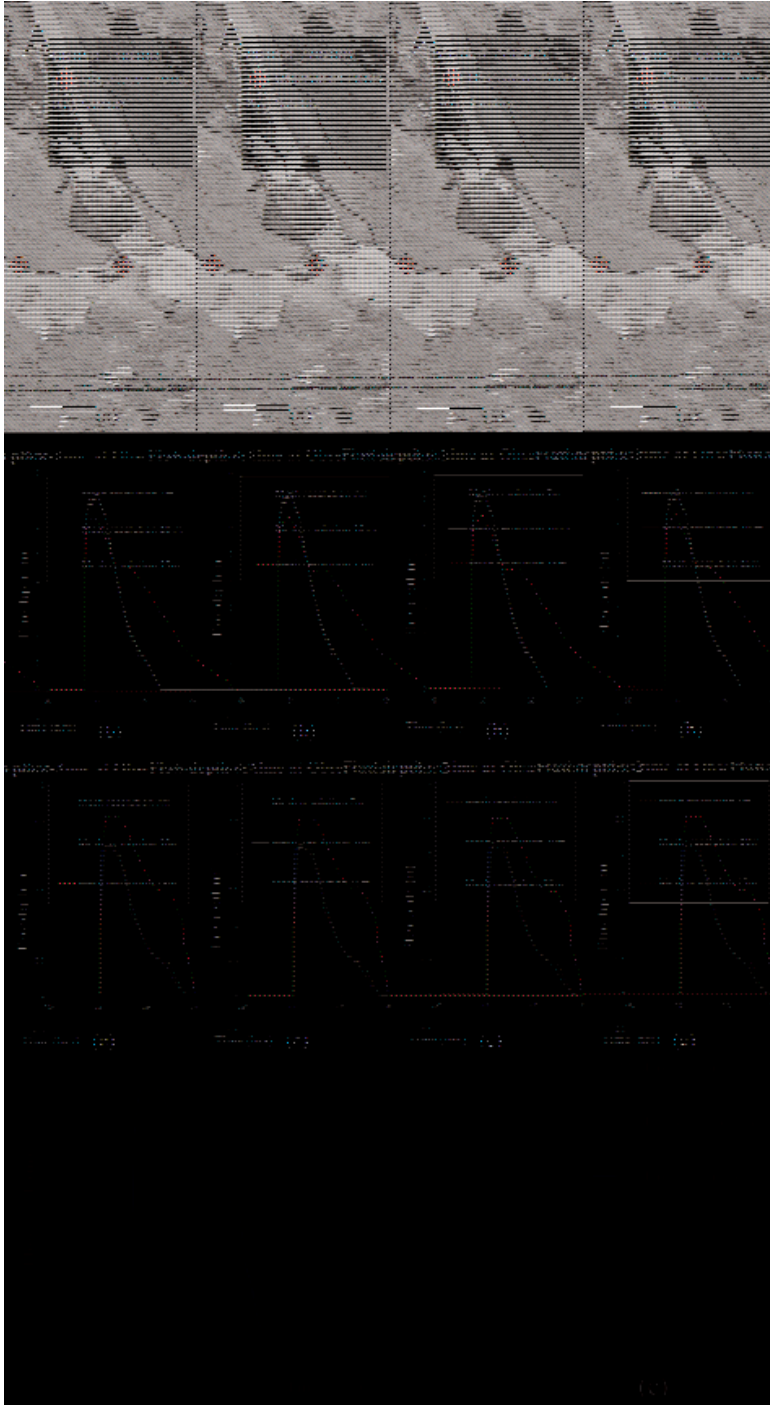


Figure 37: (a) Observation points at which flow depth variation graphs are extracted (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023) (b) flow depth vs time at Observation point 1 (c) Observation point 2.

These figures demonstrate that flow depths at the two observation points were around 7.2m (observation point 1) and 2.1m (observation point 2) when 7m and 10m grid resolutions were used. But when 15 m grid resolution is used there is significant difference in flow depth variation i.e., 6.3m (observation point 1) and 2.6m (observation point 2). The maximum velocity magnitude for models with 7m and 10m grid resolutions was nearly 8.51m/s in the observation point 1 and was about 4.95 m/s at observation point 2. When 15 m grid resolution was used, the velocity was lower and was nearly 6.87 m/s at observation point 1 and 3.64 m/s at observation point 2. Hence, to reduce the computational time, the 10 m grid resolution was chosen for the calibration of the model.

4.3.8 Analysis of observed difference DEM and flood outlines

Two topographic datasets (pre-event DEM and post-event DEM) were available for the study site and were used to understand the geomorphic changes caused by the event. The post-event 2014 DEM of resolution 1m was derived from LiDAR data collected by Natural Resources Canada, and generation of pre-event DEM was mentioned in the Section “Data acquisition”. The two DEMs were resampled to the same resolution using nearest neighbor technique and then subtracted, and a difference DEM was computed. This was used to obtain the event characteristics, identify the geomorphic changes in the terrestrial affected area and to quantify the volumes of final erosion and deposition. From this map, the characteristics of the site like the failure area, maximum failure depth, maximum deposition depth etc. were noted. Spatial variation of erosion and deposition patterns obtained from the modelled difference DEM and observed difference DEM were then compared and analysed. Post-event orthophoto provided information on the terrestrial affected area and the digitized flood extent map is shown in Figure 34(b). This map was used for the validation of the simulated inundation extent. For estimating the model accuracy, the tailings spill path was classified into four reaches: 1) Upper HC region where the slope varied from 0.7% to 1.2%, 2) Middle HC region which consisted of several steep sections and nearly 3% channel gradient, 3) HC Canyon where the HC channel narrows and steepens, and the slope gradient was nearly 7.3%, 4) Lower HC region downstream of the HC Canyon until the river mouth at QL, where the mean slope decreased to almost 0.8% (Figure 34 (b)). Critical Success Index (CSI) was used for evaluating flood extent accuracy in this study as it considers the spatial distribution of flooded area by taking into account underpredicted

and overestimated cells unlike other verification statistics like Root Mean Square Percentage Error (RMSPE)

$$CSI = \frac{A}{A+B+C} \quad (30)$$

where A is the number of cells correctly predicted by the model (hits)

B is the number of cells overestimated (false alarm)

C is the number of cells underpredicted (misses) (Lim and Brandt 2019). The sediment budget analysed from the model results was used to estimate the total volume of tailings and native materials released to QL and volume of HC sediments scoured. The outflow volume into the PL and QL was calculated by the integration of sediment discharge time series graph plotted at a cross section drawn across the outflow boundaries (shown in Figure 34 (a)). Volume of deposited sediments was estimated using the final and minimum bed elevation during the model run and volume of HC native materials eroded was analysed from the maximum erosion depth in the model domain at any timestep. Additionally, the model results may vary depending on the optimal values assigned for highly sensitive model parameters. The most appropriate values were assigned to each of the parameters, but it was also important to analyse the sensitivity of model results to possible changes in parameter values. One highly sensitive parameter was the particle size of tailings sediments. Hence, the effect of particle size on modelling mudflow and sediment transport was also studied. Figure 38 is a flow chart showing the steps in modelling.

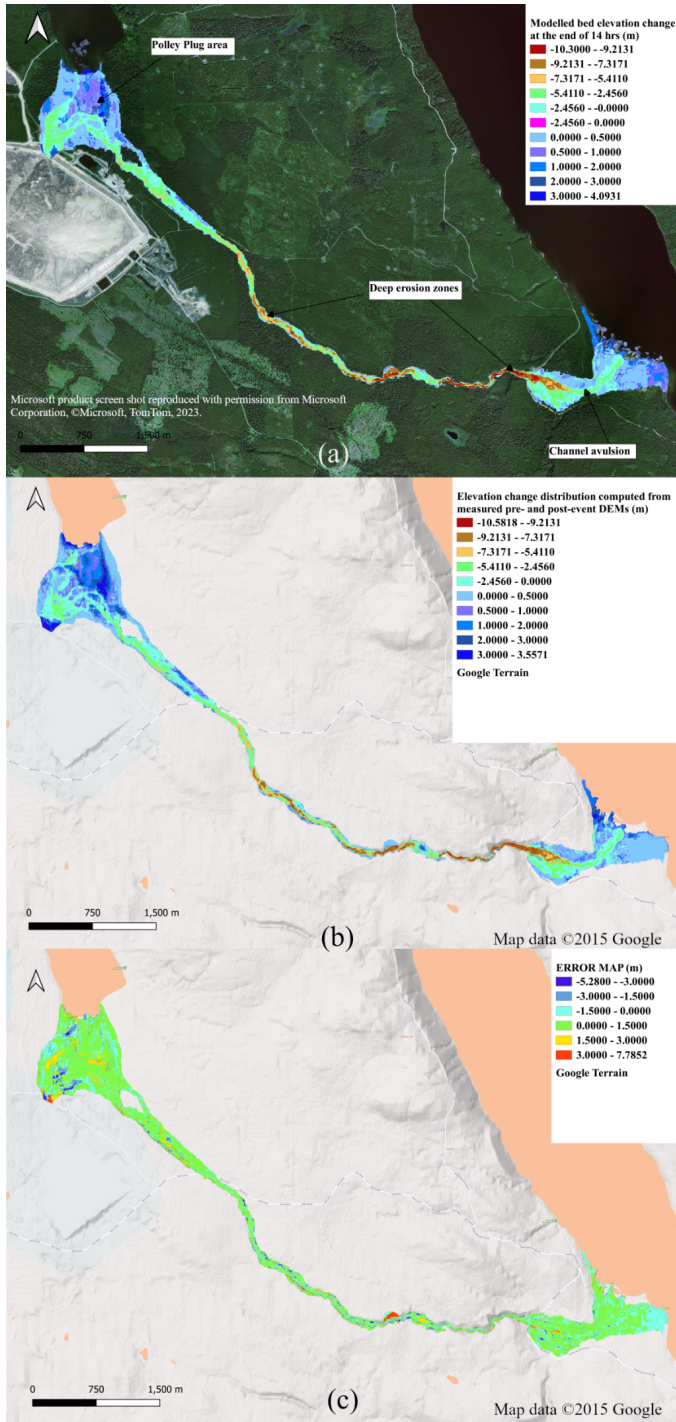


Figure 39: (a) Modelled bed elevation change at the end of 14 hrs (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023) (b) Elevation change distribution computed from measured pre- and post-event Digital Elevation Models (DEMs) (Google Terrain source: Map data ©2015

Google) (c) Error map showing the difference between observed and modelled bed elevation change (Google Terrain source: Map data ©2015 Google).

Several knickpoints (erosion zones) were noted in the Middle HC section within the HC reaches 4, 5 and 6 and a deposition zone was formed in the reach close to the outlet of Polley Lake (marked as Polley Plug area in Figure 39 (a)). Time evolution of bed and mud level at cross-section A drawn across the HC is shown in Figure 40 (a) and (b).

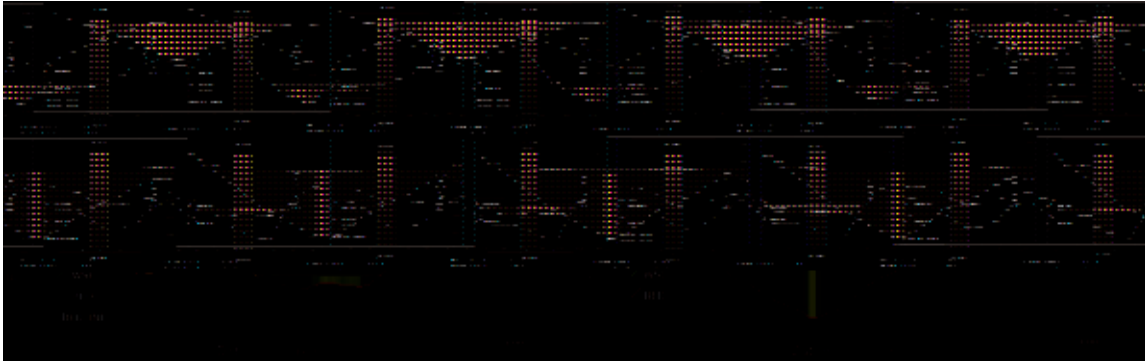


Figure 40: Bed elevation and fluid surface elevation across cross-section A (a) at the end of 1.5 hrs (b) at the end of 14 hrs, (c) Bed elevation and fluid surface elevation at the end of 14 hrs across cross-section B, (d) Bed elevation and fluid surface elevation across cross-section A at the end of 14 hrs in the case of mudflow- fixed bed model (Note: WSE – fluid surface elevation; BED – Final bed elevation; BED-INIT – Initial bed elevation; blue contours – velocity in m/s).

Bed and mud level profile at cross-section B drawn across the Polley Plug area is shown in Figure 40 (c) (cross-sections marked in Figure 34 (b)). Key geomorphic characteristics from the analysis of model results are presented in Table 8.

Table 8: Summary of key geomorphic results

Geomorphic indicator	Total
Terrestrial affected area	2.330517 km ²
Critical Success Index (CSI)	0.952
Maximum erosion depth	10.3 m
Maximum deposition depth	4.093 m
Volume of erosion	1.476 Mm ³
Volume of deposition	1.462 Mm ³

4.4.2 Comparison of modelled and observed difference DEM.

The spatial distribution of the geomorphic changes due to the event can be seen in the observed difference DEM (Figure 39 (b)), which was analysed to identify erosion and deposition areas and to estimate their respective volumes. Figure 39 (c) shows the error in the modelled final bed elevation change. Pre-event thalweg elevation along the longitudinal profile (marked in Figure 34(b)) is shown in Figure 41 (a). Figure 41 (b) shows the modelled and observed bed elevation change along the longitudinal profile and Figure 41 (c) denotes the error in the estimation of final bed elevation change by the model along the longitudinal profile and Figure 41 (d) denotes the scatter plot of observed and measured bed elevation change.

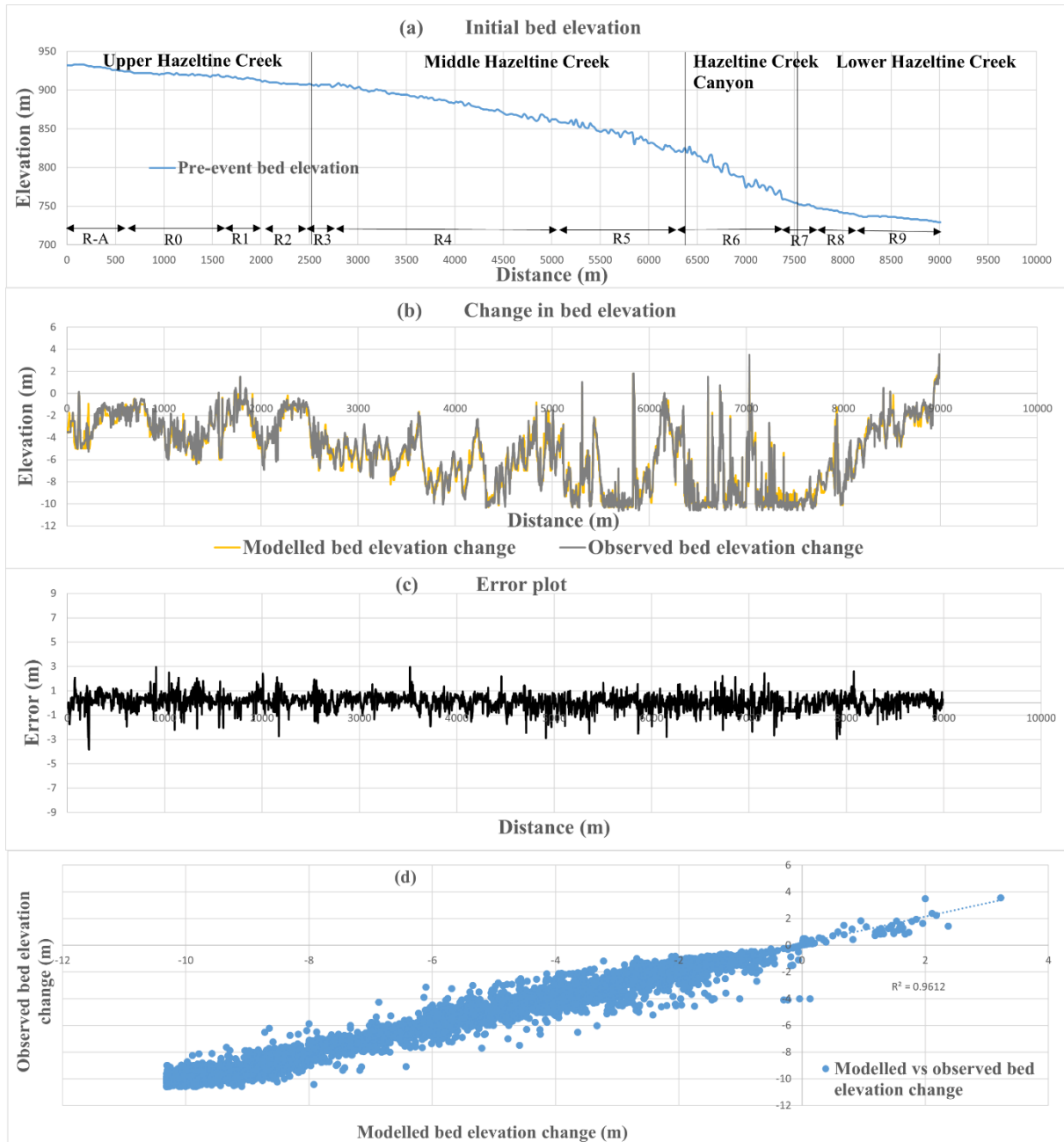


Figure 41: (a) Initial bed elevation (b) Modelled and observed bed elevation change (c) Error in model results (Mean error 12.9%) Note: Graphs a, b, and c are plotted along the longitudinal profile shown in Figure 34 (b) and R-A is shown in Figure 34(b) (d) Scatter plot of modelled vs. observed values of bed elevation changes.

For analysing the spatial variation of model results, relative accuracy between observed and modelled final bed elevation in each grid cell was calculated. Mean relative accuracy of model results was 88% when compared to the observed values and mean absolute difference error

was 0.43 m. The sum of the error was positive and the model slightly over estimated bed elevation change. Modelled and observed difference DEM results in the four zones: 1) Upper HC 2) Middle HC 3) HC Canyon and 4) Lower HC near Quesnel Lake were compared and analysed in Table 9 by calculating relative accuracy using the equation.

$$\text{Relative accuracy} = 1 - \left| \frac{\text{Observed value} - \text{Modelled value}}{\text{Observed value}} \right| \times 100 \quad (31)$$

Table 9: Comparison between the volume calculated from observed and modelled difference Digital Elevation Model (DEM).

