

Debris-flow simulations on Cheekye River, British Columbia

Abstract Cheekye River fan is the best-studied fan complex in Canada. The desire to develop portions of the fan with urban housing triggered a series of studies to estimate debris-flow risk to future residents. A recent study (Jakob and Friele 2010) provided debris-flow frequency-volume and frequency-discharge data, spanning 20-year to 10,000-year return periods that form the basis for modeling of debris flows on Cheekye River. The numerical computer model FLO-2D was chosen as a modelling tool to predict likely flow paths and to estimate debris-flow intensities for a spectrum of debris-flow return periods. The model is calibrated with the so-called Garbage Dump debris flow that occurred some 900 years ago. Field evidence suggests that the Garbage Dump debris flow has a viscous flow phase that deposited a steep-sided debris plug high in organics in centre fan, which then deflected a low-viscosity afterflow that travelled to Squamish River with slowly diminishing flow depths. The realization of a two-phase flow led to a modelling approach in which the debris-flow hydrograph was split into a high viscosity and low viscosity phase that were modelled in chronologic sequence as two separate and independent modelling runs. A perfect simulation of the Garbage Dump debris flow with modelling is not possible because the exact topography at the time of the event is, to some degree, speculative. However, runout distance, debris deposition and deposit thickness are well known and serve as a good basis for calibration. Predictive analyses using the calibrated model parameters suggest that, under existing conditions, debris flows exceeding a 50-year return period are likely to avulse onto the southern fan sector, thereby damaging existing development and infrastructure. Debris flows of several thousand years return period would inundate large portions of the fan, sever Highway 99, CN Rail, and the Squamish Valley road and would impact existing housing development on the fan. These observations suggest a need for debris-flow mitigation for existing and future development alike.

Keywords Debris-flow modelling · Model calibration · Runout modelling · Landslide

Introduction

In the last 5 years, southern British Columbia has witnessed a development boom. Given the topographic constraint of the mountainous region around Squamish at the head of the Howe Sound fjord, land suitable for residential development is scarce in the area (Fig. 1).

The head of Howe Sound is occupied by the Squamish River floodplain and low hills underlain by glacially rounded bedrock or thick Quaternary drift deposits. Within the District of Squamish lies the 10-km² largely undeveloped Cheekye Fan (Fig. 2). This landform is undeveloped because previous engineering studies found unacceptable levels of landslide risk. Landslide hazards on the Cheekye Fan have

been well studied academically (Mathews 1952, 1958; Friele et al. 1999; Ekes and Hickin 2001; Ekes and Friele 2003; Friele and Clague 2002a, b, 2005, 2008; Clague et al. 2003; Jakob and Friele 2010) and in practice (Jones 1959; Crippen Engineering 1974, 1975, 1981; Baumann 1981, 1991; Thurber and Golder 1993; Kerr Wood Leidal 2003; BGC 2007a, b, c; Kerr Wood Leidal 2008) and are summarized in Jakob and Friele (2010). The long-term geomorphic evolution of the fan as well as the stability of potential source areas in the upper Cheekye River watershed has provided input to the development of a long-term frequency-magnitude relationship (Jakob and Friele 2010), which forms the basis for a quantitative debris-flow risk assessment.

The objectives of this paper are to examine the processes and scenarios that could lead to debris flows of various return periods on the Cheekye Fan and to discuss the assumptions and variables of the two-dimensional debris-flow model chosen for the analysis. Furthermore, we simulate the well-researched Garbage Dump debris flow by calibrating input parameters to obtain a model in which runout distance and deposit thickness are similar to those observed. The calibrated model is then used to simulate a range of potential future debris flows on Cheekye River.

