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Numerical modelling of oil-sands tailings dam breach runout and overland flow

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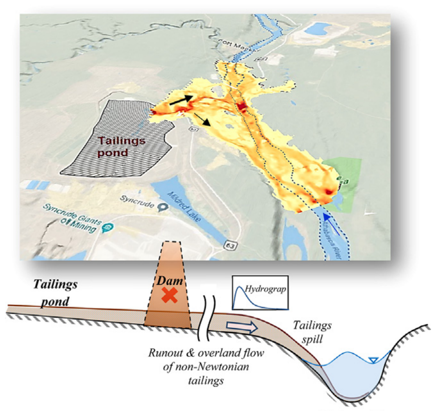
HIGHLIGHTS

- Impact of an oil-sands tailings dam breach on terrestrial/aquatic environments is studied.
- Runout, overland flow and spill of non-Newtonian tailings are simulated.
- Around half of tailings is deposited overland, the rest spills to Lower Athabasca River.
- Impact of non-Newtonian modelling and rheological parametrization is quantified.

GRAPHICAL ABSTRACT



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ABSTRACT

Tailings dams, used for containing the residue of mining processes, are very important elements of the Alberta oil-sands industry in Canada. Potential breach of any of these dams can have catastrophic impact on the environment, economy and human health and safety. Therefore, understanding the after-breach processes is a crucial step in hazard analysis and response planning. This paper studies the potential consequence of a hypothetical oil-sands tailings dam breach by performing numerical simulations of the runout and non-Newtonian overland flow of tailings, including the resulting flooding condition and subsequent spill to nearby water bodies. A non-Newtonian dam-breach model with a visco-plastic rheological relationship is used for this purpose. The model is first validated using the 2014 Mount Polley tailings dam breach in British Columbia, before its application to investigate the flooding volume, extent, and downstream hydrograph of a hypothetical breach from a selected oil-sands tailings dam. The validation results show that the model is able to reproduce the flooding extent and water level variation (due to breach wave) at a downstream lake. The oil-sands tailings spill simulation study demonstrated the importance of considering the non-Newtonian behaviour of tailings materials as the non-Newtonian approach resulted in twice as long flood travel time and slightly less spill volume to the downstream river (i.e. Lower Athabasca River) as that of a Newtonian fluid (i.e. water). The results are also found to be highly sensitive to the rheological parameters of the tailings materials such as their viscosity and yield stress that need to be determined through proper calibration.

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1. Introduction

Tailings storage facilities (TSFs), including tailings dams, are structures that are used to store the residual of mining processes. Breaches of such tailings dams have been sources of many catastrophes in the mining industry around the world. The breach causes sudden release of tailings materials, a mixture of water and sediments, associated with toxic components. Such breaches can have disastrous impacts on the economy, environment and human health and safety. In the past, the global mining industry has experienced many catastrophic breaches of tailings dams, for example in, Omai mine (1994, Guyana), Aitik mine (2000, Sweden), Kingston fossil plant (2008, USA), Germano mine (2015, Brazil), Tonglvshan mine (2017, China) and most recently, Brumadinho mine (2019, Brazil). The Canadian mining industry has not been exempted from these incidences. Breach of tailings dams in Gullbridge mine (2012, Newfoundland), Obed Mountain Coal Mine, (2013, Alberta), and Mount Polley mine (2014, British Columbia) are a few examples of such incidences. Larrauri and Uall (2018) have recently documented the historical breaches for different type of tailings dam facilities around the world.

Tailings dams are also key elements of the oil-sands mining industry in Alberta, Canada, covering an area of about 77 Km^2 impounded by some of the world's largest dam/dyke structures (Fig. 1). They are used as a means of retaining the tailings until a reclamation technology can be developed to remediate them. These dams allow for the fluid fine tailings (FFT) to settle and consolidate forming a layer of mature fine tailings (MFT) at the bottom, and the process water (PW) at the top (Fig. 2a). Tailings are associated with residual bitumen and toxic chemicals such as salts, naphthenic acids, polycyclic aromatic hydrocarbons, ions and metals (Nero et al., 2006; Allen, 2008; Kavanagh et al., 2009; Frank et al., 2014; Galarneau et al., 2014). One of the main environmental concerns about the oil-sands tailings dams, is the possible breach and release of tailings material to the nearby lands and waters (Fig. 2a). Considering the composition and volume of the tailings and the proximity of the tailings dams to the Lower Athabasca River (LAR) system, a breach can have a catastrophic impact to the environment (aquatic and terrestrial), public health, life and property. A recent numerical study by Dibike et al. (2018) showed that a sudden spill of tailings materials into the LAR can have a multi-year impact on the water quality and ecosystem several hundred kilometers downstream. These possible consequences have put pressure on the oil-sands mining industry, government, and stakeholders to provide measures to minimize the potential impact of unpredictable tailings oil-sands dam failures. Many disastrous historical tailings dam breaches, especially the failure of the Mount Polley tailings dam in 2014 has contributed to such pressure.

While prevention of a tailings dam breach is important, the assessment of the after-breach transport processes of tailings material will be a crucial element in the analysis of hazards, planning the emergency response, and mitigation of the consequences. These processes include the tailings runout, the non-Newtonian overland flow, and the resulted flooding condition (Fig. 2). Unlike a water dam-breach, our understanding of these after-breach transport processes for tailings dam-breaches is quite limited. That is, despite the larger historical failure rate of tailings dams in comparison with water dams (Martin et al., 2015). This knowledge gap, which is the common problem of the mining industry (Martin et al., 2015), stems from the complex mechanical behaviour of tailings slurries, which unlike water, behaves as a non-Newtonian system. Conventional dam breach and flood routing models are not reliable for predicting tailings dam breaches as they do not account