Reaches	Observed difference DEM. Volume (Mm ³)		Modelled difference DEM Volume (Mm ³)		Relative accuracy between observed values and modelled values (%)	
	Erosion	Deposition	Erosion	Deposition	Erosion	Deposition
Upper HC	0.548	1.1	0.605	1.06	89.59	96.36
Middle HC	0.47	0.015	0.51	0.018	91.48	80
HC Canyon	0.075	0.0001	0.08	0.00011	93.33	90
Lower HC	0.3	0.45	0.301	0.39	99.6	86.66
Total debris volume	1.393	1.5651	1.496	1.48	92.6	94.56

The total volume of deposition deviated by 5.4 % from the volume derived from the observed difference DEM analysis and the simulated volume of the erosion deviated by 7.4 % from the observed difference DEM results. Based on the total debris volume, the model generally overestimated erosion and underestimated deposition. To further validate the numerical model results, the arrival time, and the peak height of the debris wave at a hydrometric station located near Quesnel Lake were investigated and the values were 12 hours and 15.8 cm respectively. These values were in good agreement with the data recorded by Water Survey of Canada based on which the flood arrival time was 12 hours after the initiation of the breach and peak flow depth was almost 15 cm (Mahdi et al. 2020).

4.4.3 Sediment budget and its sensitivity to model parameters

For studying different processes of sediment mobilization within a catchment, sediment budget is a valuable integrating framework. Sediment budgets are underlain by the continuity equation of sediment transfer i.e., the sediment input into the landscape element is equal to the sum of sediment output and change in sediment storage (Reid and Dunne 2016). After Mount Polley tailings dam breach, about 25 Mm³ of tailings along with water were released. Because of the relatively flat terrain connecting the dam failure location and the outlet of Polley Lake, the initial surge flowed into Polley Lake. The outflow volume into the Polley Lake was calculated by the integration of sediment discharge time series graph plotted at a cross section drawn across the outflow boundary 1 and based on this, 6.1 Mm³ of mud outflowed into Polley Lake. This compares to a volume estimate of 6.4 Mm³ based on pre- and post-event bathymetric surveys (Petticrew et al. 2015). Following the tailings dam failure, some tailings materials were deposited immediately at the outlet of the Polley Lake forming a plug as shown in the model results. The debris flow eroded some of the native material of Hazeltine Creek (HC) and deposited some material along the HC bed and floodplain. Our model predictions indicated that the total volume deposited was almost 1.47 Mm³ and the volume of sediment scoured from Hazeltine Creek was approximately 1.67 Mm³. The outflow volume into Quesnel Lake was calculated by the integration of sediment discharge time series graph plotted at a cross section drawn across the outflow boundary 2 (at the confluence of HC and QL shown in Figure 34 (a)) and the estimated release volume to QL was around 19.13 Mm³. This estimate was in good agreement with the volume of 18.6 + 1.4 Mm³ inferred from the lake level gauge operated by the Water Survey of Canada (Golder Associates Ltd, 2015). The sediment deposited in Quesnel Lake included tailings, interstitial water and native material that scoured from Hazeltine Creek and accounts for the fact that in some HC locations the bed initially scoured even though final bed elevation indicated net deposition. It was also noted that when different values were assigned for particle size, the sediment budget was significantly affected. Fine sand and coarse silt particles of size 0.0625 mm and 0.046 mm were used for calibrating the model. When the particle sizes assigned were changed to 0.0625 mm and 0.0598 mm, the sediment volume leaving the study domain was 18.2 Mm³ and when the particle sizes assigned were changed to 0.0625 mm and 0.0322 mm, the volume of sediments leaving the study reach increased to about 20.3 Mm³. The sediment volume leaving the study domain for a few other simulations with

particles sizes varied by +/- 30% are summarized in Table 10. Absolute sensitivity and relative sensitivity are also calculated using the equations:

$$\text{Absolute sensitivity} = \Delta Y / \Delta X \quad (32)$$

$$\text{Relative sensitivity} = X \Delta Y / Y \Delta X \quad (33)$$

Table 10: Model sensitivity analysis to particle size.

Model run No:	Particle size 1 (mm)	Particle size 2 (mm)	Sediment volume leaving the study domain (Mm3)	Absolute sensitivity ($\Delta Y / \Delta X$)	Relative sensitivity ($X \Delta Y / Y \Delta X$)
1	0.04375	0.046	19.4	-16	-0.05
2 (calibrated values)	0.0625	0.046	19.1	-	-
3	0.08125	0.046	18.7	-21.33	-0.07
4	0.0625	0.0322	20.3	-86.96	-0.21
5	0.0625	0.0598	18.2	-65.21	-0.16

Note:

X is the input (particle size).

ΔX is the change in input.

Y is the output (sediment volume leaving the study domain).

ΔY is the change in output.

Herein, X is the input (particle size), ΔX is the change in input, Y is the output (sediment volume leaving the study domain), and ΔY is the change in output (Ahmad 2013). The negative value for relative sensitivity denotes the inverse relationship between particle size and the

sediment volume leaving the study domain. As the particle size is increased, the sediment volume leaving the study domain decreased and vice versa. The simulated sediment budget agreed with the observed evidence and the model sensitivity analysis revealed that the particle size of tailings sediments can significantly affect the sediment budget within the study area.

4.4.4 Comparing mudflow over erodible and fixed bed.

To evaluate the impact of bed exchange in the flow dynamics, another model run was performed by neglecting the bed-exchange flux i.e., by disregarding scour and deposition. All other parameters used were the same as mentioned in the Section “Numerical model setup”. Figure 40 (d) shows the fluid surface elevation at the end of 14 hrs in the case of mudflow- fixed bed model. Figure 42 shows the mud flow depth at time, (a) $t = 30$ minutes, and time, (b) $t = 1.5$ hours following the breach with and without considering bed exchange.

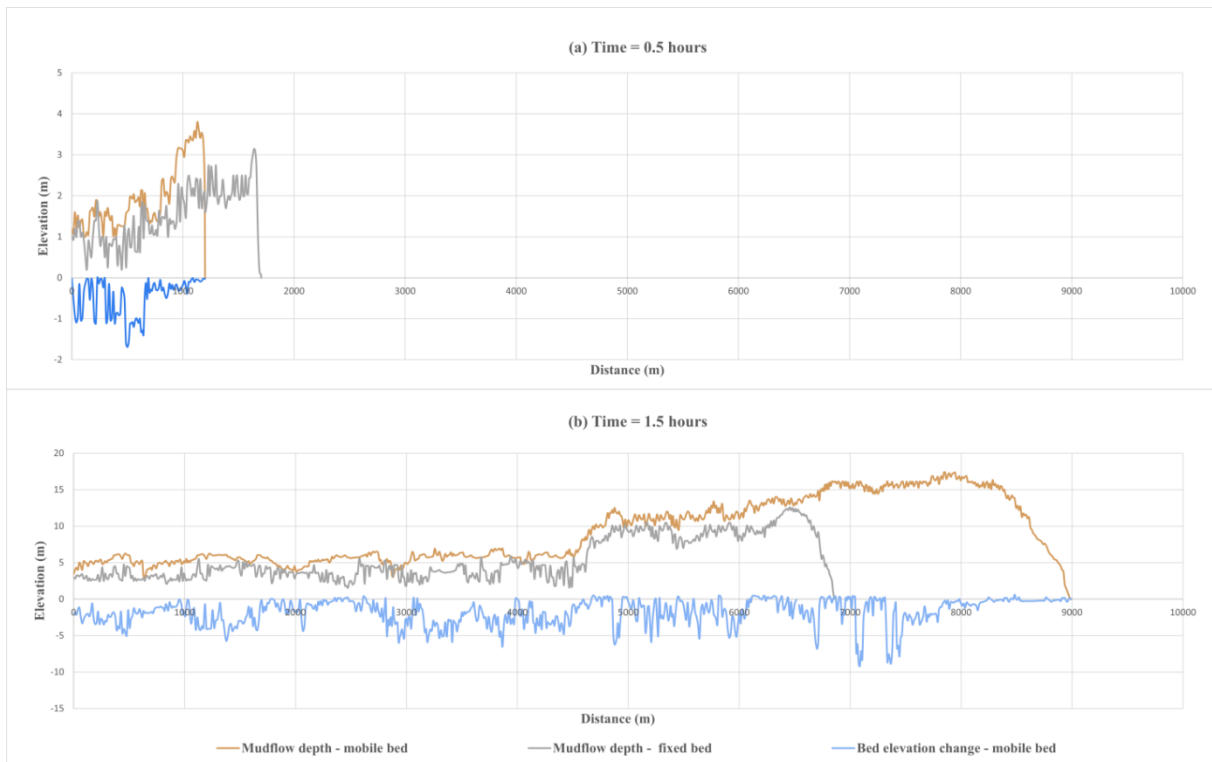


Figure 42: Mudflow depth and change in bed elevation (a) $t = 0.5$ hrs and (b) $t = 1.5$ hrs, with and without considering bed entrainment.

It was noted that the maximum mudflow depth of the flood wave along the HC was higher when bed entrainment was considered because the solid particles entrained supplemented the

volume of sediments involved in the mudflow. Also, at $t = 30$ minutes the wave-front when the entrainment term was neglected was ahead of the wavefront that considered bed exchange. In other words, the tailings flow initially travelled faster if bed erosion was not considered. However, as the flood wave moved further downstream over the steep slopes, the wavefront that considered entrainment raced ahead of the wavefront that neglected bed exchange. Thus, eventually the tailings flow travelled faster if bed erosion was considered. Figure 43 depicts the debris density distribution in the mudflow-mobile bed model at the end of 1.5 hrs and it could be noted that density was reduced at the upstream region as the flood wave progressed downstream.



Figure 43: Mud density distribution at time $t = 1.5$ hrs after the dam failure (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023).

4.4.5 Event analysis and discussion

The event occurred as a sequence of rapid surges characterized initially by discharge with high sediment concentration followed by decreasing discharge with low sediment concentration. Based on the analysis of model results, three different mechanisms of disturbance were noted: 1) erosion of the pre-event channel and floodplain by the tailings materials released, 2) deposition of tailings, eroded native material and embankment material, 3) cycles of erosion and deposition in which native materials were eroded and entrained materials were deposited. Thickened tailings got deposited up to a height of 3 m on the sides of the breach location in the Polley plug area (shown in Figure 39 (a)). In the Middle Hazeltine Creek, the channel bed degraded and multiple knickpoints (deep erosion zones) were formed (marked in Figure 39 (a)). In the HC Canyon, the vertical erosion of the channel bed was quite high, with values of up to nearly 10.3 m. The post-event outlet of HC channel was also about 250 m to the right of the pre-event channel location and there was channel avulsion as shown in Figure 39 (a). Mudflow and deposition characteristics based on the numerical model results in each of the four reaches mentioned in the Section “Analysis of observed difference DEM and flood outlines” are summarized in the Supplemental Materials under the section entitled “Event analysis”. Further analysis of channel avulsion is discussed in the Supplemental Materials under the section “Channel avulsion”.

For this case it was essential to utilize a non-Newtonian flow solver to replicate accurately the flood propagation time; an otherwise equivalent Newtonian simulation results in the flood wave reaching Quesnel Lake in 1 hour instead of the 1.5 hours predicted by the non-Newtonian model. The time evolution of tailings transport when the non-Newtonian nature of tailings was neglected is shown in Figure C53. The time evolution of tailings transport when the non-Newtonian nature of tailings was considered is shown in Figure C54. It can be concluded that a Newtonian model predicts a faster travel time compared to a non-Newtonian model. The influence of sediment exchange in the flow dynamics was assessed by comparing tailings flow over erodible and fixed bed. In the initial stages of flood wave progression, the wavefront propagated faster over a fixed bed than with bed exchange. Later, as the flood wave travelled further downstream over the longitudinal steep slopes, the wavefront that considered entrainment raced ahead of the wavefront that neglected bed exchange. Iverson et al. (2011) observed experimentally that debris flow speed can either increase or decrease with bed

entrainment, depending upon the water content of the bed material. Similarly, in their study on landslide dynamics, Pudasaini and Krautblatter (2021) found that erosive landslides can significantly enhance or reduce mobility and this trend is site and material specific. In the present study, part of the flow momentum would have been used to initiate and accelerate the entrainment of solid mass from the erodible bed in the initial hours. As the wave travelled over the steep slope, bed materials were entrained and added to the flow and thus the volume and density of the solid phase increased. This increment in mass enhanced momentum and the wave-front advanced at higher velocity than when entrainment was neglected. Moreover, when the fluid density distribution at the end of 1.5 hrs was plotted, it was noted that in the steep eroding regions of HC, because of the entrainment, the density was higher compared to the original mud density. From Figure 43, it can be inferred that the entrained sediment concentration was higher within the wave-front and middle regions and less so in the tail zone.

4.4.6 Limitations

The major assumption in this two-dimensional (depth averaged) numerical model was that any vertical variability of fluid properties like density, viscosity, and yield stress was neglected. Turbulence modelling was performed using a simplified method and the use of advanced turbulence models may improve the results. The equation developed by Wu (2008) has been used to model sediment transport and this equation considers total bed load and not bed load and suspended load separately. A model that considers bed load and suspended load separately might improve the model results. Moreover, rheology tests on the Mount Polley tailings' sample were not performed in this study and the rheological values were assigned based on the experimental research conducted by Wang, Wei, et al. (2018). Combining the numerical model with experimental data could further clarify the movement mechanism and the flow characteristics under different flow conditions as well as demonstrate whether the hydrostatic pressure assumption and the model equations adequately represent the physical flows. The breach outflow hydrograph used in this study was developed based on the release volume obtained from literature but in real-life risk-assessment problems, the release volume is unknown a priori. Several uncertainties exist when estimating this release volume. The release volume highly depends on the volume and location of the supernatant pond. If the supernatant pond volume is larger, then the release volume will also be larger. Also, when a tailings dam with water storage collapses, initially a floodwave with water forms and propagates

downstream and then dense mudflow mobilizes through the breach. The tailings water may advance with higher velocity while mudflow may travel only a relatively shorter distance. These two-phase mudflow characteristics were not incorporated in this study, and this represents a significant limitation. The volume of tailings released also depends on the failure mechanisms and breach slopes. Detailed site-specific failure mode analysis should be conducted. Sensitivities to different breach slopes should be investigated and a range of release volume should be developed for risk assessment. Also, the peak of the breach outflow hydrograph was estimated by using softwares based on historic data and it is important to ensure the suitability of this approach when conducting tailings dam risk assessments.

4.4.7 Real-life applications

Potential breach of a tailings dam can cause catastrophic impact on environment, downstream settlements, and communities. Modelling the after-breach process helps in emergency planning, hazard analysis and mitigation of consequences. Highly sediment-laden unsteady flows following a tailings dam collapse can involve high levels of energy and can cause immense flow-bed interaction and thus morphological changes in the downstream channels. The mudflows gain mass and momentum as they travel over steep bed slopes because of material entrainment. The solid phases present in the mixture and landscape, varying from boulders to fine silt, can affect the wave-front velocity and arrival time. The present study models highly sediment laden tailings flow over non-uniform erodible bed by considering variable fluid properties and different solid phases. Mudflow depth and bed elevation change recorded at each cell in the computational domain helps to assess the spatially distributed hazard level during a tailings dam failure. The non-structured mesh adopted in this study can reduce computational costs and perform simulations for early flood warning.

4.5 Conclusions

The integrated non-Newtonian morphodynamic model was able to simulate tailings flow pattern and sediment dynamics during a tailings dam breach event more realistically and accurately. The model simulated values were within the same order of magnitude as the observed data, thus providing confidence in applying the model for tailings and sediment transport modelling. The model was also able to predict the total volume of sediments released

into the downstream lake with almost 97.3% accuracy. The following conclusions can be drawn from this study:

- An integrated mudflow morphodynamic model that considers variable density and multiple sediment classes is essential to predict immediate physical impacts following the failure like channel avulsion, changes in channel geometry, multiple knickpoints and deposition zones. The transition of the downstream channel provided valuable insight as to what kind of channel evolution can be expected in a relatively steep gravel and cobble bed channel system following a tailings dam failure.
- From the analysis of the results, it can be concluded that during hyper-concentrated sediment flow, high volume of material entrainment can occur over the steep slopes of the channel and deposition on flatter terrain. In the steep eroding regions of HC, because of the entrainment, the density is higher compared to the original tailings density. It is also concluded that the sediment concentration is higher within the wave-front and middle regions and less so in the tail zone.
- The bulking effects of intense sediment degradation augments the downstream peak discharge and total sediment load. As the particle size is decreased, the sediment volume leaving the study domain increased.
- The standard mudflow model with fixed bed underestimated the downstream flood arrival time as the model could not consider the significant changes in the channel bed that reached up to 10 m in vertical direction. The large contrast in velocity between the movable and fixed bed models resulted in completely different run-out scenarios and unless precisely quantified this could have serious implications when conducting risk assessment of tailings dam failures and while planning for evacuation.

5. Conclusions

The following conclusions can be drawn from this study:

- When GeoBase DEMs are used for back analysis of the event using the mudflow -fixed bed model (Flo-2D), a physically meaningful set of values could not be assigned when trying to minimize the error between observed and modelled data. It was also found that one set of input parameters could not be used for calibrating the model with two types of DEMs with acceptable accuracy. The fundamental reason for the reduced performance of GeoBase DEM is that the resolution was greater than the channel width and hence there was lack of definition of the downstream channel.
- The sensitivity analysis showed that the flood extent output from Flo-2D was highly influenced by DEMs, while other model outputs such as arrival time and maximum mudflow depth were sensitive to DEMs, inflow sediment concentration and rheological properties (viscosity and yield stress). Runout distance was more sensitive to viscosity η (especially coefficient β_1) than yield stress. It was noted that with increasing sediment concentration and viscosity, both flood depth and flood arrival time increased. Manning's n values had comparatively less influence on flow behaviour.
- Raster Mosaic tool in ArcGIS Pro software (ESRI 2020) and the blending process developed by Gallant (2019) for merging elevation data from multiple sources were compared and the merging procedure gave satisfactory results.
- The integrated non-Newtonian morphodynamic model (Riverflow 2D) was able to simulate tailings flow pattern and sediment dynamics during a tailings dam breach event more realistically and accurately. A model that considers variable density and multiple sediment classes is essential to predict immediate physical impacts following the failure like channel avulsion, changes in channel geometry, multiple knickpoints and deposition zones.
- During hyper-concentrated sediment flow, high volume of material entrainment can occur over the steep slopes of the channel and deposition on flatter terrain. In the steep eroding regions of HC, simulation results showed that because of the entrainment, the modelled density is higher compared to the original tailings density. It is also concluded that the modelled sediment concentration is higher within the wave-front and middle

regions and less so in the tail zone.

- The standard mudflow model with fixed bed underestimated the downstream flood arrival time as the model could not consider the significant changes in the channel bed that reached up to 10 m in vertical direction. The large contrast in velocity between the movable and fixed bed models resulted in completely different run-out scenarios.
- Sediment supply, transfer, and deposition were estimated by conducting a sediment budget study and the mudflow – mobile bed model gave satisfactory results.
- The study using Flo-2D model was able to consider the non-Newtonian nature of tailings. The limitation of the study is that it did not consider the sediment transport and the model was also not able to capture dynamics of the flood wave at the measurement station. The gauge measurements showed that the flood wave had a steep wave front followed by a series of water surface oscillations, whereas the numerical model produced a more diffusive wave. The error in water level variation may have been due to the lack of consideration of the advection and diffusion of the subaqueous sediment density flow.
- The study using the Riverflow 2D model was able to consider both the non-Newtonian nature of tailings and the bed entrainment during tailings flow. The major limitation is that the model did not consider the vertical variability of fluid properties and two-phase nature of tailings flow.

6. Recommendations for future work

- There are different rheological models, such as the Herschel-Bulkley, frictional, Voellmy, Bingham, and turbulent models. There is a pressing need to study each rheological model individually to analyze historical failure events and obtain a better understanding of the selection of the rheological model.
- Rheological properties of tailings are site specific and hence experimental research of material rheology would be useful before being given as model input.
- The entrainment of additional solids from the bed layer during the tailings flow can cause a dramatic increase in the sediment supply and considerable changes in the channel morphology. Only a limited number of two-dimensional models have modelled such scenarios. With the advancement of computational fluid dynamics (CFD) models, the use of non-hydrostatic three-dimensional models can also be explored to consider downstream erosion and deposition during TDBA and flood wave routing.
- Turbulence modelling was performed using a simplified method and the use of advanced turbulence models may improve the results.
- Combining the numerical model with experimental data could further clarify the movement mechanism and the flow characteristics under different flow conditions as well as demonstrate whether the hydrostatic pressure assumption and the model equations adequately represent the physical flows.
- It is necessary to assess the suitability of the empirical regression relationships for breach hydrographs developed from water retention dam failures for application to tailings dam breaches. New analyses should be conducted specifically for tailings dam failures. The analysis should be completed based on tailing types and not by combining all data so that each category indicates the same ore type, materials, and rheology.
- The multi-layer flow of saturated tailings and water for dams where the tailings are capped by supernatant water is not modelled in most tailings dam failure risk assessment studies. There is a need to consider the presence of a supernatant water layer above the coarse layers of tailings, and it is necessary to model mixing and settling while predicting the inundation extent.

Appendix A

The WISE-URANIUM inventory (Chronology of major tailings dam failures (wise-uranium.org)) was used to track down the historical dam failure imageries on the Planet website (Planet | Homepage) for the content of this appendix. The authors intended to centralize the high-quality sky view of historical tailings dam failures with key information attached to them. The chronological events on the WISE-URANIUM website were searched and if the imagery was available, then it was added to the database. Unfortunately, the Planet imageries older than 2017 were very spotty and of poor quality and, thus, some important tailings dam breaches were left out (such as Mount Polley dam failure in BC, Canada, August 4, 2014). The authors remain open to share this database with other researchers should they need to add high quality imageries of the other events from other resources.

Location: Williamson Mine, Mwadui Lohumbo, Tanzania

Date: 2022, Nov. 7

Ore: Diamond

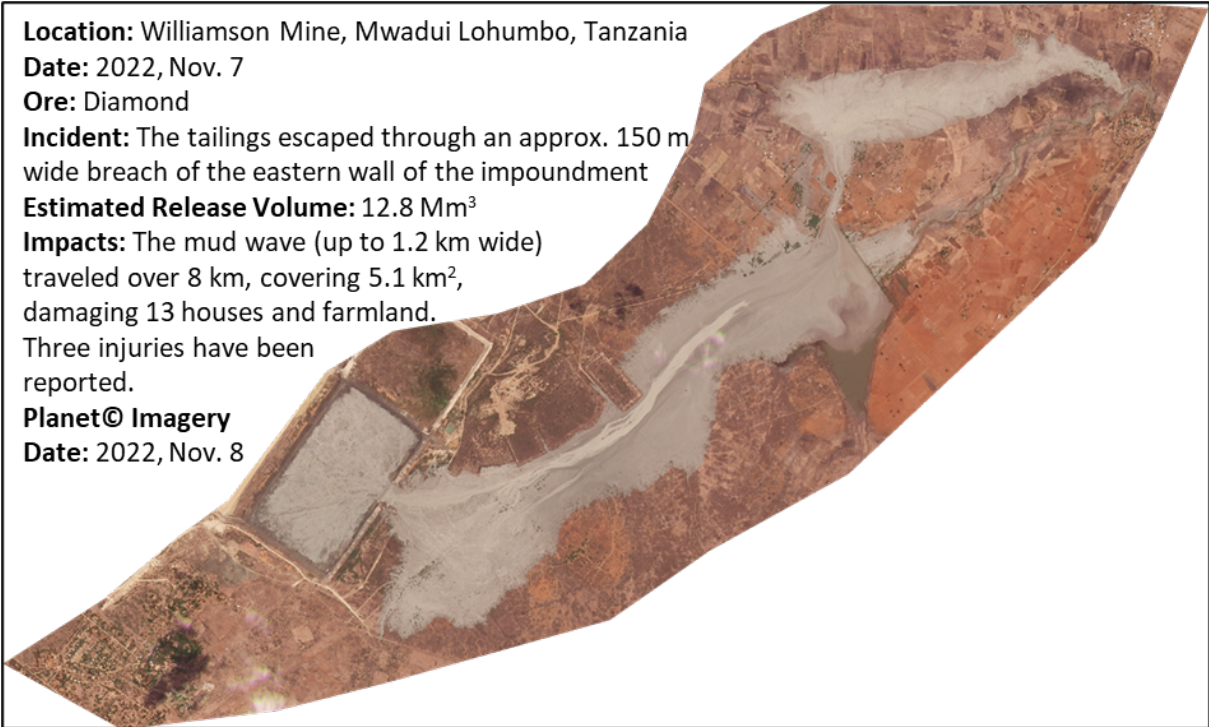
Incident: The tailings escaped through an approx. 150 m wide breach of the eastern wall of the impoundment

Estimated Release Volume: 12.8 Mm³

Impacts: The mud wave (up to 1.2 km wide) traveled over 8 km, covering 5.1 km², damaging 13 houses and farmland. Three injuries have been reported.

Planet© Imagery

Date: 2022, Nov. 8



<https://www.youtube.com/watch?v=N8RM2k9Ppi8>

Location: Jagersfontein, Kopanong, Xhariep, Free State, South Africa

Date: 2022, Sep. 11

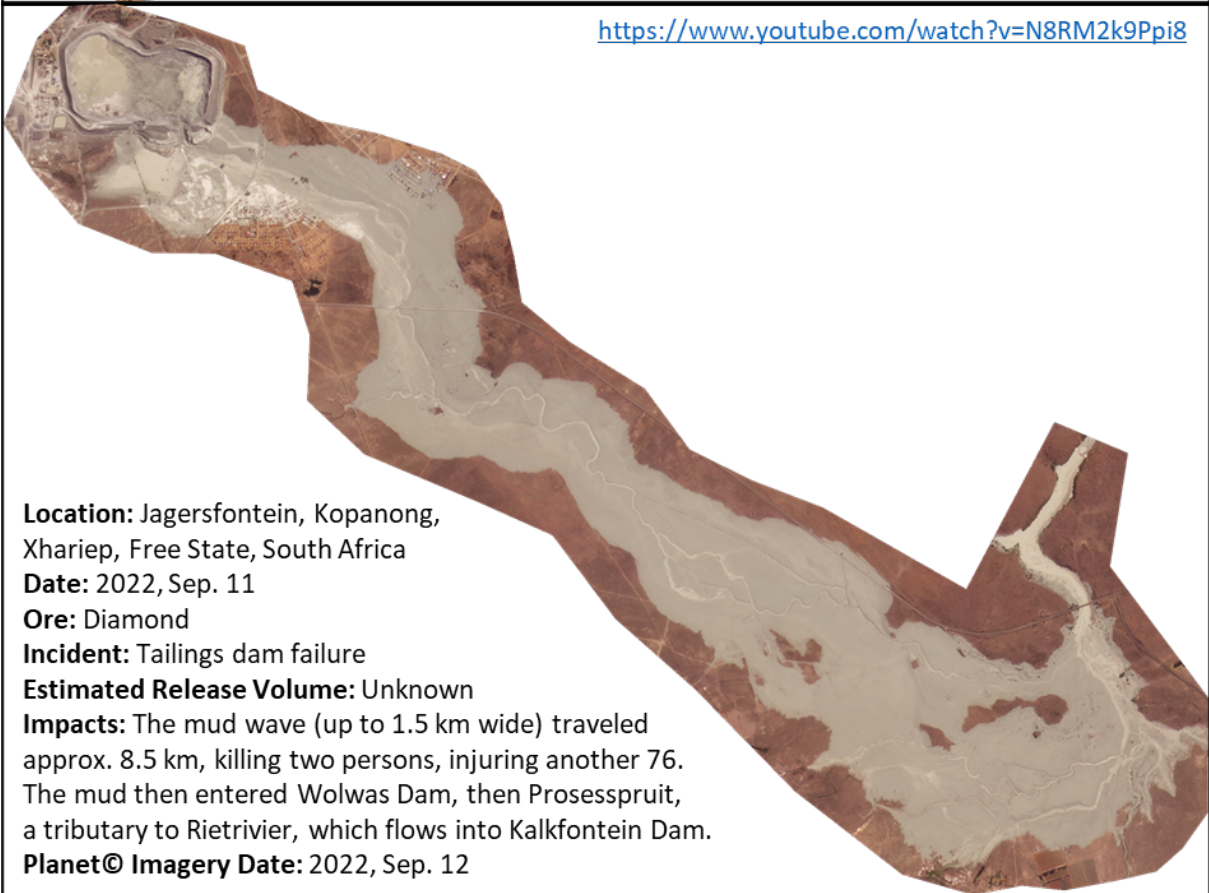
Ore: Diamond

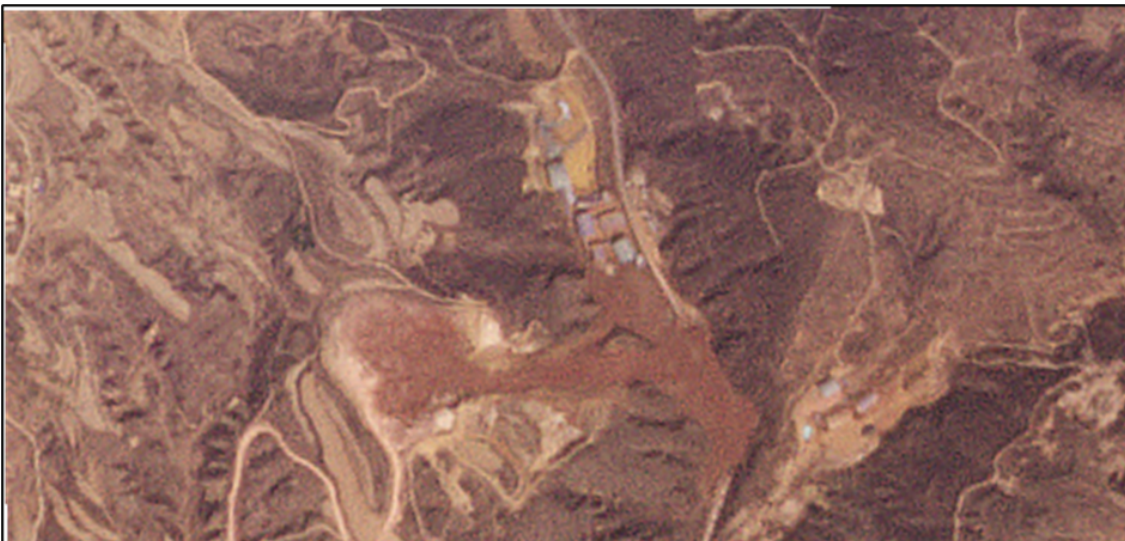
Incident: Tailings dam failure

Estimated Release Volume: Unknown

Impacts: The mud wave (up to 1.5 km wide) traveled approx. 8.5 km, killing two persons, injuring another 76. The mud then entered Wolwas Dam, then Prosesspruit, a tributary to Rietrivier, which flows into Kalkfontein Dam.

Planet© Imagery Date: 2022, Sep. 12





Location: Wenquan Township, Jiaokou County, Shanxi Province, China

Date: 2022, Mar. 27

Ore: Bauxite

Incident: Tailings dam failure

Estimated Release Volume: Unknown

Impacts: Part of the factory area was buried; a large pit was formed in the tailings pond, the dam body was flushed with a gap of about 70 to 80 meters, causing 0.5 ha of arbor forest land to be buried, more than 200 meters of seasonal ditches and rural roads were blocked.

Planet© Imagery Date: 2022, Mar. 28



Location: Banjhiberana village, Thelkolo area, Sambalpur district, Odisha, India

Date: 2022, Jan. 20

Ore: Iron

Incident: Breach of tailings pond wall holding iron slurry generated from beneficiation plant

Estimated Release Volume: Unknown

Impacts: at least 20-30 acres [8-12 hectares] of farmland were submerged under the iron ore slurry while two ponds were contaminated, causing a fish kill; a security guard is reported missing.

Planet© Imagery Date: 2022, Jan. 22



https://www.youtube.com/watch?v=6A8l6Oi_Feg

Location: Yedikardes village, Sebinkarahisar district of Giresun, Turkey

Date: 2021, Nov. 18

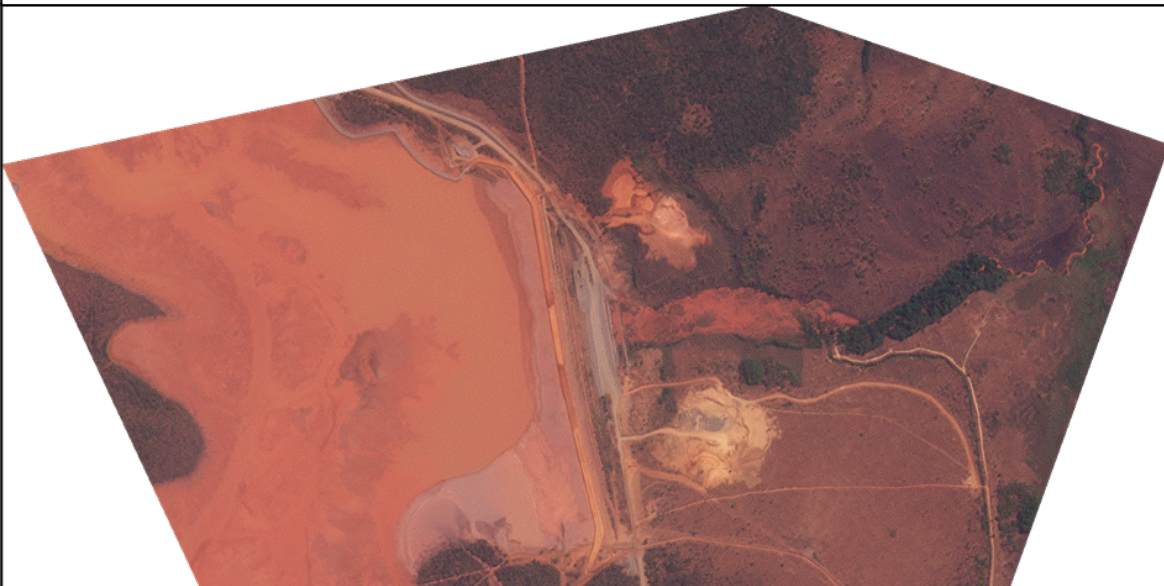
Ore: Lead, Zinc, Copper

Incident: Tailings dam #2 failure

Estimated Release Volume: ~4,500 tons

Impacts: The tailings flowed into dam #1 and then into the Darabul Stream and reached Kiliçkaya Dam 5 km downstream.

Planet© Imagery Date: 2021, Nov. 22



Location: Catoca mine, Saurimo, Lunda Sul, Angola

Date: 2021, Jul. 27

Ore: Diamond

Incident: Breach in spillway duct leads to massive spill of "rejected pulp"

Estimated Release Volume: Unknown

Impacts: Lova River polluted 100 km downstream; pollution of Tchicapa River rendered drinking water in the Muatova neighborhood in the City of Lucapa unsafe.

Planet© Imagery Date: 2021, Jul. 27



Location: Tieli, Yichun City, Heilongjiang Province, China

Date: 2020, Mar. 28

Ore: Molybdenum

Incident: Decant structure of the tailings dam tilted, resulting in the release of supernatant water and tailings through a drainage tunnel, while the embankment itself remained intact

Estimated Release Volume: 2.53 Mm³

Impacts: water and tailings flowed through surrounding area, reaching Yijimi River 3 km downstream, threatening the drinking water resource of 68,000 people in Tieli City; by Apr. 4, the pollution reached 208 km downstream

Planet© Imagery Date: 2020, May 15

Location: Nossa Senhora do Livramento, Mato Grosso, Brazil

Date: 2019, Oct. 1

Ore: Gold

Incident: Tailings dam failure

Estimated Release Volume: Unknown

Impacts: Tailings flowed 1-2 km, thereby disrupting a power line.