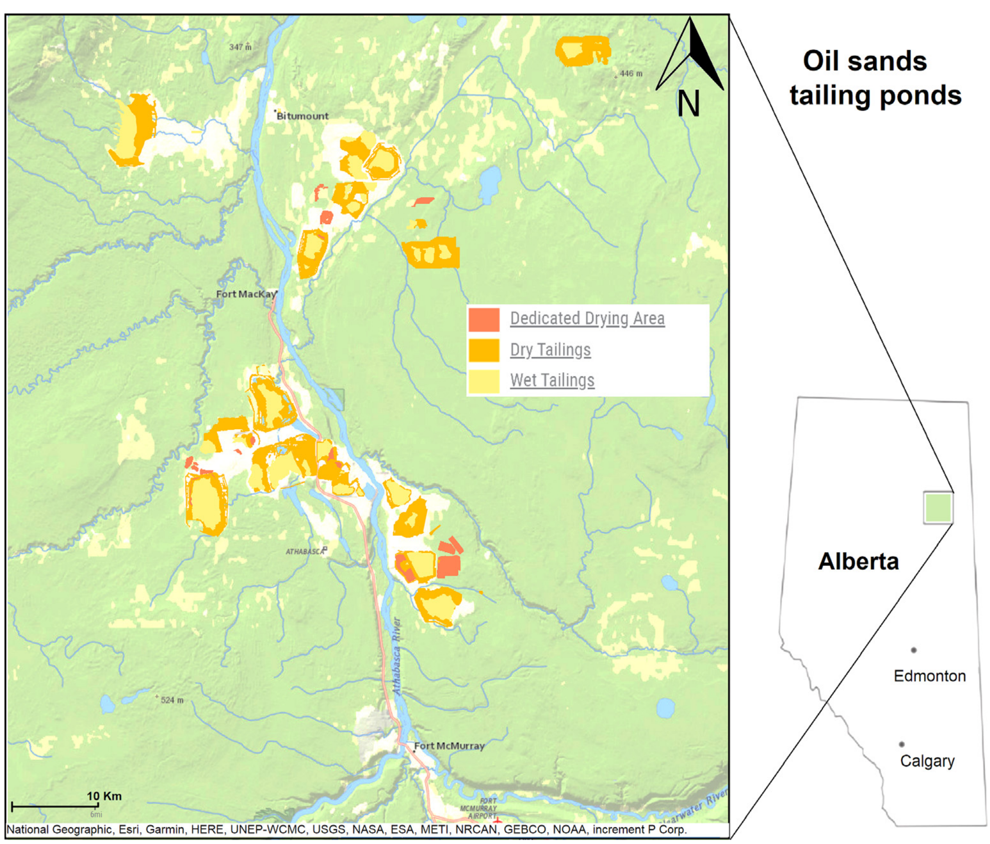

Fig. 1. Locations of Alberta oil-sands tailings storage facilities near the Lower Athabasca River (LAR) (Image modified from Government of Alberta (2019)).

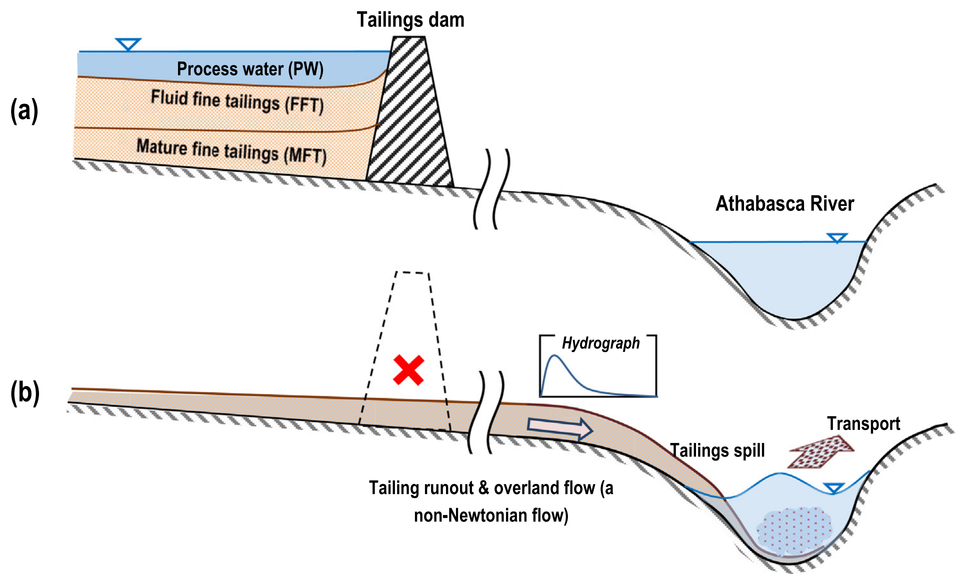

Fig. 2. Schematic of (a) the oil-sands tailings storage facility, (b) tailings dam after-breach processes.

for the non-Newtonian visco-plastic behaviour of slurries (O'Brien and Julien, 2000).

Nguyen and Boger (1998) did an experimental analysis of tailings material of an Aluminum tailings pond in Australia, and the variation of the yield stress show that the tailings materials behave according to Herschel-Buckley rheological model. Their analysis also showed a great dependency of tailings behaviour to the concentration. For low concentrations (<20%) they found the yield stress to be vary in the range of 0.5–2.5 Pa, and for higher concentrations, they found an exponential increase. O'Brien and Julien (2000) experimental analysis, also showed an exponential relationship between yield stress and the solid concentration. Boger (2013), through the analysis of 11 different tailings ponds around the world, showed that the behaviour of the tailings material at low concentration is independent of the tailing material.

A limited number of past studies have concentrated on prediction and analysis of tailings failure runout characteristics (e.g., outflow volume, flow hydrograph, peak discharge, runout distance, and inundation area). Some of them (e.g., Rico et al., 2008; Larrauri and Uall, 2018) have concentrated on the prediction of the breach outflow characteristics, based on the statistical analysis of data from the historical tailings breaches. Some others have tried to use Newtonian and non-Newtonian numerical models to predict of runout characteristics. Jeyapalan et al. (1983) used the TFLOW model associated with a Bingham-plastic rheological model for simulation of Gypsum Tailings Dam incident (USA, 1966). Martin et al. (2015) analyzed the breach of three tailings ponds for the purpose of hazard classification. Sauthier et al. (2010) compared two numerical models RASH-3D and DAN-3D for the simulation of the behaviour of slurry flow.

For the specific case of the oil-sands tailings dams, numerous studies in the past have investigated the fate of oil-sands contaminants within the pond structures (e.g., Lévesque, 2014), into groundwater (e.g., Frank et al., 2014), and into the atmosphere (e.g., Galarneau et al., 2014; Small et al., 2015). A number of studies (e.g., Shakibaeinia et al., 2016, 2017) have also focused on the transport of sediments and contaminants within the LAR. However, none of those past studies has tried to assess the downstream consequences of an unforeseen tailings dam breach and the subsequent release of its effluent into the LAR system. Only most recently, Dibike et al. (2018) made the first attempt to numerically study the impact hypothetical breaches of oil-sands tailings dams, focusing on the transport of the tailings material within Athabasca River. However, they did not consider the runout and overland flow of tailings from the breach location to the river, and simply assumed that the whole breach volume will spill to the LAR.