Planet© Imagery Date: 2019, Oct. 1



Location: Cobriza mine, San Pedro de Coris, Churcampa province, Huancavelica region, Peru

Date: 2019, Jul. 10

Ore: Copper

Incident: Tailings dam failure

Estimated Release Volume: 67,488 m³

Impacts: Tailings covered an area of 41,574 m² and reached Mantaro River

Planet© Imagery Date: 2019, Jul. 11



<https://www.youtube.com/watch?v=sKZUZQytads>



Location: Córrego de Feijão mine, Brumadinho, Minas Gerais, Brazil

Date: 2019, Jan. 25

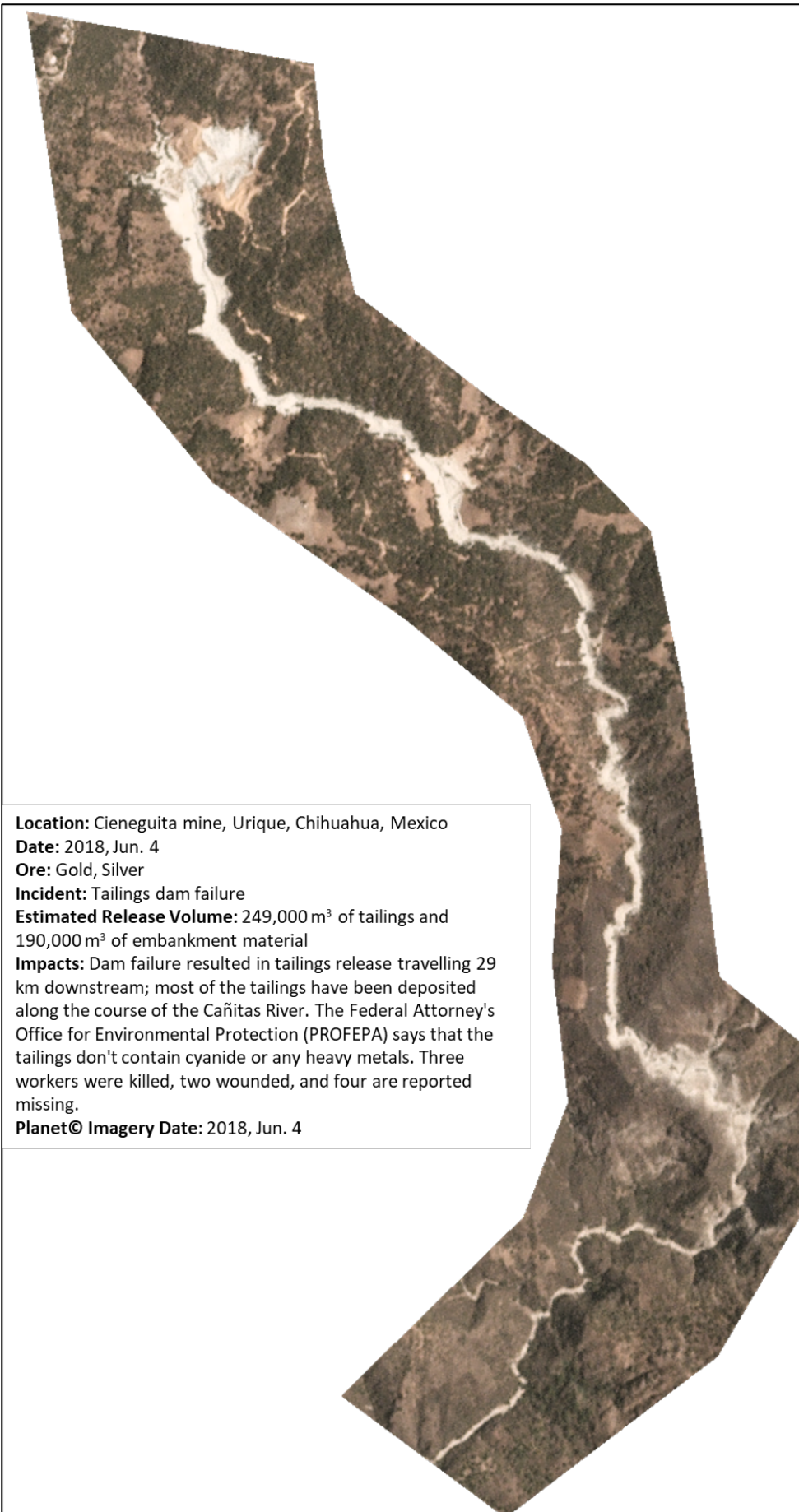
Ore: Iron

Incident: Tailings dam #1 failure

Estimated Release Volume: 12 Mm³

Impacts: The tailings wave devastated the mine's loading station, its administrative area, and two smaller sediment retention basins (B4 and B4A); it then traveled approx. 7 km downhill until reaching Rio Paraopeba, thereby destroying a bridge of the mine's railway branch, and spreading to parts of the local community Vila Ferteco, near the town of Brumadinho; the slurry was then carried further by Rio Paraopeba; 267 people were killed, and several are still reported missing.

Planet© Imagery Date: 2019, Jan. 29



Location: Cieneguita mine, Urique, Chihuahua, Mexico

Date: 2018, Jun. 4

Ore: Gold, Silver

Incident: Tailings dam failure

Estimated Release Volume: 249,000 m³ of tailings and 190,000 m³ of embankment material

Impacts: Dam failure resulted in tailings release travelling 29 km downstream; most of the tailings have been deposited along the course of the Cañitas River. The Federal Attorney's Office for Environmental Protection (PROFEPA) says that the tailings don't contain cyanide or any heavy metals. Three workers were killed, two wounded, and four are reported missing.

Planet© Imagery Date: 2018, Jun. 4

Location: Cadia, New South Wales, Australia

Date: 2018, Mar. 9

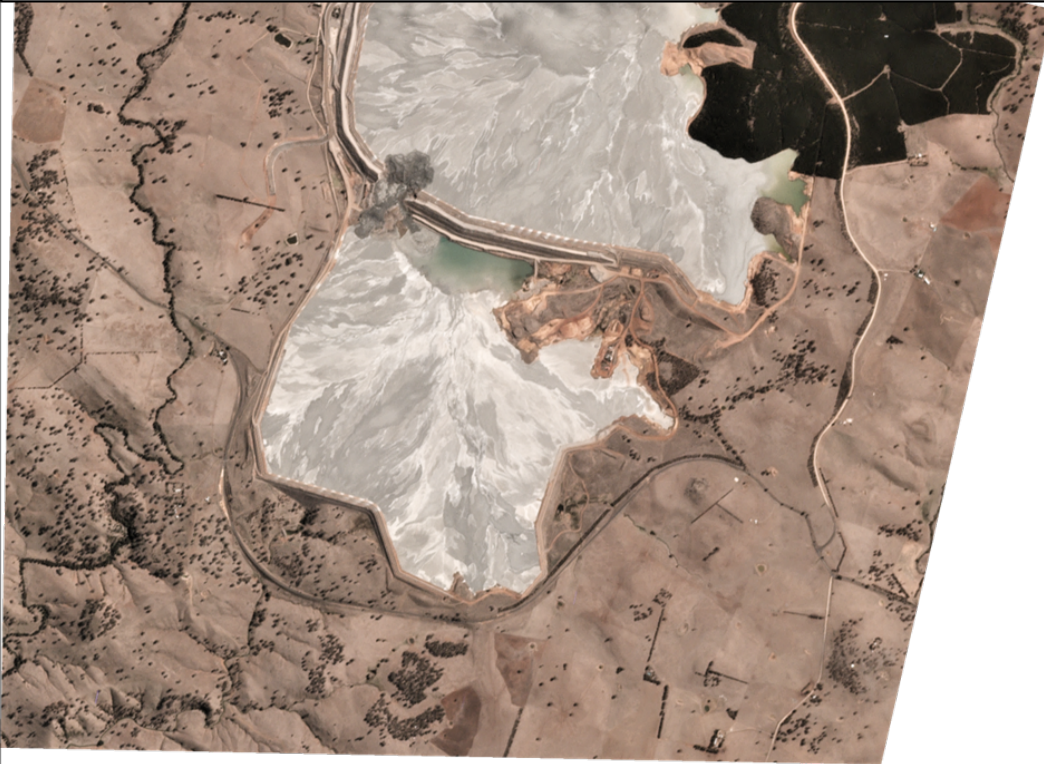
Ore: Gold, Copper

Incident: Tailings dam failure, mainly due to the existence of a low-density foundation layer in the vicinity of the slump.

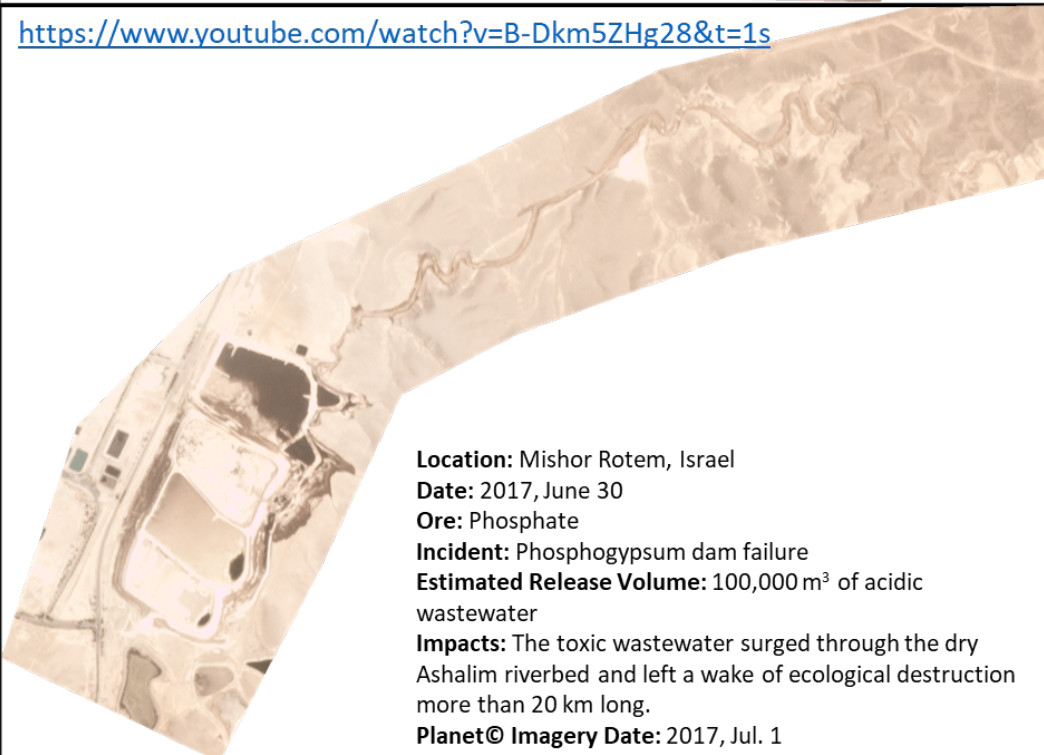
Estimated Release Volume: 1.33 Mm³

Impacts: Embankment failure results in "limited breakthrough" of tailings material from the northern to the southern tailings dam.

Planet© Imagery Date: 2018, Mar. 16



<https://www.youtube.com/watch?v=B-Dkm5ZHg28&t=1s>



Location: Mishor Rotem, Israel

Date: 2017, June 30

Ore: Phosphate

Incident: Phosphogypsum dam failure

Estimated Release Volume: 100,000 m³ of acidic wastewater

Impacts: The toxic wastewater surged through the dry Ashalim riverbed and left a wake of ecological destruction more than 20 km long.

Planet© Imagery Date: 2017, Jul. 1



Location: Tonglvshan Mine, Hubei province, China

Date: 2017, Mar. 12

Ore: Copper, Gold, Silver, Iron

Incident: A partial dam failure occurred at the northwestern corner of the tailings pond, opening a crevasse (gap) of approx. 200 meters

Estimated Release Volume: Approx. 200,000 m³ of tailings

Impacts: The tailings flooded the fish pond downstream of approx. 27 hectares. Two persons were reported dead, and one was reported missing.

Planet© Imagery Date: 2017, Mar. 14

Appendix B

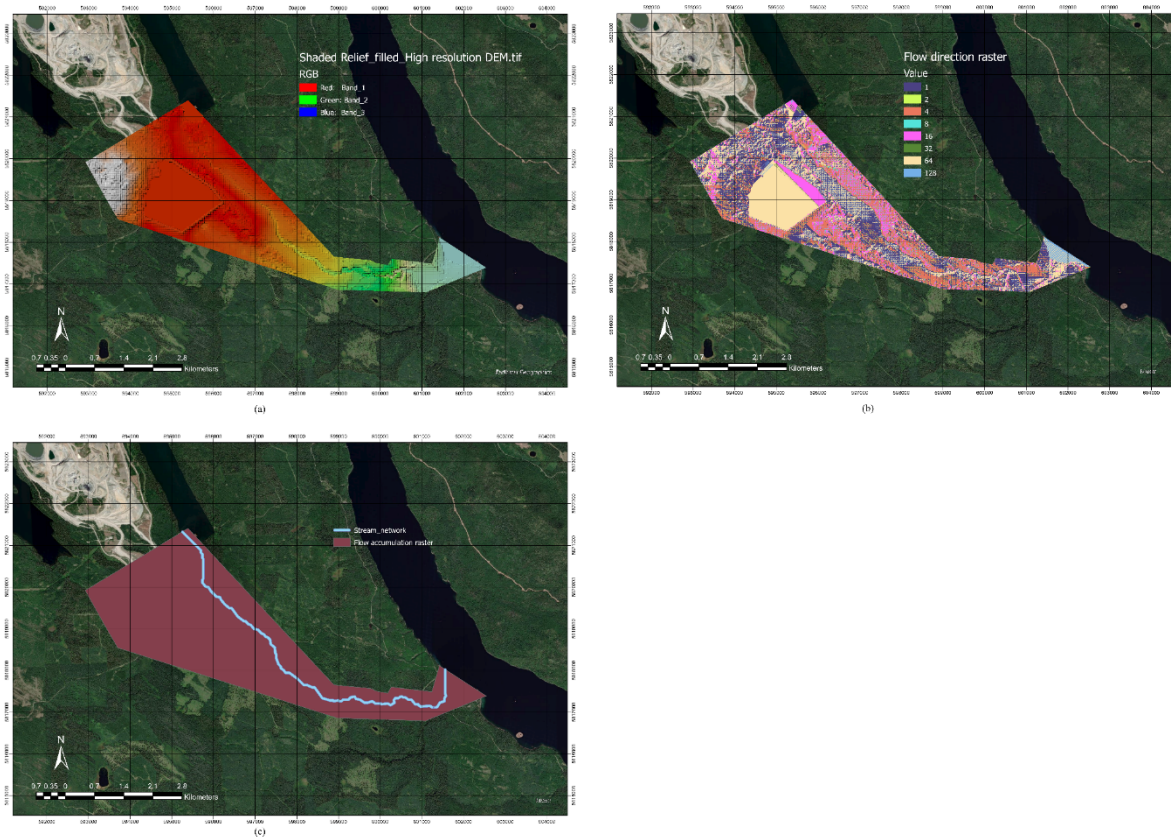


Figure B44: a) raster after filling the sinks b) flow direction raster c) stream network extracted from the flow accumulation raster.

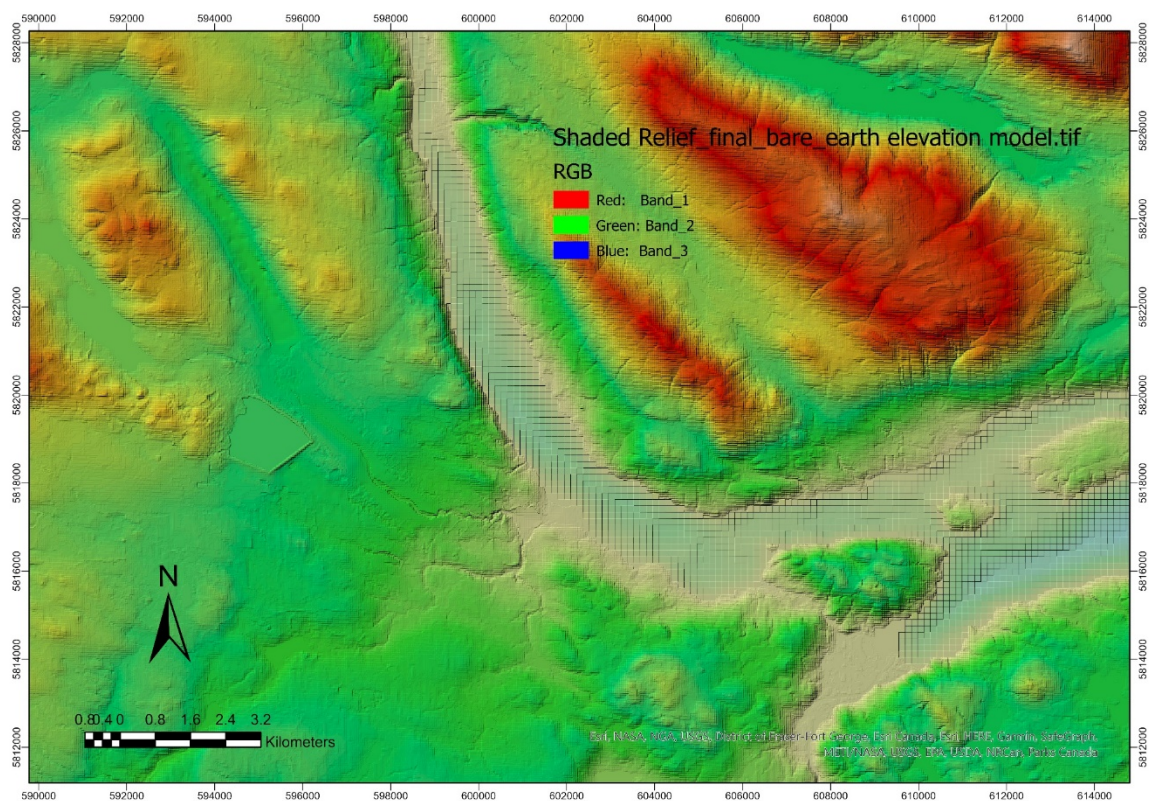


Figure B45: Bare earth elevation model

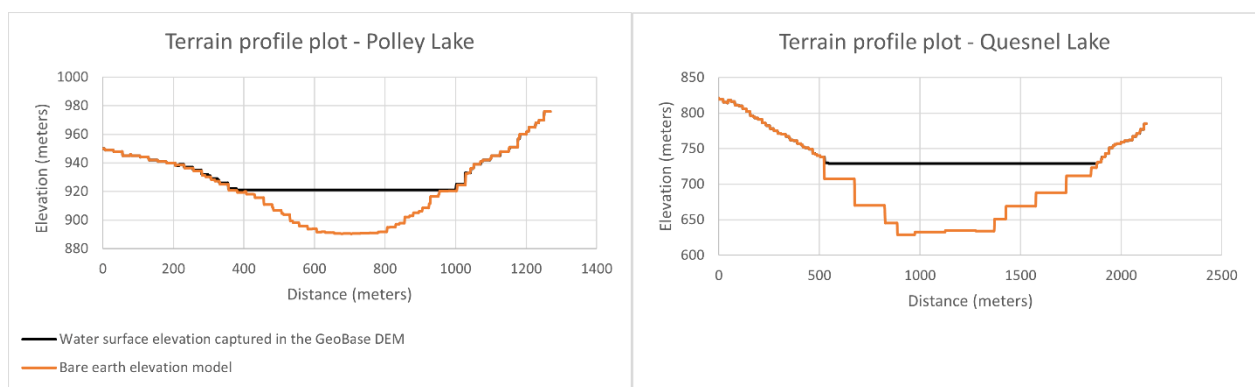


Figure B46: Terrain profile plots at a cross section drawn across a) Polley Lake b) Quesnel Lake

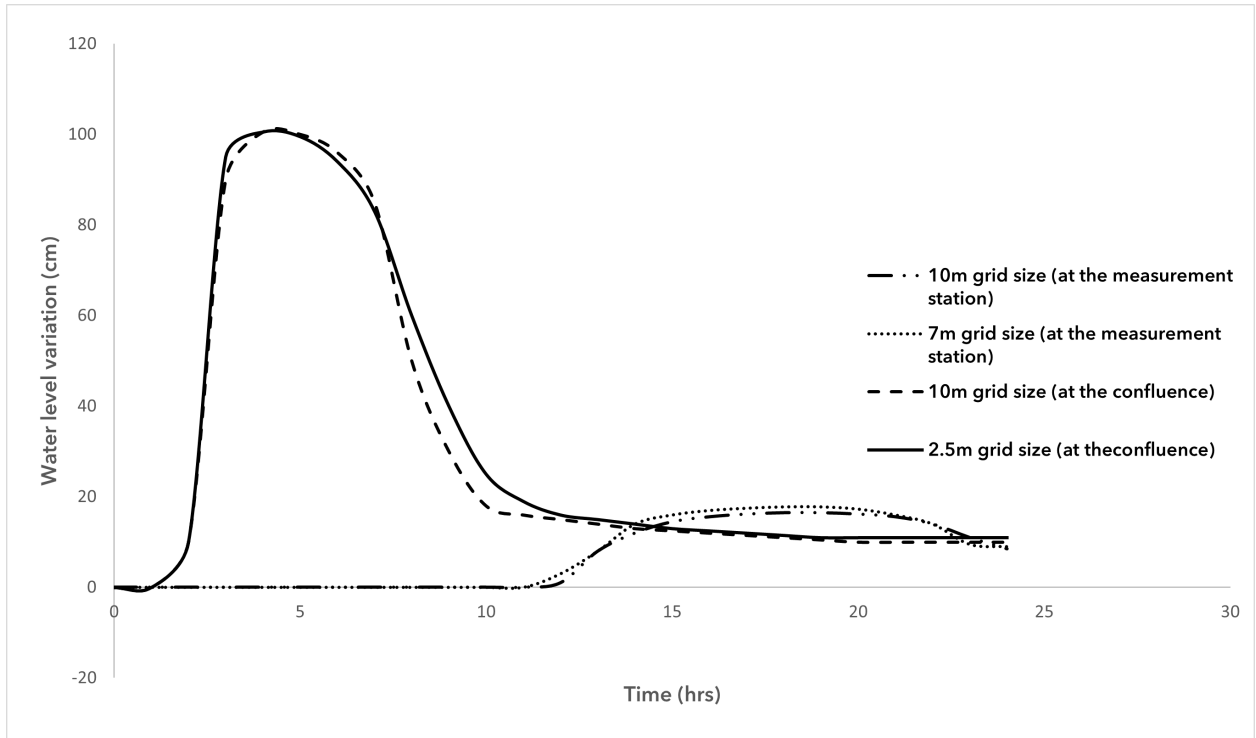


Figure B47: Water level variation at the confluence of the Hazeltine Creek (HC) and the Quesnel Lake (QL) (using grid sizes 10m x 10m and 2.5m x 2.5m) and at the measurement station (using grid sizes 10m x 10m and 7m x 7m).

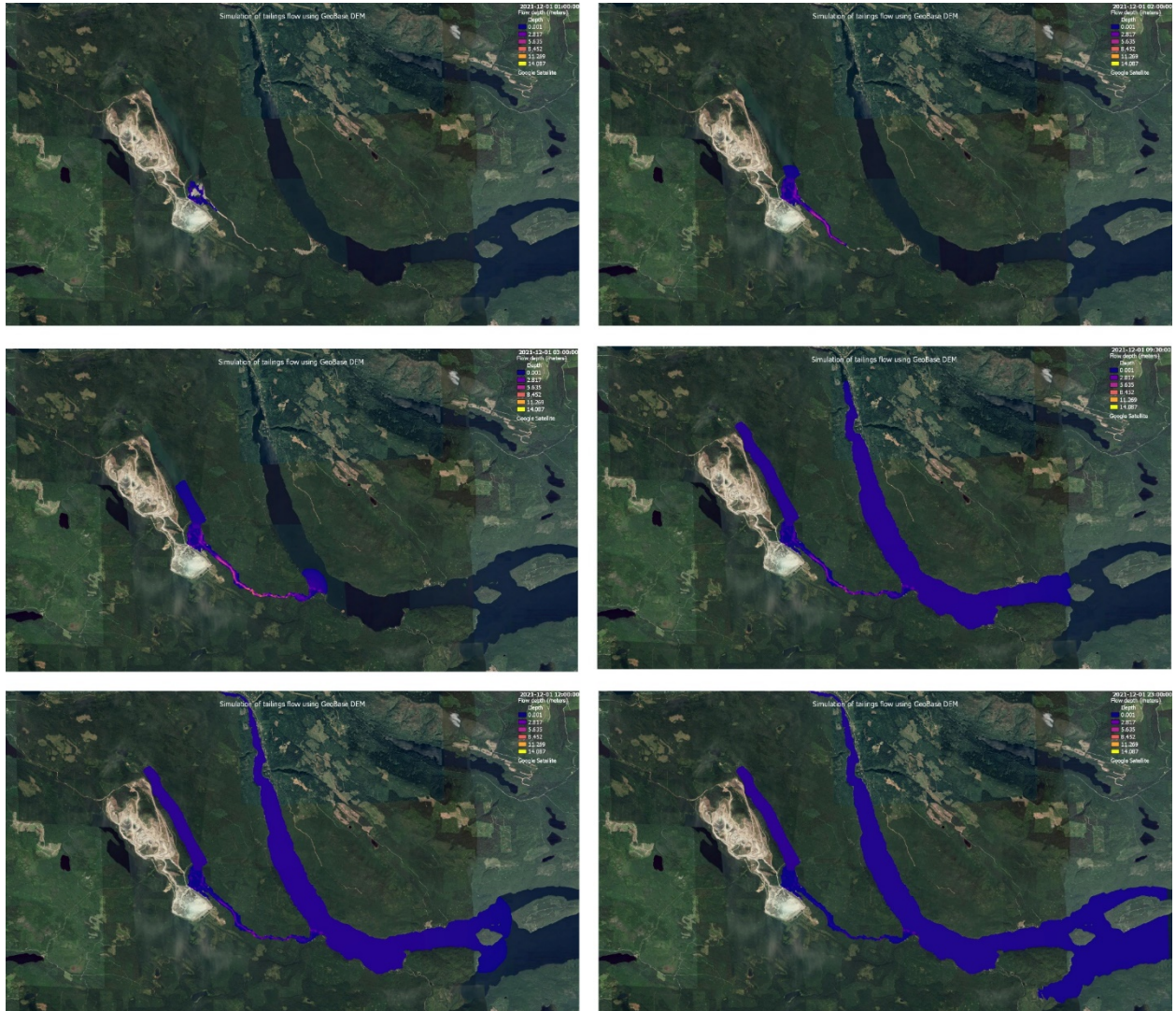


Figure B48: Time evolution of simulated tailings transport after the breach using GeoBase digital elevation model. Note: Flow depth above initial water level in the case of lakes.

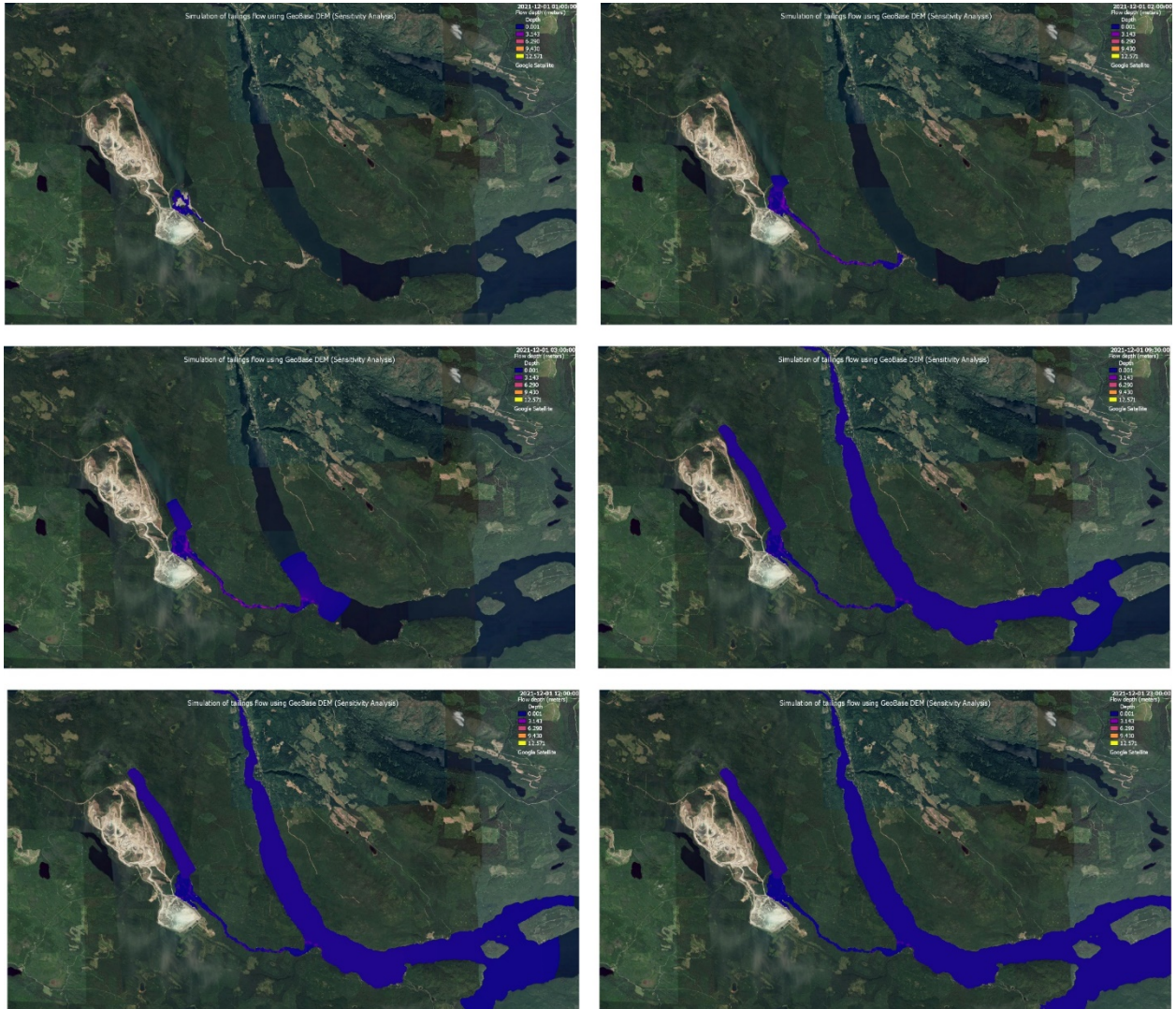


Figure B49: Time evolution of simulated tailings transport after the breach using GeoBase DEM (when the parameters used to calibrate the high-resolution DEM based simulation are given as model inputs and sensitivity analysis is conducted) Note: Flow depth above initial water level in the case of lakes.

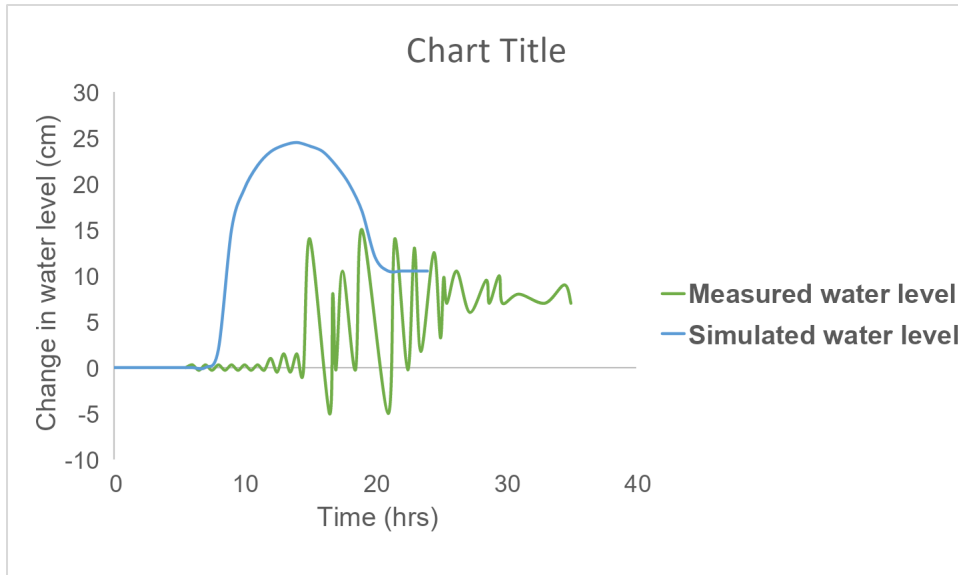


Figure B50: Comparison of the observed and the simulated water level variation at the hydrometric station in GeoBase DEM based simulation using 10m x 10m grid size (when the parameters used to calibrate the high-resolution DEM based simulation are given as model inputs).

Appendix C

Topography

When the GeoBase DEM of resolution 18 m was used, a wider flow path was observed near the breach location and in the Upper Hazeltine Creek as shown in Figure C51(a). The model also missed flooding in several grid cells in the Upper Hazeltine Creek and Lower Hazeltine Creek. This could be because of GeoBase DEM representing reflective surface elevations at those regions and not bare earth elevation. The overall CSI score when GeoBase DEM was used as bathymetry was around 0.7. In the model results using the high-resolution DEM, the flood extent was in good agreement with the recorded flood outlines and the model achieved a good CSI score of about 0.9. The model was able to replicate a treed island formed within the tailings flow path as shown in Figure C51(b). Figures C51 (a) and (b) show the flood extent when GeoBase DEM of resolution 18m and DEM of resolution 2.5m were used respectively.

Event analysis

Upper Hazeltine Creek

Adjacent to the breach location, the released tailings eroded the native materials and formed irregular scour paths. The bed was eroded up to 5.4 m depth and the mud travelled north to Polley Lake and downslope to the Hazeltine Creek. Thickened tailings were deposited up to a height of 3 m on the sides of the breach location. The large quantity of embankment material that travelled towards PL plugged the PL outlet. A volume of about 0.5 Mm³ was deposited in the Polley plug area (shown in Figure 39 (a)) and the height of deposition varied from 1 m to 3.9 m with an average of 1.4 m. About 6.1 Mm³ of mud outflowed into Polley Lake and the remaining portion then travelled through the forested valley and followed HC. The 0.3 m deep by 5 m wide HC channel was eroded to depths up to 7 m and widths of nearly 200 m. The debris flow also resulted in the formation of a treed island which resisted the flow either due to raised elevation or due to high roughness. Channel aggradation took place at some time steps of the simulation and some of the thin tailings deposited were visible in the outer boundary of the evolved channel.

Middle Hazeltine Creek

The channel bed was primarily gravel and cobbles in the Middle Hazeltine Creek based on Minnow Environmental Inc (2007). In this section, the mudflow travelled rapidly with velocities up to 9 m/s and native material was eroded to depths ranging from 3 m to 10 m with

an average of 6.44 m. Because of the increase in channel slope, vegetation was completely removed, the channel bed degraded and multiple knickpoints (deep erosion zones) were formed (marked in Figure 39 (a)). The steep eroding zone was formed quickly in the initial time steps of the model run and the tailings deposits in this area were limited. The major knickpoint incised into the bed was 10 m in depth. These deep erosion zones were formed in Reach 4, at 2.2 km and 2.6 km downstream of the treed island. Total volume of erosion in this reach was about 0.51 Mm³.

HC Canyon

The HC Canyon was the steepest and the narrowest section of the HC with features like tall cascade, pools, and bed rock steps. The channel bed was lined with bed rock, boulders, and cobbles (Golder Associates Ltd, 2015). The steep gradient of the canyon was almost 6.1% and the flow travelled at extremely rapid velocities up to 12 m/s. The flow was confined to the stable walls of the canyon and hence there was only limited widening of the channel. However, the vertical erosion of the channel bed was quite high, with values of up to nearly 10.3 m. The channel degradation stopped upon reaching the elevation of the underlying consolidated bed rock. There was negligible tailings deposition in this section (volume of deposition <0.1Mm³).

Lower HC

In this reach, the channel substrate decreased in grain size from cobble to gravel. As the flow travelled downslope from the steep canyon, the floodplain was scoured and a large knickpoint was formed at HC Canyon exit to the Lower HC and the drop in elevation was around 9 m. Tailings and native materials were deposited to variable depths ranging from 0.15 m to 1.5 m in the wide overbank areas. The volume of deposition was estimated to be 0.4 Mm³ in the overbank areas. The mud flow carved a wider and deeper valley along the pre-event HC by scouring native materials and sediments from the creek bed and banks and there was channel avulsion as shown in Figure 39 (a). The post-event outlet of HC channel was about 250 m to the right of the pre-event channel location.

Channel avulsion

The hydrology tools in ArcGIS Pro were used to model the flow path across the surface. To understand the flow direction from each cell to its steepest downslope neighbor, flow direction arrays were generated from pre-event DEM and modelled final bed elevation raster. Flow accumulation rasters were generated from these DEMs for highlighting the total accumulated

flow from higher elevation cells to lower elevation cells. These flow accumulation rasters were used to extract the stream network before and after the event. Figure C52 (a) shows the pre-event stream network generated from pre-event DEM and Figure C52 (b) shows the post-event stream network generated from the modelled final bed elevation raster. Figure C52 (c) shows the comparison between pre-event and post-event stream networks and from this analysis channel avulsion was observable.