This paper, therefore, aims to numerically investigate the non-Newtonian runout and flooding condition resulting from the hypothetical breach of oilsands tailings dams. The study is based on a 2D depth-averaged numerical model, i.e. FLO-2D (O'Brien, 2007), and its mudflow module with capability of non-Newtonian overland flow simulation using a visco-plastic rheological model. It was first developed and applied applied For simulation of mudflow (O'Brien et al., 1993). FLO-2D is a well-accepted and widely-used model for flood routing, and one of the few models with capability of dealing with non-Newtonian floods for cases such as slurries, debris and mud flow (d'Agostino et al., 2006; Calligaris et al., 2008; Wu et al., 2013; Peng and Lu, 2013). The model is first calibrated and validated using a historical tailings dam breach case (i.e. the breach of Mount-Polly mine, 2014), then is applied for study of runout and flooding condition (flood volume, extend, and hydrograph) resulted from the hypothetical breach of an example oil-sands tailings dam. The effect of tailings characteristics and rheological parameters are also investigated through sensitivity analysis.

1.1. Study area and data

The study area is the oil-sands development region near the lower portion of the Athabasca River (LAR) next to the city of Fort McMurray, Alberta, Canada (Fig. 3). The Mildred Lake Settling Basin (MLSB) (located 40 km north of Fort McMurray and owned by Syncrude Canada Ltd (2010)) was selected as the example case study. It is used as a primary source of recycled water for one of the mines in the region as well as storage for fluid tailings, flotation and froth tailings, and coke solids. The selection of this TSF is based on its relatively large volume and proximity to the LAR. Syncrude Canada (2010 and 2011) estimated the total volume, FFT volume, and process water volume of MLSB to be 540, 120 and 12 Million m^3 respectively. MLSB is also one of the examples TSFs that was studied by (Dibike et al., 2018).

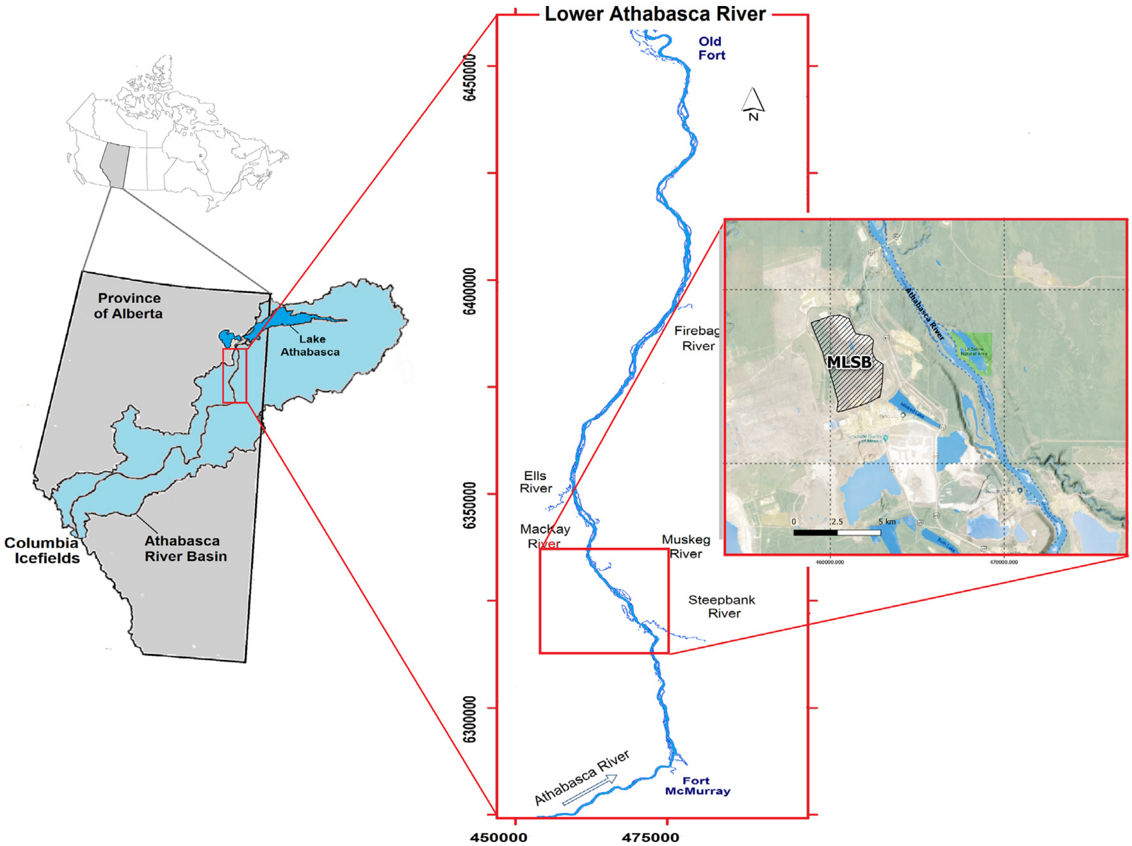

Fig. 3. The study region in the lower Athabasca River, including the MLSB TSF.

1.1.1. Topography

Topographic data of the study area has been derived through an optimal combination of the high-resolution (0.5 m) surveyed bathymetry data by Environment Canada using a Geoswath sonar sensor, (2) high-resolution (5 m) LIDAR data along the LAR floodplain provided by AESRD, and (3) DEM data of the region (with 20 m resolution) from Geobase (2017). The topographic/drainage analysis of the data shows that the shortest drainage path of MLSB toward LAR is around 7.8 km through the creek, which has a confluence with LAR at coordinate 57.120530, −111.599691.