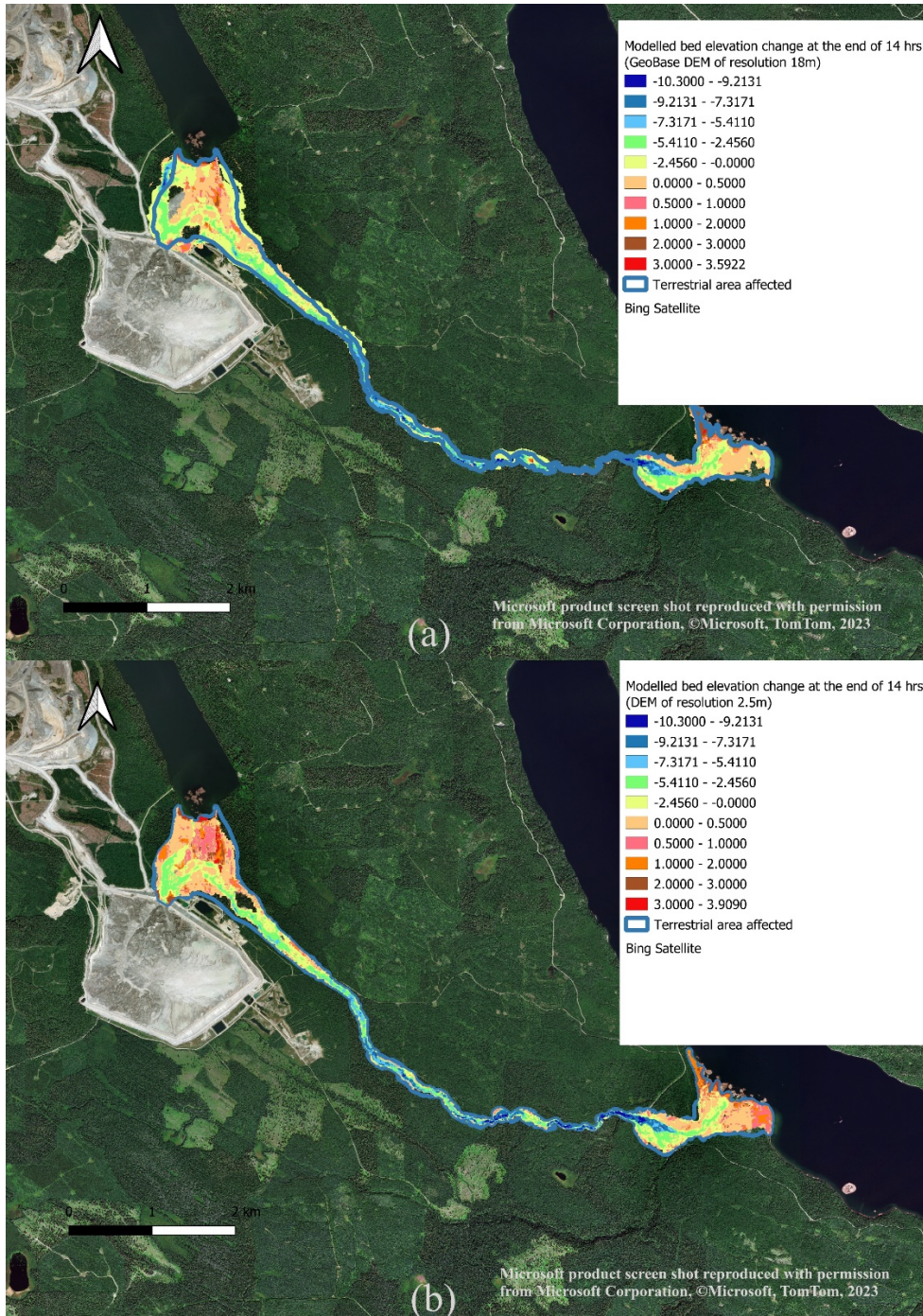


Figure C51: Comparison between the modelled flood extent and terrestrial affected area map when (a) GeoBase DEM of resolution 18m is used (b) DEM of resolution 2.5m is used extracted (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023).

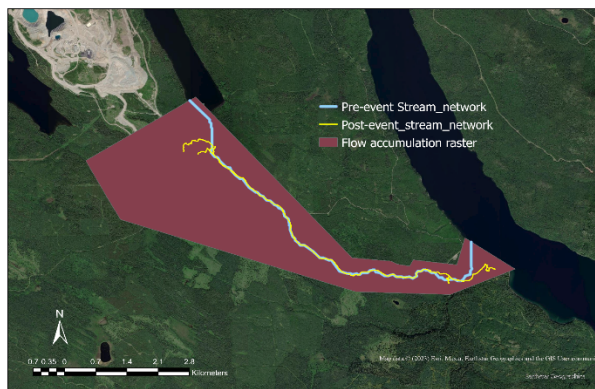
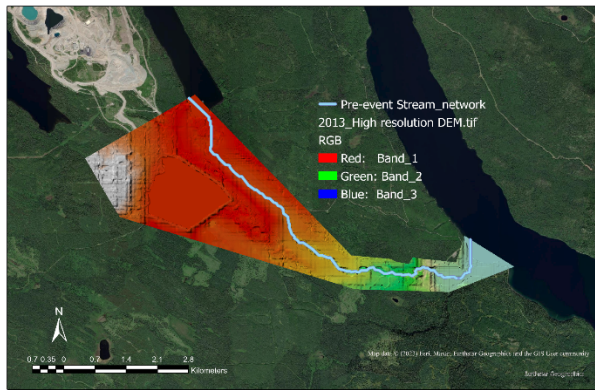


Figure C52: (a) The pre-event stream network generated from pre-event DEM (b) post-event stream network generated from the modelled final bed elevation raster (c) the comparison between pre-event and post-event stream networks (World imagery source: Map data © 2023 Esri, Maxar Earthstar geographics and the GIS User community)

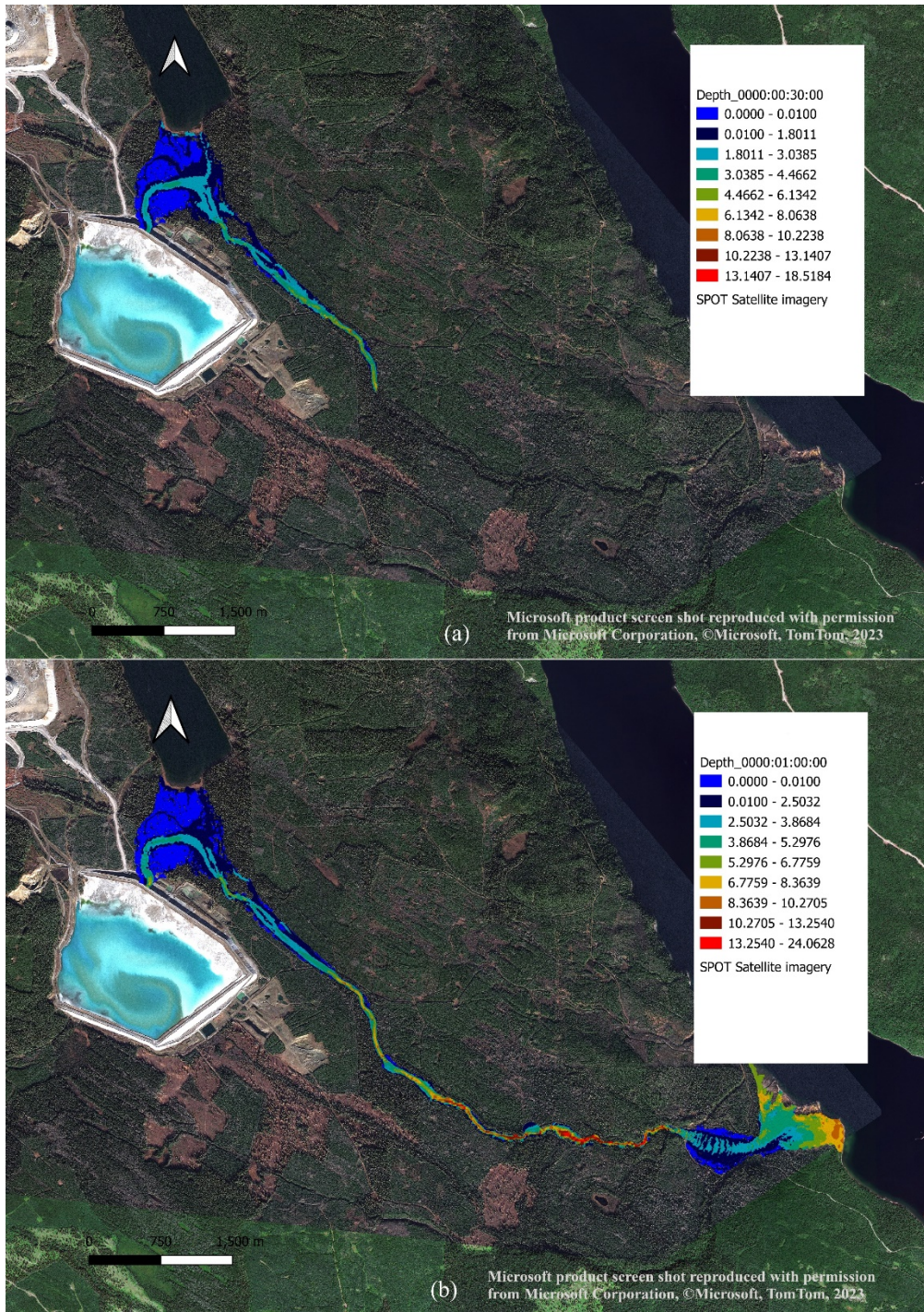


Figure C53: Flow depth at the end of (a) 0.5 hr (b) 1 hr extracted (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023)

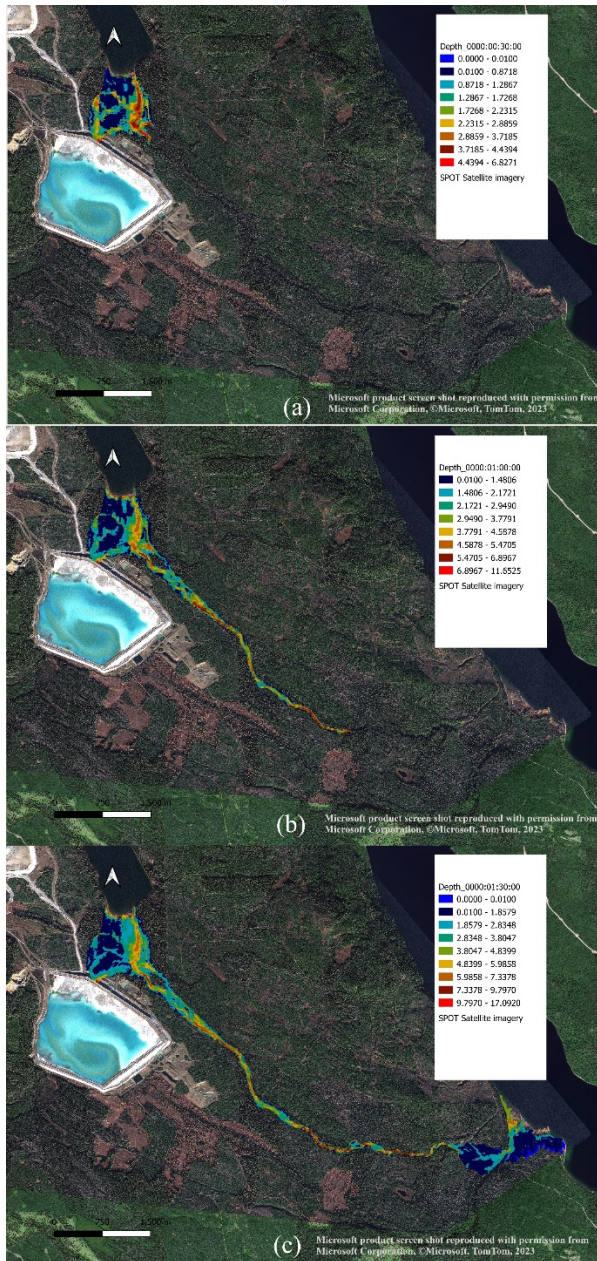


Figure C54: Flow depth at the end of (a) 0.5 hr (b) 1 hr (c) 1.5 hr (Bing Satellite imagery source: Microsoft product screen shot reproduced with permission from Microsoft Corporation, ©Microsoft, TomTom, 2023)

References

- Acker, S., Beechie, T., Shafroth, P., 2008. Effects of a Natural Dam-Break Flood on Geomorphology and Vegetation on the Elwha River, Washington, U.S.A. Northwest Science - NORTHWEST SCI. 82. 210-223. 10.3955/0029-344X-82. S.I.210.
- Ahilan, S., Guan, M., Sleigh, A., Wright, A., Chang, H., 2018. The influence of floodplain restoration on flow and sediment dynamics in an urban river. J. Flood Risk Management, 11, S986-S1001.
- Ahmad, Z. 2013. Prediction of longitudinal dispersion coefficient using laboratory and field data: Relationship comparisons. Hydrology Research. 44. 362. 10.2166/nh.2012.047.
- Aleotti, P., Polloni G., 2003. Two-dimensional model of the 1998 Sarno debris flows (Italy): preliminary results. In: Rickenmann D, Chen CL (Eds.), Third International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment. Davos, Switzerland. pp. 553-563
- Amec, 2011. Mount Polley Mine Tailing Storage Facility 2011 Stage 7 Expansion Stability Analyses.
- Armstrong, M., Langrené, N., Petter, R., Chen, W., Petter, C., 2019. Accounting for tailings dam failures in the valuation of mining projects. Resour. Policy 2019, 63, 101461.
- Atif, I., Cawood, F.T., and Mahboob, M.A. 2020. Modelling and analysis of the Brumadinho tailings disaster using advanced geospatial analytics. Journal of the Southern African Institute of Mining and Metallurgy, 120(7), 405-414. <https://dx.doi.org/10.17159/2411-9717/1196/2020>
- Azam, S., Li, Q., 2010. Tailings dam failures: a review of the last one hundred years. Geotechnical News, December.
- Barker, B., M. Schaefer., 2007. Dam Safety Guidelines Technical Note 1: Dam Break Inundation Analysis and Downstream hazard Classification. For the Washington State, Department of Ecology. Olympia, Washington.
- Baynes E.R.C., Attal M., Dugmore A.J., Kirstein L.A., Whaler K.A., 2015. Catastrophic impact of extreme flood events on the morphology and evolution of the lower Jökulsá á Fjöllum (northeast Iceland) during the Holocene. Geomorphology 250: 422–436.
- Benkhaldoun, F., Sari, S., Seaid, M., 2012. A flux-limiter method for dam-break flows over erodible sediment beds, Applied Mathematical Modelling, Volume 36, Issue 10, 2012, Pages

4847-4861, ISSN 0307-904X, <https://doi.org/10.1016/j.apm.2011.11.088>

Blight, G., Robinson, M., & Diering, J. (1981). The flow of slurry from a breached tailings dam. *Journal of the South African Institute of Mining and Metallurgy*, 1.

Boger, D. V., & Walters, K., 2012. *Rheological phenomena in focus* (Vol. 4): Elsevier.

Bouchut, F., Fernández-Nieto, E. D., Mangeney, A., Narbona-Reina, G., 2016. A two-phase two-layer model for fluidized granular flows with dilatancy effects. *Journal of Fluid Mechanics*, 801, 166– 221.

Burritt, R. L., and Christ, K. L., 2018. Water risk in mining: Analysis of the Samarco dam failure, *J. Clean Prod.*, 178, 196-205, [10.1016/j.jclepro.2018.01.042](https://doi.org/10.1016/j.jclepro.2018.01.042).

Camargos, L.M., Rodrigues, P.C.H., Nero, M.A., Methodology for verifying mining tailing dams' volume using geoprocessing - Barragem Maravilhas II (quadrilátero ferrífero - mg), *Revista Brasileira de Geomorfologia*, v. 20, <http://dx.doi.org/10.20502/rbg.v20i4.1552>

Canada marine charts 2021. <http://www.gpsnauticalcharts.com/main/ca-nautical-charts-by-folio.html> (Accessed January 20, 2021)

Canadian Dam Association (CDA) 2007, revised 2013. *Dam Safety Guidelines*.

Canadian Dam Association (CDA), 2021. *Technical Bulletin: Tailings Dam Breach Analysis*, CDA Publications.

Canadian Digital Elevation Model 2013. http://ftp.maps.canada.ca/pub/nrcan_rncan/elevation/cdem_mnec/doc/CDEM_product_specs.pdf (Accessed: December 11, 2020).

Carrivick, J., Manville, V., & Graettinger, A., & Cronin, S., 2010. Coupled fluid dynamics-sediment transport modelling of a Crater Lake break-out lahar: Mt. Ruapehu, New Zealand. *Journal of Hydrology*. 388. 399-413. [10.1016/j.jhydrol.2010.05.023](https://doi.org/10.1016/j.jhydrol.2010.05.023).

Castro-Díaz, M.J., Fernández-Nieto, E.D., González-Vida, J.M., Pares-Madronal, C., 2011. Numerical Treatment of the Loss of Hyperbolicity of the Two-Layer Shallow-Water System. *J Sci Comput* 48, 16–40. <https://doi.org/10.1007/s10915-010-9427-5>

Cesca, M., D'Agostino, V., 2008. Comparison between FLO-2-D and RAMMS in debris-flow modelling: a case study in the Dolomites, edited by de Wrachien, D., Brebbia, C. A., and Lenzi, M. A., *Monitoring, Simulation, Prevention and Remediation of Dense Debris Flows II*, 60, 197–206, 2006.

Che, Defu & Liang, Aiman & Li, Xuexin & Ma, Baodong.,2018. Remote Sensing Assessment

of Safety Risk of Iron Tailings Pond Based on Runoff Coefficient. *Sensors*. 18. 4373. 10.3390/s18124373.

Chen, H., Chin, B., Friedel, R., 2019. Dam breach tailings runout modelling for inactive/closed tailings storage facility. Canadian Dam Association 2019 Annual Conference Calgary, Alberta.

Chen, J., Cunning, J. (2021). Application of critical state soil mechanics in tailings dam breach analysis. CDA 2021 Annual Conference, October 25-28, Virtual.

Chen, M., Jing, X., Liu, X., Huang, X., Nie, W., 2022. Multiscale investigations of overtopping erosion in reinforced tailings dam induced by mud-water mixture overflow, *Geofluids*, 7209176, 2022. doi.org/10.1155/2022/7209176

Chen, S., Lin, T., Chen, C., 2015. Modelling of Natural Dam Failure Modes and Downstream Riverbed Morphological Changes with Different Dam Materials in a Flume Test. *Engineering Geology*. 188. 10.1016/j.enggeo.2015.01.016.

Cheon, E., Lee, S.-R., Lee, D.-H., 2020. Hazard Assessment Based on the Combination of DAN3D and Machine Learning Method for Planning Closed-Type Barriers against Debris-Flow. *Water*, 12, 170. <https://doi.org/10.3390/w12010170>.

Chen, S.C., Wu, C.Y., Huang, B.T., 2010. The efficiency of a risk reduction program for debris-flow disasters — a case study of the Songhe community in Taiwan. *Natural Hazards and Earth System Sciences* 10(7): 1591-1603.

Church, M., McLean D.G., Walcott, J.F., 1987. Riverbed gravels: sampling and analysis. In: *Sediment Transport in Gravel-Bed Rivers*. C.R. Thorne, J.C. Bathurst and R.D. Hey (eds.) John Wileyand Sons, Chichester p. 43-88.

Clemente, J. L., Snow, R. E., Bernedo, C., Strachan, C. L., & Fourie, A., 2011. Dam break analysis applied to tailings dams: USSD workshop summary and perspectives. Paper presented at the USSD Workshop, Denver, Colorado.

CloudCompare 2.7. 2020. Retrieved from <https://cloudcompare.software.informer.com/2.7/>

Cuervo, V., Burge, L., Beaugrand, H., Hendershot, M., Evans, S.G., 2017. Downstream Geomorphic Response of the 2014 Mount Polley Tailings Dam Failure, British Columbia

Davies, M. P. 2002. Tailings impoundment failures: Are geotechnical engineers listening? *Geotechnical News*, September,2002, 31-36.