1.1.2. Breach hydrograph

To determine the breach hydrograph, the water and tailings materials are assumed to run out of the tailings dam. Rico et al. (2008) developed serval empirical formulas that help to calculate the maximum discharge and volume released through the breach, based on information from 28 past tailings dam failures. The breach outflow total volume and hydrograph peak is given by (Rico et al., 2008):

$$V_F = 0.354\ V_T^{1.01} \tag{1}$$

$$Q_{\max} = 40.1\ V_T^{0.295} H^{1.24} \tag{2}$$

where V_F is outflow volume, V_T is total stored volume, $Q_{\max}$ is the peak discharge and H is height of water above the base of breach. Based on these relations and several other imperial relationships suggestion by Rico et al. (2008) and Barker and Schaefer (2007) a hydrograph was developed by Dibike et al. (2018) for breach of MLSB TFS. Table 1 shows the estimated outflow volume based on Rico et al. (2008) empirical equations.

Table 1
Breach outflow volumes (Mm^3) from MLSB TFS estimated based on Rico et al. (2008).

Total pond volume		540
Outflow	Volume PW	12
	Volume FFT	121
	Mobilized sediments	71
	Total outflow volume	204

2. Numerical model

The numerical model used in this study is FLO-2D (O'Brien and Julien, 2000), a commercially available software (distributed by FLO-2D Software Inc.) for two-dimensional flood or single-phase mud-flood simulations. The model is cable of dealing with the overland flow of non-Newtonian materials, unlike the classical Newtonian models. This model has been widely used for the assessment of mud and debris flow since it development in 1993. FLO 2D uses a finite difference algorithm to solve the Saint-Venant equations, which include the continuity and momentum conservation as:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = i \tag{3}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial h}{\partial x} + (S_f - S_0)g = 0 \tag{4}$$

where i is the source/sink term, h is the flow depth and u is the depth-averaged velocity, g is gravitational acceleration, S_0 is bed slop, and S_f is friction slope which is calculates base on the shear stress. To model the debris or mudflow, the shear stress is given by the following equation:

$$\tau = \tau_c + \tau_{mc} + \tau_v + \tau_t + \tau_d \quad (5)$$

where τ_c is cohesive yield stress; τ_{mc} is Mohr-Coulomb shear; τ_v is viscous shear stress; τ_t and $\tau_d$are turbulent and dispersive shear stress respectively. The constitutive law for shear stress and strain-rate used is:

$$\tau = \tau_y + \eta\frac{\partial u}{\partial y} + C\left(\frac{\partial u}{\partial y}\right) \quad (6)$$

where $\tau_y = \tau_c + \tau_{mc}$ is yield stress and η is dynamic viscosity, and C represent the turbulent- dispersion:

$$C = \rho_m l^2 + \frac{\pi}{12}\left(\frac{6}{\pi}\right)^{1/3}\sin^2(\alpha_1)\rho_s\left(1 - e_n^2\right)C_v^{1/3} \quad (7)$$

where ρ_s density of debris, ρ_m is density of mixture, e_n is energy restitution coefficient, α_1 is averaged impact angle of solid. Based on Eq. (6) one can calculate friction slope as (Julien and lan, 1991) as:

$$S_f = \underbrace{\frac{\tau_y}{\gamma h}}_{\text{yield stress slope}} + \underbrace{\frac{\eta k u}{8\gamma h^2}}_{\text{viscous slope}} + \underbrace{\frac{\eta_T^2 u^2}{h^{4/3}}}_{\text{turbulence slope}} \quad (8)$$

where k is a resistance parameter, η_T is turbulent viscosity. The yield stress and dynamic viscosity are given by:

$$\tau_y = \alpha_1 \exp(\beta_1 C_v) \quad (9)$$

$$\eta = \alpha_2 \exp(\beta_2 C_v) \quad (10)$$

where C_v is volume concentration of sediments and α and β are the coefficients which depend on the material properties. Here in this study the α and β coefficients are considered as calibration factor within the range suggested by O'Brien and Julien (2000).

FLO-2D uses Eqs. (8)–(10) to predict the non-Newtonian behaviour of the materials. The discharge, and water depth are calculated based on the flow governing equation discretized using a central difference method and solved using Newton-Raphson

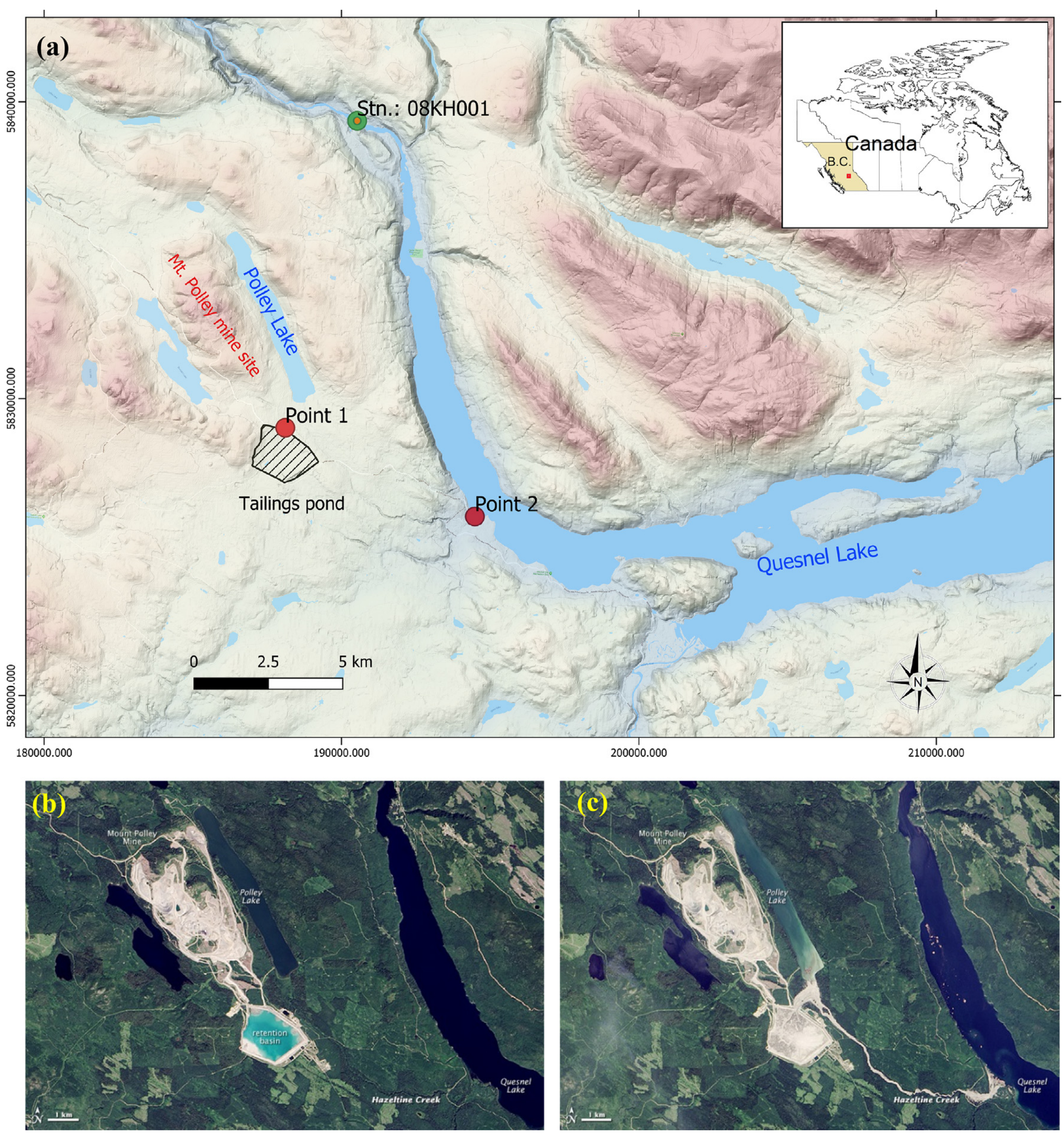

Fig. 4. (a) Map of Mount Polley mine site in British Columbia. Satellite image of the site (b) before and (c) after the tailings dam breach (images are from NASA 2014).

method (to determine the averaged depth and velocity in each flowing direction). The net discharge is calculated based on the summation of the discharged in eight directions for a grid element and after multiplying the velocity and the cross-sectional flowing area, the net discharge can be determined as:

$$\Delta Q_i^{t+1} = \sum_{i=1}^{8} Q_i^{t+1} \tag{11}$$

where $t+1$ indicate the next time step; $i$represent the number of flowing directions. The flow depth at next time step can be obtained as

$$\Delta H_i^{t+1} = \frac{\Delta Q_i^{t+1} \Delta t}{A_{surf}} \tag{12}$$

where A_{surf} and $\Delta t$are the surface grid area and time step respectively.

The outputs data, including water depth, velocity and impact force as well their maximum values for each time interval, can be converted into ESRI shapefile for displaying in geographic information system (GIS). The poste processing integrated in FLO-2D call mapper which has the possibility also to plot the flow depth and velocity variation in each grid element, as well the water depth profile.

3. Model calibration and validation

Since the study case is a hypothetical tailings dam breach, it cannot be used for validation purpose. Instead, a historical tailings dam breach (i.e. the Mount Polley incident of 2014) is used for model parametrization and validation. The Mount Polly mine (an open pit copper and gold mine owned by Imperial Metals) is located in the Cariboo region of British Columbia, Canada, adjacent to Hazeltine Creek, Polley Lake and Quesnel Lake (Fig. 4). In the early morning of August 4th 2014, its tailings dam breach released ~25 Mm^3 of tailings and water (10.6 Mm^3 supernatant water, 7.3 Mm^3 tailings solid, 6.5 Mm^3 interstitial water, 0.6 Mm^3 construction materials) (Petticrew et al., 2015). The materials discharged into Polley Lake and flowed along Hazeltine Creek channel into the Quesnel Lake.

The geometry of the Mount Polly mine model is constructed by interpolation of the topographic DEM data on a mesh system with