Danish Hydraulic Institute (DHI): MIKE 21 Flow Model Mud Transport Module User Guide 2017.

- Daneshvar, P., & Zsaki, A. M. (2010). Modeling of tailings flow using Smoothed Particle Hydrodynamics for risk assessment of tailings dam breaches.
- Das, B., 2008. Advanced Soil Mechanics. Taylor & Francis, London & New York.
- Derdous O., Djemili L., Bouchehed H., and Tachi S.E. 2015. A GIS based approach for the prediction of the dam break flood hazard – A case study of Zardezas reservoir “Skikda, Algeria”. Journal of Water and Land Development. No. 27 p. 15–20.
- Dibike, Y.B., Shakibaeinia, A., Droppo, I.G., and Caron, E. 2018. Modelling the potential effects of Oil-Sands tailings pond breach on the water and sediment quality of the Lower Athabasca River, Science of total environment 642: 1263-1281.
- Dodson & Associates, Inc. (2009). DAMBRK, <http://www.dodson-hydro.com/software/hydro-cd/programs/dambrk.htm>
- Dror. R. 2015. Image analysis <https://web.stanford.edu/class/cs279/notes/image-analysis-notes.pdf> (Accessed: June 20, 2021).
- Duluth Reader (2019). A Timeline of the Worst Corporate-made Environmental Disaster in the History of British Columbia: Imperial Metals’ Mount Polley Copper Mine Dam Failure of August4,2014,http://duluthreader.com/articles/2019/04/25/16743_a_timeline_of_the_worst_corporate_made
- Dutto, P., Stickle, M., Pastor, M., Manzanal, D., Yague, A., Moussavi Tayyebi, S., Lin, C., Elizalde, M. 2017. Modelling of fluidised geomaterials: the case of the Aberfan and the Gypsum tailings impoundment flowslides. Materials (Basel) 10, 562. <https://doi.org/10.3390/ma10050562>
- Eagle, L., Carrivick, J., Milner, A., Brown, L., Klaar, M., 2021. Repeated high flows drive morphological change in rivers in recently deglaciated catchments. Earth Surface Processes and Landforms. 46. 10.1002/esp.5098.
- ESRI 2020. ArcGIS Pro 2.7 Redlands, CA: Environmental Systems Research Institute.
- Evans, J., Geerken, R. 2006 Classifying rangeland vegetation type and coverage using a Fourier component-based similarity measure. Remote Sens. Environ. 2006, 105, 1–8.
- Flávio., C., Luciana., K., Rogério., J., Iara., C., Felipe., C., Guilherme., S., Kenedy., C., Mateus., M., Nelson., U., Marcos., M., Carlos., P. 2017. Fundação tailings dam failures: The environment tragedy of the largest technological disaster of Brazilian mining in global context. Perspectives in Ecology and Conservation. 15. 10.1016/j.pecon.2017.06.002.

FLO- 2D Software Inc. 2019. FO-2D Reference Manual (Build no. 19 2019), Arizona, USA.

FLO-2D, 2022. FLO-2D Reference Manual. Nutrioso AZ: FLO-2D. Nutrioso AZ: FLO-2D

Flow Science, 2021. FLOW-3D User Manual. Flow Sci. Inc.

Floodsite, 2009. HR Breach model, http://www.floodsite.net/html/HR_Breach_Model.htm

Gallant, J.C. 2019. Merging lidar with coarser DEMs for hydrodynamic modelling over large areas 23rd International Congress on Modelling and Simulation, Canberra, ACT, Australia, 1 to 6 December 2019

Ghahramani, N., Chen, H., Clohan, D., Liu, S., Llano, M., Rana, N., McDougall, S., Evans, S., Take, W., 2022. A benchmarking study of four numerical runout models for the simulation of tailings flows. *Science of The Total Environment*. 827. 154245. 10.1016/j.scitotenv.2022.154245.

Ghahramani, N., Mitchell, A., Rana, N.M., McDougall, S., Evans, S.G. and Take, W.A., 2020. Tailings-flow runout analysis: examining the applicability of a semi-physical area-volume relationship using a novel database, *Natural Hazards, and Earth System Sciences*, 20(12), 3425.

Gildeh, H. K., Halliday, A., Arensa, A., Zhang, H., 2020. Tailings dam breach analysis: a review of methods, practices and uncertainties, *J. Mine Water and the Environment*, <https://doi.org/10.1007/s10230-020-00718-2>.

Golder Associates Ltd., 2015. Mount Polley Mining Corporation Post Event Environmental Impact Assessment Report- Key findings report.

Grangeia, C., Avila, P., Matias, M., Silva, E.F.D., 2011. Mine tailings integrated investigations: the case of Rio tailings (Panasqueira Mine, Central Portugal). *Eng Geol* 123:359–372

Greco, M., Di Cristo, C., Iervolino, M., 2019. Numerical simulation of mudflows impacting structures. *J. Mt. Sci.* 16, 364–382. <https://doi.org/10.1007/s11629-018-5279-5>

Guan, M., Carrivick, J., Wright, N., Sleight, A., Staines, K., 2016. Quantifying the combined effects of multiple extreme floods on river channel geometry and on flood hazards. *Journal of Hydrology*. 538. 10.1016/j.jhydrol.2016.04.004.

Gutman, G., Ignatov, A. 1998. The derivation of the green vegetation fraction from NOAA/AVHRR data for use in numerical weather prediction models. *Int. J. Remote Sens.* 1998, 19, 1533–1543.

Han. G., Wang. D. 1996. Numerical modeling of Anhui debris flow. *J Hydraul Eng* 122(5):262–265

<https://www.hec.usace.army.mil/confluence/rasdocs/rasmuddebris/non-newtonian-technical-reference-manual/yield-stress>.

Henriquez, J., Simms, P., 2009. Dynamic imaging and modelling of multilayer deposition of gold paste tailings. *Minerals Engineering*, 22(2), 128-139.

Hessel, R., 2002. Modelling soil erosion in a small catchment on the Chinese Loess Plateau. Applying LISEM in extreme conditions, *Netherlands Geographical Studies* 307. KNAG: Utrecht, The Netherlands.

Huamanyauri, J., Huanchi, J., Hinostroza, J., Huamán, M., 2023. Comparison of Methods in Estimating the Released Volume in a Tailings Dam Break Analysis, *Proceedings of Tailings and Mine Waste 2023*, November 5–8, 2023, Vancouver, Canada.

Hubl, J., Steinwendtner, H., 2001. Two-dimensional simulation of two viscous debris flows in Austria. *Physics and Chemistry of the Earth Part C-Solar-Terrestrial and Planetary Science* 26(9):639-644.

Hunter, J. (2015). Mount Polley spill taints Alaska-B.C. mine relations.

Hydronia, L.L.C. 2022. Two-Dimensional Flood and River Dynamics Model, Reference Manual. Available online: www.hydronia.com (RiverFlow2D Version 8.02 accessed on March 2022).

Idriss, I.M., Boulanger, R.W., 2008. Soil Liquefaction during Earthquake. EERI Publication, Monograph MNO-12, Earthquake Engineering Research Institute, Oakland.

Ishihara, K., Ueno, K., Yamada, S., Yasuda, S., Yoneoka, T., 2015. Breach of a tailings dam in the 2011 earthquake in Japan. *Soil Dyn Earthq Eng* 68:3–22

Iverson, R. M., George, D. L., 2014. A depth-averaged debris-flow model that includes the effects of evolving dilatancy. I. Physical basis. *Proceedings of the Royal Society A*, 470(20130), 819.

Iverson, R., Reid, M., Logan, M., Lahusen, R., Godt, Jonathan., Griswold, Julia., 2011. Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment. *Nature Geoscience*. 4. 10.1038/ngeo1040.

Jefferies M.G., Been K., 2015. Soil liquefaction: a critical state approach. CRC Press, Boca Raton, FL.

Jelti S., Boulerehcha M., 2022. Numerical modeling of two-dimensional non-capacity model

for sediment transport by an unstructured finite volume method with a new discretization of the source term. *Math Comput Simul* 197(3):253–276.

Jiang, X., Cheng, H., Gao, L., Liu, W., 2021. The formation and geometry characteristics of boulder bars due to outburst floods triggered by overtopped landslide dam failure, *Earth Surf. Dynam.*, 9, 1263–1277, <https://doi.org/10.5194/esurf-9-1263-2021>

Johnson, L.E (2009). *Geographic Information Systems in Water Resources Engineering* CRC Press, Taylor and Francis group.

Juez, C., Murillo, J., García-Navarro, P., 2013. 2D simulation of granular flow over irregular steep slopes using global and local coordinates, *Journal of Computational Physics*, Volume 255, Pages 166-204, ISSN 0021-9991, <https://doi.org/10.1016/j.jcp.2013.08.002>.

Julien, P. Y., Lan, Y. Q., 1991. “Rheology of hyperconcentrations.” *J. Hydraul. Eng.*, 1173, 346–353.

Jung, H.C. and Jasinski, M. 2015. Sensitivity of a Floodplain Hydrodynamic Model to Satellite-Based DEM Scale and Accuracy: Case Study—The Atchafalaya Basin. *Remote Sensing*. 7. 7938-7958. [10.3390/rs70607938](https://doi.org/10.3390/rs70607938).

Gildeh, H.K., Halliday, A., Arenas, A., Zhang, H., 2020. Tailings Dam Breach Analysis: A Review of Methods, Practices, and Uncertainties. *Mine Water and the Environment*. 40. 1-23. [10.1007/s10230-020-00718-2](https://doi.org/10.1007/s10230-020-00718-2).

Knight Piesold Consulting 2017. KGHM AJAX MINING INC. Afton tailings storage facility-dam breach inundation study.

Kocyigit, O., Gurer, I., 2007. Effect of the Voellmy Coefficients on Determining Run-out Distance: A Case Study at Uzungöl, Turkey. *G.U. Journal of Science* 20(3): 79-85 (2007).

Kossoff, D., Dubbin, W.E., Alfredsson, M., Edwards, S.J., Macklin, M.G. and Hudson-Edwards, K.A., 2014. Mine tailings dams: characteristics, failure, environmental impacts, and remediation. *Applied Geochemistry*, 51, pp.229-245.

Kostaschuk, R., Aden, A., and Desloges, J.R. 2021. Erosion, deposition, and contamination by high-magnitude subaqueous debris flows and turbidity currents: Insights from the failure of a tailings dam near Quesnel Lake, British Columbia, *Sedimentology*, [doi:10.1111/sed.12836](https://doi.org/10.1111/sed.12836).

Kowalski, J., McElwaine, J.N., 2013. Shallow two-component gravity-driven flows with vertical variation. *J. Fluid Mech.* 714, 434–462

Kunkel, J., 2011a. Downstream Modeling of Tailings Flow from Failure of a 380-ft High

Tailing Dam. USSD Workshop, Denver CO.

Kuo, Y.S., Tsai, Y.J., Chen, Y.S., Shieh, C.L., Miyamoto, K., Itoh, T., 2013. Movement of deep-seated rainfall-induced landslide at Hsiaolin Village during Typhoon Morakot. *Landslides*, 10(2), 191–202.

Labanda, J., Marco, P., & Llorens, J., 2004. Rheological model to predict the thixotropic behaviour of colloidal dispersions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 249(1), 123-126.

Lane S.N., Tayefi V., Reid S.C., Yu D., Hardy R.J., 2007. Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms* 32: 429– 446.

Larrauri, C., Lall, U., 2018. Tailings Dams Failures: Updated Statistical Model for Discharge Volume and Runout. *Environments*. 5. 28. 10.3390/environments5020028.

Lepage, F., Damov, D., Campbell, P. (2022). Large scale PMF study and HEC-RAS 2D dam failure modelling at Ghost Dam. CDA 2022 Annual Conference, October 17-19, St. John's, Newfoundland and Labrador.

Li, J., Cao, Z., Hu, K., Pender, G. & Liu, Q., 2018. A depth-averaged two-phase model for debris flows over erodible beds. *Earth Surface Processes and Landforms* 43, 817–839.

Ligier, P.L., 2020. Implementation of non-Newtonian rheological models in TELEMAC-2D in Online proceedings of the papers submitted to the 2020 TELEMAC-MASCARET User Conference.

Ligier. P., Okumura N., Alderman C., 2022. Overview and lessons learned from performing tailings dam breach modelling with TELEMAC-2D, 28th TELEMAC User Conference, Paris-Saclay, France, 18-19 October 2022.

Lim N.J and Brandt S.A 2019a. Are Feature Agreement Statistics Alone Sufficient to Validate Modelled Flood Extent Quality? A Study on Three Swedish Rivers Using Different Digital Elevation Model Resolutions, *Mathematical Problems in Engineering*, vol. 2019, Article ID 9816098, 16 pages, 2019. <https://doi.org/10.1155/2019/9816098>

Lim N.J. and Brandt S.A. 2019b. Flood map boundary sensitivity due to combined effects of DEM resolution and roughness in relation to model performance, *Geomatics, Natural Hazards and Risk*, 10:1, 1613-1647, DOI: 10.1080/19475705.2019.1604573

Liu, H., 2018. An experimental and numerical study of runout from a tailings dam failure, *The*

University of Western Australia.

Liu, K.F., Huang, M.C., 2006. Numerical simulation of debris flow with application on hazard area mapping. *Computational Geosciences* 10:221-240

Llano, M., Williams, D. and Ruest, M. 2017. Analysis of Tailings Dam-Break and Run-Out. *Tailings 2017 4th International Seminar on Tailings Management*.

Lumbroso, D., Davison, M., Body, R., and Petkovšek, G. 2021. Modelling the Brumadinho tailings dam failure, the subsequent loss of life and how it could have been reduced, *Nat. Hazards Earth Syst. Sci.*, 21, 21–37, <https://doi.org/10.5194/nhess-21-21-2021>, 2021.

Luo, Y., Chen, L., Xu, M., Tong, X.L., 2012. Review of dam-break research of earth-rock dam combining with dam safety management. *Procedia Eng* 28(12):382–388.

Luscombe, B.W., Hassan.H.M., 1993. Applying remote sensing technologies to natural disaster risk management: Implications for developmental investments. *Acta Astronautica*, Volume 29, Issues 10-11, October-November 1993, Page-871-876, [https://doi.org/10.1016/0094-5765\(93\)90169-W](https://doi.org/10.1016/0094-5765(93)90169-W)

Lyu., Z., Chai., J., Xu., Z., Qin., Y., Cao., J. 2019. "A Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History", *Advances in Civil Engineering*, vol. 2019, Article ID 4159306, 18 pages, 2019. <https://doi.org/10.1155/2019/4159306>

Mahdi, A., Shakibaeinia, A., Dibike., 2020. Numerical modelling of oil-sands tailings dam breach runout and overland flow *Science of the Total Environment* 703 (2020) 134568 <https://doi.org/10.1016/j.scitotenv.2019.134568>.

Mao, J., Wang, S., Ni, J., Xi, C. and Wang, J. 2017. Management System for Dam-Break Hazard Mapping in a Complex Basin Environment. *ISPRS International Journal of Geo-Information*. 6. 162. 10.3390/ijgi6060162.

Marchi, L., Borga, M., Preciso, E., Sangati, M., Gaume, E., Bain, V., Delrieu, G., Bonnifait, L., Pogačnik, N., 2009. Comprehensive post-event survey of a flash flood in Western Slovenia: Observation strategy and lessons learned. *Hydrol. Processes Int. J.*, 23, 3761–3770.

Martin, V., Akkerman, A., 2017. Challenges with conducting tailings dam breach studies, 85th Annual Meeting of International Commission on Large Dams, Prague, Czech Republic, July 3–7.

Martin, V., Fontaine, D., Cathcart, J., 2015. Challenges with conducting tailings dam breach studies, *Proceedings of Tailings and Mine Waste 2015*, Vancouver, Canada:314–328.

Martínez-Aranda, S., Murillo, J., Garcia-Navarro, P., 2020. A robust two-dimensional model for highly sediment-laden unsteady flows of variable density over movable beds. *Journal of Hydroinformatics*. 22. 10.2166/hydro.2020.027.

Martínez-Aranda, S., Murillo, J., Garcia-Navarro, P., 2022. A GPU-accelerated Efficient Simulation Tool (EST) for 2D variable-density mud/debris flows over non-uniform erodible beds, *Engineering Geology*, Volume 296, 2022, 106462, ISSN 0013-7952, <https://doi.org/10.1016/j.enggeo.2021.106462>.

McDougall, S., Hungr, O., 2004. A model for the analysis of rapid landslide motion across three-dimensional terrain. *Can. Geotech. J.* 41, 1084–1097. <https://doi.org/10.1139/t04-052>.

McKellar, M., Walsh A., Barlow K., Mulligan, R.P., McDougall, S., Evans, S.G., Andy Take, W., 2023. Physical and Numerical Modelling of Tailings Dam Breach Processes (CanBreach Project), *Proceedings of Tailings and Mine Waste 2023*, November 5–8, 2023, Vancouver, Canada.

McLeod, H. and Bjelkevik. A. (2017). “Tailings Dam Design: Technology Update (ICOLD Bulletin),” in *Proceedings of the 85th Annual Meeting of International Commission on Large Dams*, July 3-7, 2017. Prague, Czech Republic: Czech National Committee on Large Dams.

Md ali, A., Solomatine, D., and Di Baldassarre, G. 2015. Assessing the impact of different sources of topographic data on 1-D hydraulic modelling of floods. *Hydrology and Earth System Sciences*. 19. 631-643. 10.5194/hess-19-631-2015.

Melo M., Eleutério J., 2023 Probabilistic Analysis of Floods from Tailings Dam Failures: A Method to Analyze the Impact of Rheological Parameters on the HEC-RAS Bingham and Herschel-Bulkley Models. *Water*. 2023; 15(16):2866. <https://doi.org/10.3390/w15162866>.

Meng, X., Wang, Y., 2016. Modelling and numerical simulation of two-phase debris flows. *Acta Geotech.* 11, 1027–1045. <https://doi.org/10.1007/s11440-015-0418-4>

Minnow Environmental Inc 2007. Hazeltine Creek habitat characterization. Consultant report prepared for Mount Polley Mining Corporation.

Mitchell. C, (2020). Edenville Dam breaks, sparking immediate evacuations in Michigan, <https://www.msn.com/en-us/weather/topstories/edenville-dam-breaks-sparking-immediate-evacuations-in-michigan/ar-BB14kwIC>.

Moon, N., Parker, M., Boshoff, H., Clohan, D., 2019. Advances in non-Newtonian dam break studies. 165-172. 10.36487/ACG_rep/1910_09_Boshoff.

Mount Polley tailings spill 2019. In Wikipedia. Retrieved from https://en.wikipedia.org/wiki/Mount_Polley_tailings_spill.

Naef, D., Rickenmann, D., Rutschmann, P., & McArdell, B., 2006. ‘Comparison of flow resistance relations for debris flows using a one-dimensional finite element simulation model’, *Nat. Hazards Earth Syst. Sci.* 6, 155–1

National Topographic Data Base (NTDB) 2005. http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/ntdb_bndt/doc/stdntdb3_en.pdf (Accessed: June 20,2021).

O’Brien, J. S., and Julien, P. Y. 1988. Laboratory Analysis of Mudflow Properties. *Journal of Hydraulic Engineering*, 114(8), 877–887. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1988\)114:8\(877\)](https://doi.org/10.1061/(ASCE)0733-9429(1988)114:8(877))

O’Brien, J. S., Gonzalez-Ramirez, N., Tocher, R. J., Chao, K. C., and Overton, D. D., 2015. Predicting Tailings Dams Breach Release Volumes for Flood Hazard Delineation. In Association of State Dam Safety Officials, New Orleans.

O’Brien, J.S. and Julien, P.Y. 2000. FLO-2D. User’s Manual. Flo-Engineering, Version.

O’Brien, J.S., 1986. Physical processes, rheology, and modelling of mudflows. PhD thesis, Colorado State Univ, Fort Collins, CO, USA.

O’Brien, J.S., Julien, P. Y., 1985. Physical properties and mechanics of hyper concentrated sediment flows. *Proc., ASCE Specialty Conf. on the Delineation of Landslides, Flash Floods and Debris Flow Hazards in Utah*, Utah Water Research Lab., Univ. of Utah at Logan, Utah, 260-279.

O’Brien, J.S., Julien, P.Y., Fullerton, W.T., 1993. Two-Dimensional Water Flood and Mudflow Simulation. *Journal of Hydraulic Engineering*, 119, 244-261.

Oliva, G., Setola, R., Scala, A. 2017. Sparse and distributed Analytic Hierarchy Process. *Automatica* 2017, 85, 211–220.

Ouyang, C., He, S., Tang, C., 2015. Numerical analysis of dynamics of debris flows over erodible beds in Wenchuan earthquake-induced area. *Eng. Geol.* 194, 62–72.

Pailha, M., Pouliquen O., 2009. A two-phase flow description of the initiation of underwater granular avalanches, *J. Fluid Mech.*, 633, 115–135.

Palu, M., and P. Y. Julien. 2019. “Case study: Modeling the sediment load of the Doce River after the Fundão Tailings Dam collapse, Brazil.” *J. Hydraul. Eng.* 145 (5): 05019002.

[https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001582](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001582)

Palu, M., and P. Y. Julien. 2020. “Test and improvement of 1D routing algorithms for dam-break floods.” *J. Hydraul. Eng.* 146 (6): 04020043. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001755](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001755).

Pandya P.H., Jitaji T.D., 2013. A brief review of method available for dam break analysis. *Indian Journal of Research*. Vol. 2. No 4 p. 117–118.

Pasculli, A.; Cinosi, J. ; Turconi, L. ; Sciarra, N. 2021. Learning Case Study of a Shallow-Water Model to Assess an Early-Warning System for Fast Alpine Muddy-Debris-Flow. *Water*, 13, 750. <https://doi.org/10.3390/w13060750>

Pelanti, M., Bouchut, F. C., Mangeney, A., 2008. A Roe-type scheme for two-phase shallow granular flows over variable topography. *ESAIM Mathemat. Model. Numer. Anal.* 42 (5), 851–885

Pellegrino, A.M., Schippa, L., 2018. A laboratory experience on the effect of grains concentration and coarse sediment on the rheology of natural debris-flows. *Environ Earth Sci* 77, 749. <https://doi-org.proxy.bib.uottawa.ca/10.1007/s12665-018-7934-0>

Peng, S.H., Lu, S.C., 2013. FLO-2D simulation of mudflow caused by large landslide due to extremely heavy rainfall in southeastern Taiwan during Typhoon Morakot. *J. Mt. Sci.* 10, 207–218. <https://doi.org/10.1007/s11629-013-2510-2>

Petticrew, E.L., Albers, S.J., Baldwin, S.A., Carmack, E.C., Dery, S.J., Gantner, N., Graves, K.E., Laval, B., Morrison, J., Owens, P.N., Selbie, D.T., Vagle, S., 2015. The impact of a catastrophic mine tailings impoundment spill into one of North America's largest fjord lakes: QL, British Columbia, Canada. *Geophys. Res. Lett.* 42, 3347–3355.

Pirulli, M., Barbero, M., Marchelli, M., Scavia, C. 2017. The failure of the Stava Valley tailings dams (Northern Italy): numerical analysis of the flow dynamics and rheological properties. *Geoenvironmental Disasters*. 4, p. 3. <https://doi.org/10.1186/s40677-016-0066-5>

Pitman, E. B., Le, L., 2005. A two-fluid model for avalanche and debrisflows, *Philos. Trans. R. Soc. A*, 363, 1573–1602.

Pradhan, N.R., Floyd, I.E., Heath, R., Downer, C.W., and Gibson, S., 2018. “Development of ‘Debris Library’ and ‘GSSHA’ linkage-architecture for non-Newtonian sediment fluid flow”, 2018 AGU Fall Meeting, Washington D.C., 10-14 December, Paper Number: EP21D-2277.

Pudasaini, S.P., 2012. A general two-phase debris flow model. *Journal of Geophysical*

Research, 117, F03010. <https://doi.org/10.1029/2011JF002186>

Pudasaini, S.P., Krautblatter, M., 2021. The mechanics of landslide mobility with erosion. *Nat Commun* 12, 6793. <https://doi.org/10.1038/s41467-021-26959-5>

Raman, A., and Liu, F. 2019. An investigation of the Brumadinho Dam Break with HEC RAS simulation.

Rana, N.M, Ghahramani, N., Evans S.G., McDougall. S, Small, A., Take W.A., Catastrophic mass flows resulting from tailings impoundment failures. 2021. *Engineering Geology*, Volume 292, 106262, ISSN 0013-7952, <https://doi.org/10.1016/j.enggeo.2021.106262>.

Reid, L.M., Dunne, T., 2016. Sediment budgets as an organizing framework in fluvial geomorphology. In: Kondolf, G.M.; Piégay, H., eds. *Tools in Fluvial Geomorphology*. Chichester, UK: John Wiley & Sons, Ltd: 357-379. Chapter 16.

Report on Mount Polley tailings storage facility breach 2015. Retrieved from <https://www.mountpolleyreviewpanel.ca/sites/default/files/report/ReportonMountPolleyTailingsStorageFacilityBreach.pdf>

Rickenmann, D., Koschni, A., 2010. Sediment loads due to fluvial transport and debris flows during the 2005 flood events in Switzerland, *Hydrol. Process.*, 24, 993–1007, <https://doi.org/10.1002/hyp.7536>.

Rico, M., Benito, G., Salgueiro, A.R., 2008. Reported tailings dam failures: a review of the European incidents in the worldwide context *J. Hazard. Mater.*, 152, pp. 846-852

RiverMechanics.net, (2020). FLDWAVE description, <http://www.rivermechanics.net/index.php/about-models/11-model-descriptions/14-sdb-j-description-3>

Roamn, C., Barbosa, G., Lombardo, M., Cortes, C. (2022). Importance of tailings rheology in dam failure consequence classification. CDA 2022 Annual Conference, October 17-19, St. John's, Newfoundland and Labrador.

Robertson P.K., 2009, Interpretation of cone penetration tests—a unified approach. *Canadian Geotechnical Journal*, 46: 1337–1355.

Roche, C., Thygesen, K., Baker, E. (Eds.) 2017. *Mine Tailings Storage: Safety Is No Accident*. A UNEP Rapid Response Assessment. United Nations Environment Programme and GRID-Arendal, Nairobi and Arendal, Retrieved from <https://www.grida.no/resources/11431>.

Rosatti, G., Begnudelli, L., 2013. Two-dimensional simulation of debris flows over mobile bed:

Enhancing the TRENT2D model by using a well-balanced Generalized Roe-type solver. *Computers & Fluids* 71: 179-195.

Rotta, L., Alcantara, E., Park, E., Negri, R. & Lin, Y. & Bernardo, N. & Mendes, T., 2020. The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil. *International Journal of Applied Earth Observation and Geoinformation*. 90. 102119. 10.1016/j.jag.2020.102119.

Sadrekarami, A., 2016. Static Liquefaction Analysis Considering Principal Stress Directions and Anisotropy. *Geotech Geol Eng* 34, 1135–1154. <https://doi.org/10.1007/s10706-016-0033-7>.

Sammartano, G. & Spano, A. 2016. DEM Generation based on UAV Photogrammetry Data in Critical Areas. 92-98. 10.5220/0005918400920098.

Samuels, P., Morris, M., Hassan, M., Ghataora, G., 2008. Development of the HR BREACH model for predicting breach growth through flood embankments and embankment dams.

Sankano, V., Halabi, A., Futai, M., Pileggi, R. (2021). Evaluation of different flow protocol to estimate theological properties for a dam break analysis. CDA 2021 Annual Conference, October 25-28, Virtual.

Sarno, L., Carravetta, A., Martino, R., Papa, M.N., Tai Y.C., 2017. Some considerations on numerical schemes for treating hyperbolicity issues in two-layer models, *Advances in Water Resources*, Volume 100, 2017, Pages 183-198, ISSN 0309-1708, <https://doi.org/10.1016/j.advwatres.2016.12.014>.

Savage, S.B., Hutter, K., 1989. The motion of a finite mass of granular material down a rough incline. *J. Fluid Mech*, 199, 177–215.

Scholtz A., Chetty S., 2021. A comparison between HECRAS 6.0 and Flo-2D as tools used in tailings dam breach analysis. *Global Tailings Standards and Opportunities 2021*, Southern African Institute of Mining and Technology

Schumann, G.J.-P.; Brakenridge, G.R.; Kettner, A.J.; Kashif, R.; Niebuhr, E., 2018. Assisting Flood Disaster Response with Earth Observation Data and Products: A Critical Assessment. *Remote Sens.*, 10, 1230.

Shi, D. and Yang, X., 2015. Support Vector Machines for Land Cover Mapping from Remote Sensor Imagery. 10.1007/978-94-017-9813-6_13.

Shuttle D.A., Cunning J., 2007. Liquefaction potential of silts from CPTu. *Canadian*

Geotechnical Journal, 44: 1–19.

Simpson. G., Castelltort. S., 2006. Coupled model of surface water flow, sediment transport and morphological evolution, *Computers & Geosciences*, Volume 32, Issue 10, 2006, Pages 1600-1614, ISSN 0098-3004, <https://doi.org/10.1016/j.cageo.2006.02.020>.

Spasojevic M., Holly F.M., 1990. 2D bed evolution in natural watercourses: new simulation approach. *Journal of Waterway, Port, Coastal, and Ocean Engineering ASCE* 116(4): 425– 443.

Sreekumar, U., Nistor, I., Rennie, C., Mohammadian,A., 2023. Numerical modelling of downstream morphological evolution during Mount Polley tailings dam failure. *Journal of Hydraulic Engineering*. DOI: 10.1061/JHEND8/HYENG-13497

Sreekumar, U., Rennie, C., Mohammadian,A., Nistor,I., Lovitt,J., and Zhang,Y., 2022. Modelling the transport of tailings after Mount Polley tailings dam failure using multisource geospatial data. *Canadian Journal of Civil Engineering*. 49(12): 1870-1884. <https://doi.org/10.1139/cjce-2021-0596>

Strachan, C., 2001. Tailings dam performance from USCOLD incident-survey data. *Mining Engineering* 53(3): 49–53.

Sun E., Zhang X.K., Li Z.X., 2012. The internet of things (IOT) and cloud computing (CC) based tailings dam monitoring and pre-alarm system in mines. *Saf Sci* 50(4):811–815.

Tai, Y.C., Heß, Julian., Wang, Yongqi., 2019. Modeling Two-Phase Debris Flows with Grain-Fluid Separation Over Rugged Topography: Application to the 2009 Hsiaolin Event, Taiwan. *Journal of Geophysical Research: Earth Surface*. 124. 10.1029/2018JF004671.

Tellez, H., Medina, M., Mohammadian, A., 2023. Tailings Dam Break Analysis Performed for the PFS Study of a Downstream Raised TSF in South America, *Proceedings of Tailings and Mine Waste 2023*, November 5–8, 2023, Vancouver, Canada.

Tuflow 2021. https://www.tuflow.com/insights/2021_04-brumadinho-tailings-dam-failure/

Van Rijn, L. C., 1993. Principles of sediment transport in rivers, estuaries, and coastal seas, Aqua, Blokzijl, The Netherlands.

Vanderkimpen P., Melger E., and Peeters P., 2009. Flood modeling for risk evaluation a MIKE FLOOD vs.SOBK 1D2D benchmark study. *Flood Risk Management: Research and Practice*, Proceedings of the Europe Conference on Flood Risk Management Research into Practice (FLOODRISK 2008), Oxford, UK, 30September - 2 October 2008: Flood Risk Management: Research and Practice. pp. 77-84.

- Wan, Z., Wang, Z., 1994. Hyper concentrated flow, IAHR Monograph Series, Balkema, Rotterdam, The Netherlands.
- Wang, C., Harbottle, D., Liu, Q. and Xu, Z. 2014. Current state of fine mineral tailings treatment: A critical review on theory and practice. *Minerals Engineering*. 58. 113–131. 10.1016/j.mineng.2014.01.018.
- Wang, G.J., Kang J.W., 2017. Study on tailings dam over-topping failure model test and break mechanism under the rainfall condition. *Technical Gazette* 24(6):1897–1904
- Wang, K., Yang, P., Hudson-Edwards, K., Lv, W.S., Yang, C., and Jing, X. 2018. Integration of DSM and SPH to Model Tailings Dam Failure Run-Out Slurry Routing Across 3D Real Terrain. *Water*. 10. 1087. 10.3390/w10081087.
- Wang, X., Wei, Z., Li, Q., and Chen, Y. 2018. Experimental research on the rheological properties of tailings and its effect factors. *Environ Sci Pollut Res Int*. 2018 Dec ;25(35): 35738-35747. doi: 10.1007/s11356-018-3481-1. Epub 2018 Oct 24. PMID: 30357670.
- Wanjuan S., Xihan M., Gaiyan R., Zhan G., Linyuan L., Guangjian Y., 2017. Estimating fractional vegetation cover and the vegetation index of bare soil and highly dense vegetation with a physically based method, *International Journal of Applied Earth Observation and Geoinformation*, Volume 58, Pages 168-176, ISSN 1569-8432, <https://doi.org/10.1016/j.jag.2017.01.015>.
- West, M., Morris, M., Hassan, M., 2018. A guide to breach prediction, Discussion Paper. HR Wallingford Ltd, Wallingford. <https://eprints.hrwallingford.com/1341/1/HRPP770-A-guide-to-breach-prediction.pdf>
- White, T., Mitchell, A., Whittall, J., McDougall, S., 2023. Waste Dump Failure Runout Analyses: Applying Improved Empirical Correlation Methods to Waste Dump Datasets, *Proceedings of Tailings and Mine Waste 2023*, November 5–8, 2023, Vancouver, Canada.
- WISE-URANIUM, 2024. <https://www.wise-uranium.org/mdaf.html>
- Wong, J.S., Freer, J.E., Bates, P.D., Sear, D.A., and Stephens, E.M., 2015. "Sensitivity of a hydraulic model to channel erosion uncertainty during extreme flooding." *Hydrological Processes*, 29(2), 261-279.
- Wu, W., 2007. *Computational River Dynamics* (CRC Press, 2007). Section 2.5 NET EXCHANGE FLUX OF SUSPENDED LOAD NEAR BED - Page 44.
- Wu, W., 2008. *Computational River Dynamics*, Taylor and Francis.

- Wu, Y.H., Liu, K.F., Chen, Y.C., 2013. Comparison between FLO-2D and Debris-2D on the application of assessment of granular debris flow hazards with case study, *J. Mount. Sci.*, 2013, vol. 10, no. 2, pp. 293–304.
- Xia, C.-c., Li, J., Cao, Z.-x., Liu, Q.-q. & Hu, K.-h., 2018. A quasi-single-phase model for debris flows and its comparison with a two-phase model. *Journal of Mountain Science* 15, 1071–1089.
- Xin Z., Xiaohu, X., Kaili X., 2011. Study on the Risk Assessment of the Tailings Dam Break, First International Symposium on Mine Safety Science and Engineering, *Procedia Engineering* 26 (2011) 2261 – 2269.
- Yao, C., Wu, L., Yang, J., 2020. Influences of tailings particle size on overtopping tailings dam failures, *Mine Water and the Environment*, 2020. doi.org/10.1007/s10230-020-00725-3.
- Yong, R. N., Thomas, H. R., & Penman, A. D. M., 2001. Tailings dams: risk of dangerous occurrences. Paper presented at the Geo-environmental Engineering: Geo-environmental Impact Management: Proceedings of the third conference organized by the British Geotechnical Association and Cardiff School of Engineering, Cardiff University, and held in Edinburgh on 17–19 September 2001.
- Yu, D., Tang, L., Chen, C., 2020. Three-dimensional numerical simulation of mud flow from a tailings dam failure across complex terrain *Nat. Hazards Earth Syst. Sci.*, 20, 727–741, 2020. <https://doi.org/10.5194/nhess-20-727-2020>
- Yue, Z., Cao, Z., Li, X., C. Tao., 2008. Two-dimensional coupled mathematical modeling of fluvial processes with intense sediment transport and rapid bed evolution. *Sci. China Ser. G-Phys. Mech. Astron.* 51, 1427–1438. <https://doi.org/10.1007/s11433-008-0135-1>
- Zabolotnij, E., Morgenstern, N., and Wilson, W. 2022. Mechanism of Failure of the Mount Polley Tailings Storage Facility. *Canadian Geotechnical Journal*. Just-IN <https://doi.org/10.1139/cgj-2021-0036>
- Zenz, G.; Goldgruber, M., 2013. ICOLD Proceeding, 12th International Benchmark Workshop on Numerical Analysis of Dams. In *Proceedings of the ICOLD Proceedings*, Gerald Zenz and Markus Goldgruber, Graz, Austria, 2 October 2013; Volume 12, p. 210.
- Zongjie L., Junrui C., Zengguang X., Yuan Q., and Jing C. 2019. A Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History, *Advances in Civil Engineering*, vol. 2019, Article ID 4159306, 18 pages, 2019. <https://doi.org/10.1155/2019/4159306>
- Zuoan., W., Guangzhi., Y., Wang, J.G., Ling.,W., Guangzhi., L. 2013. Design, construction

and management of tailings storage facilities for surface disposal in China: Case studies of failures. *Waste management & research: the journal of the International Solid Wastes and Public Cleansing Association, ISWA*. 31. 106-112. 10.1177/0734242X12462281.