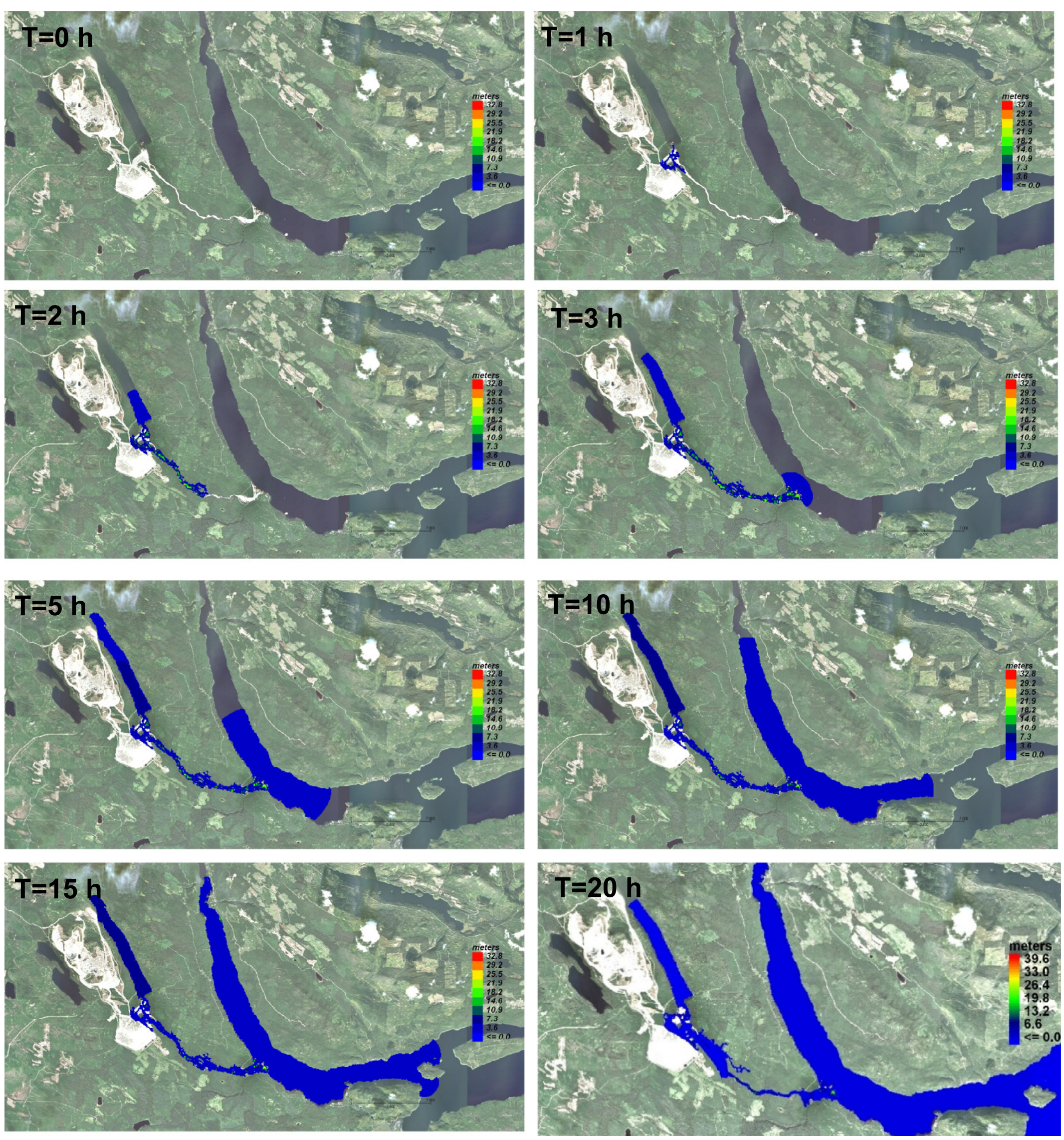

Fig. 5. Time evolution of simulated overland flow following Mount Polley TSF breach (figures show the flow depth).

30 m by 30 m grid resolution. The input data include the breach hydrograph constructed based on the total volume of the breach outflow and the formulation provided in Section 2. The calibration is performed for the rheological parameters α and β (used for calculation viscosity and yield stress). The available data for validation of the model are the breach final inundation area and water level at the Quesnel Lake at the Water Survey of Canada (WSC) hydrometric station number 08KH011. Unfortunately, in this case, the data related to the time evolution of inundation area, the travel time, and the volume of the materials discharged into the lakes are not available.

Fig. 5 shows the time evolution of simulated tailings breach overland flow and flooding condition for the Mount Polley tailings breach. After the breach, a portion of the materials flow to the Polley Lake and the rest flow along the Hazeltine Creek channel and finally reach the Quesnel Lake less than 3 h after the breach. Comparison of the simulated inundation area with the satellite imagery data in Fig. 6 shows a similar flow path and inundation area. Wider flow path along the Hazeltine Creek observed in the simulation results is due to the coarse mesh size (30 m). Fig. 7a compare the flood hydrographs at the breach location and the confluence of Hazeltine Creek, and Quesnel Lake. As the figure shows the peak of the hydrograph reaches Quesnel Lake after around 3 h. The simulation predicts about 87% the total breach volume to reach the Quesnel Lake. To provide a quantified validation, the simulated and measured water level variation at the Quesnel Lake after the breach event are compared in Fig. 7b. The measured lake water level show an initial oscillation for the first 24 h that eventually dampened resulting in water level rise of about 7–10 cm. The simulated results also show a similar trend, with the one corresponding to the medium rheological parameters (viscosity of η = 0.3 Pa.s and yield stress of τ_y = 1.3 Pa) being the most optimal closely matching the observations. These rheological parameters are found to be within the ranged recommended by O'Brien, 2007. The other two simulation results show the sensitivity of the model output to these parameters as the viscosity controls the flow speed and energy dissipation. As shown in the same figure (Fig. 7b), the lower and higher viscosity values of 0.1 and 0.7 Pa.s resulted in an average water level increase of about 22 cm and 4 cm, respectively. If the non-Newtonian nature of the tailings flow was not considered (i.e. if a viscosity of water is used), the simulated water level at the measurement station could increase by more than 2 m.

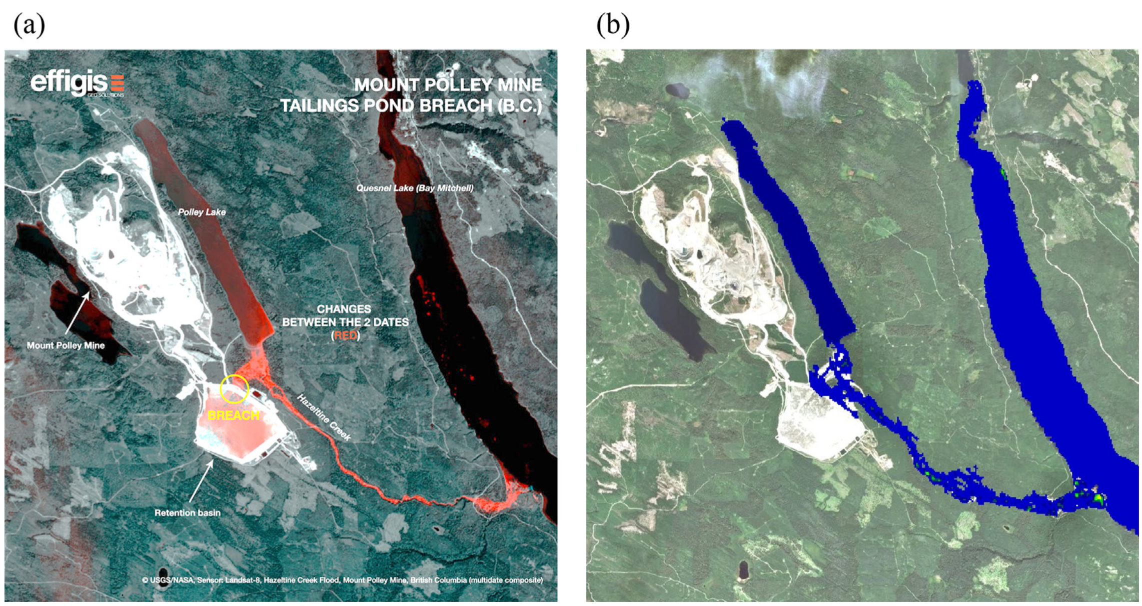

Fig. 6. Comparison of simulated and actual inundation area. (a) Difference of NASA aerial photos of the Mount Polley Mine site before and after the tailings dam breach (Image by Effigis), (b) simulated flooding extent.

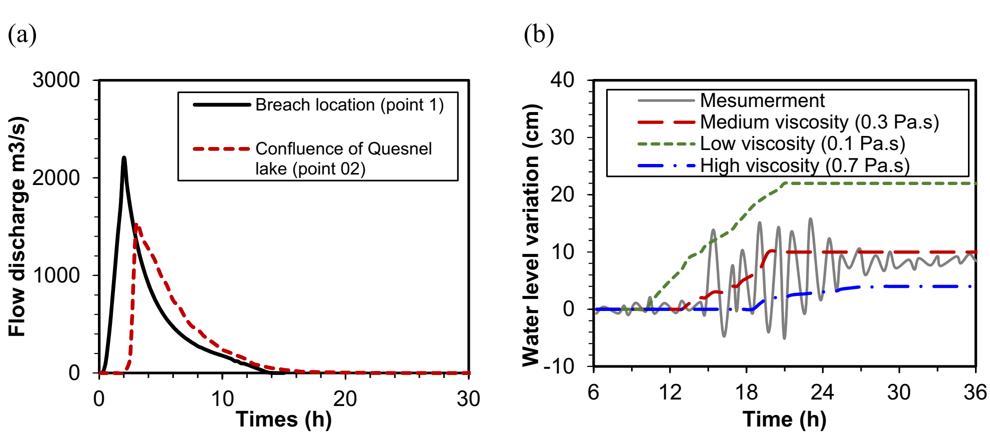

Fig. 7. (a) Tailings flow hydrograph at breach location and at the confluence of Hazeltine Creek, and Quesnel Lake (i.e. points 1 and 2 in Fig. 4), (b) Time series of simulated and measures water level at Quesnel Lake (WSC hydrometric station number 08KH011).

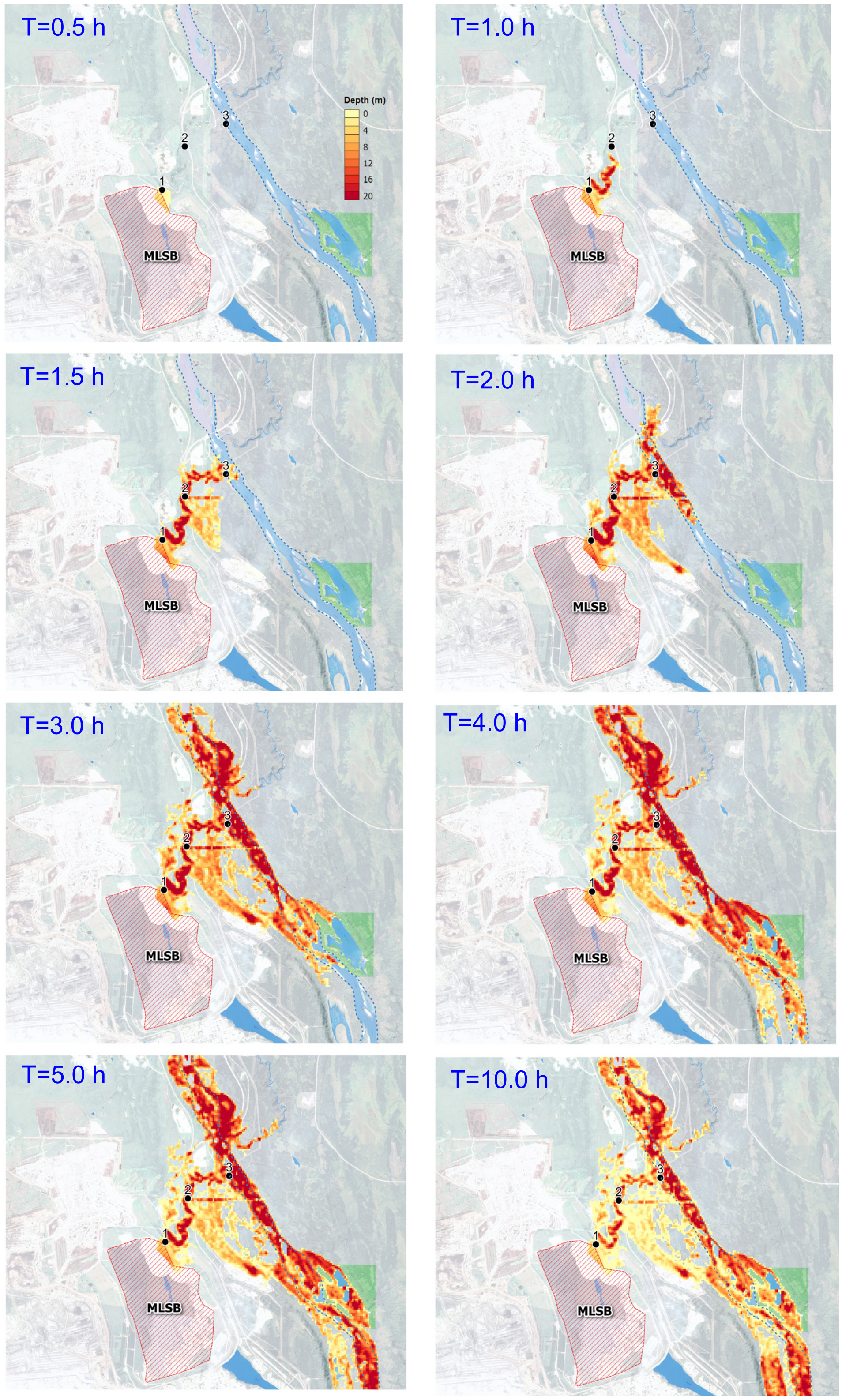

Fig. 8. Time evolution of simulated overland flow and flooding condition following a hypothetical breach of MLSB TSF in the lower Athabasca oil-sands region (figures show the flow depth).

4. Model application and results

The topographic data for the lower Athabasca region were interpolated on a mesh system with 30 m by 30 m grid resolution. Manning coefficient selected to be 0.04 based on the soil and land cover properties over the region and the model was run for an average flow condition in the Athabasca River. The model was simulated for a 25 h period starting from the breach initiation with simulation step of 0.25 h. The reference material properties and the rheological parameters were assumed to be similar to those of the

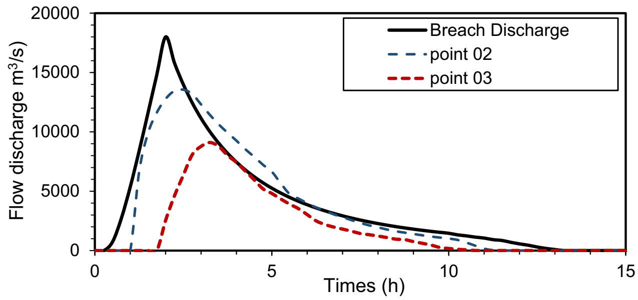

Fig. 9. Simulated flow hydrograph at various points along the flow path (as shown on Fig. 8) following a hypothetical breach of MLSB TSF.

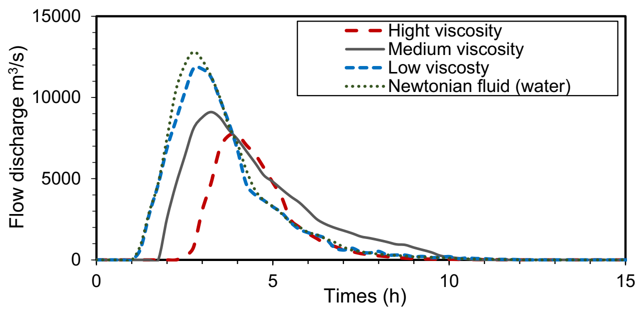

Fig. 10. Simulated flow hydrograph at point 3 (as shown on Fig. 8), for various viscosity scenarios, following a hypothetical breach of MLSB TSF.

Mount Polley model, i.e. viscosity of η = 0.3 Pa.s and yield stress of τ_y = 1.3 Pa, which corresponds to a volume concentration around 22%. A sensitivity analysis is performed to investigate the effect of these parameters. To consider the worst-case scenario, it is assumed that the dam breach happens at a point near the north-west corner of the tailings pond, which has the closest drainage path to the Athabasca River (which is through a creek). The flow discharge of the creek is not taken into the account considering its negligible value compared to a hypothetical tailings breach runout.

Fig. 8 shows the time evolution of simulated runout and flooding condition for the hypothetical breach. As expected, the material flow through the closest drainage path toward the Athabasca River. As time goes on, the inundation area expands and covers the land downstream of the breach. Then the tailings spills into the LAR, in various locations, and propagate in the LAR in both upstream and downstream directions. Tailing will also inundate the LAR floodplain at the right bank and even spills to the Saline Lake.

Fig. 9 shows the breach hydrograph at various point along the drainage path. The points 1, 2 and 3 are located at the breach location, middle of the flow path (Coordinate: 57.112455, −111.627051) and at the creek confluence with the Athabasca River (Coordinate: 57.120464, −111.600813), respectively (see Fig. 8 for the location of these points). The initial tailings flow reach points 2 and 3 within the first 1 and 1.5 h after the breach. About 53.43% of tailings outflow volume is predicted to reach point 3 and spill into the Athabasca River within the first 10 h after the initial tailings breach.

Nevertheless, sensitivity analysis shows that these results largely depend on the rheological properties of the tailings flow used for the simulation. For instance, changing the viscosity can largely affect the time and volume of tailings material reaching the Athabasca River. Fig. 10 and Table 2 compare the hydrographs, tailings volumes and times of the tailings material spilling into the LAR, for various viscosity scenarios. The reference non-Newtonian model with a medium viscosity was compared to those with lower and higher viscosities, as well as a Newtonian model with a viscosity equivalent to that of water. The results show that decreasing the viscosity will reduce the travel time and increase the volume of tailings materials reaching the LAR. A Newtonian model predicts twice spill volume (to LAR) with a 60% faster travel time compared to a non-Newtonian model with high viscosity. Table 2 also presents the mass of the tailings materials which has been deposited overland after the tailings runout.

5. Summary and conclusion

A non-Newtonian dam-breach runout model was set up using the FLO-2D software and implemented to study the overland flow and inundation condition resulting from a hypothetical breach of the MLSB tailings dam in the Athabasca oil-sand region. The MLSB tailings dam was selected as an example for this study considering its large volume and its proximity to the lower Athabasca River (LAR). The simulation model was first calibrated and validated for a historical tailings dam breach (i.e. The 2014 breach of Mount Polley tailings dam in British Columbia). After identifying the best rheological parameters through calibration, the validations showed the ability of the model to predict the path and flooding extent of the breach outflow, as well as water level rise in the downstream lake (i.e. Quesnel Lake).

The calibrated and validated model parameters were then applied for simulation of a hypothetical breach runout scenario from the MLSB tailings dam in the lower Athabasca region. A breach was considered at the north-west corner of the tailings dam, which has the closet drainage path to the LAR (through a creek). Simulation results predicted about 52% of tailings volume resulting from the tailings breach reaches the confluence of LAR with an initial travel time, through the creek, of about 1.5 hrs. The simulated mass of tailings material released to LAR and those deposited overland were 57.24 MT and 52.92MT respectively. The simulation result also showed a large flooding region downstream of tailings dam breach. Model sensitivity analysis showed that these results largely depend on the rheological properties of tailings materials (viscosity and yield stress). Therefore, a detailed rheometric analysis of tailings material can provide the data for a more conclusive numerical study.

Table 2
Percentage of breach outflow volume, sediment mass deposited and reaching the LAR and the time taken for the leading edge of the flow to arrive at the LAR corresponding to different viscosity scenarios.

Condition	Volume released to LAR		Sediment mass balance		Time to reach LAR (h)
	Total volume Mm^3	% of breach volume	Mass released to LAR (MT)	Overland Mass deposited (MT)	
Newtonian Flow (i.e water η = 0.001 Pa.s)	121	59.31	–	–	0.75–1
Low viscosity (η = 0.05 Pa.s)	115	56.4	62.1	48.06	1–1.25
Medium viscosity (η = 0.3 Pa.s)	106	52	57.24	52.92	1.5–2
High viscosity (η = 2.00 Pa.s)	69	33.82	34.56	75.6	2–2.5

The applied numerical model for this study, FLO-2D, is one the most widely-used models for dam-breach simulation and one of the few available models that can deal with the non-Newtonian behaviour of tailings flow. However, the depth average and single-phase nature of this model (and other similar models) can limit its ability to accurately predict the highly dynamic multi-phase nature of flow in such types of tailings dam breach events. Furthermore, the simplified rheological relationship of this model may not be able to accurately predict the non-Newtonian behaviour of tailings. The ability of this model to predict the breach outflow and the resulted hydrograph is also limited. Therefore, further research is suggested on developing a fully dynamic multiphase three-dimensional numerical model, with complex rheological models for simulation of similar tailings dam breach outflows. The unknown rheological properties have been a major source of uncertainty in the results of this study. Due to restricted access for sampling of tailings materials, no rheological measurements have been reported in past studies on oil-sands tailings. Therefore, sampling and rheometric testing of oil-sands tailings are recommended for future studies.

Declaration of Competing Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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