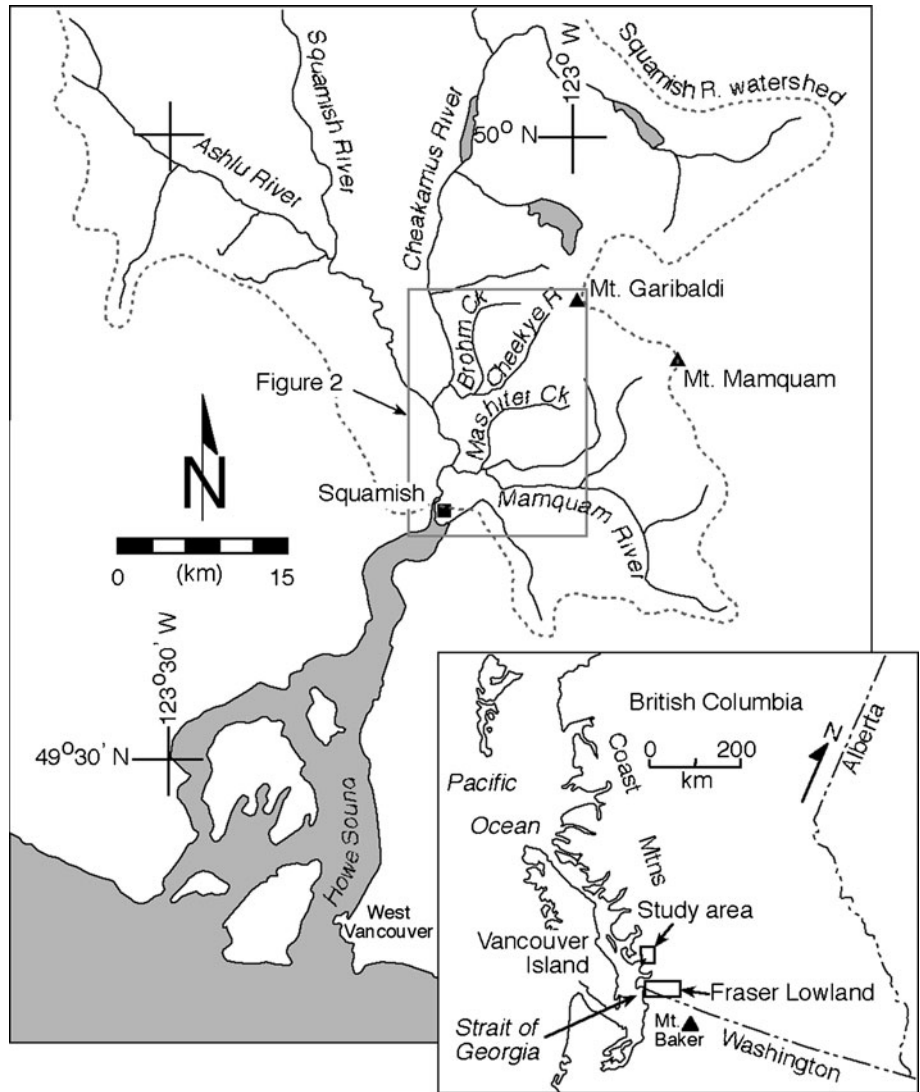
Methods

The two-dimensional hydraulic model FLO-2D (2004) was chosen to simulate debris-flow impact areas and intensities (maximum flow depth and velocity) on Cheekye Fan. FLO-2D is suited for this type of application as it can model unconfined flows across fan surfaces and simulate flows of varying sediment concentrations. It has been applied numerous times worldwide and is on the U.S. Federal Emergency Management Agency's list of approved hydraulic models.

FLO-2D is a depth-averaged volume conservation-based flood routing model that was developed specifically for the analysis of mud flows. Flow progression is controlled by topography and flow resistance. The governing equations include the continuity equation and the dynamic wave momentum equation. The debris-flow runout area is discretized using a rectangular grid, and the equations of motion are solved using a central finite difference scheme, in which the average flow velocity across a grid element boundary is computed one direction at a time, with eight potential flow directions.

Given an input hydrograph, FLO-2D routes debris flows as a fluid continuum using a quadratic rheologic model to simulate flow resistance as a function of sediment concentration. Remobilization of deposits cannot be simulated. A yield strength must be exceeded by an applied stress to initiate flow. FLO-2D models the total shear stress, τ , in hyperconcentrated flows and debris flows as a summation of five shear stress components: the cohesive shear stress (τ_c), the Mohr-Coulomb or frictional shear stress (τ_f), the viscous shear

Fig. 1 General study area location at the head of Howe Sound in southwestern British Columbia. The inset box is shown in detail in Fig. 2



stress (τ_y), the turbulent shear stress (τ_t), and the dispersive shear stress (τ_d):

$$\tau = \tau_c + \tau_f + \tau_v + \tau_t + \tau_d \quad (1)$$

When written in terms of shear rates (dv/dy), the following quadratic rheological model can be defined (O'Brien and Julien 1985):

$$\tau = \tau_y + \eta \left(\frac{dv}{dy} \right) + C_i \left(\frac{dv}{dy} \right)^2 \quad (2)$$

where τ_y is the yield strength, η is the dynamic viscosity and C_i is the inertial shear stress coefficient. The first term in Eq. 2 is the sum of the cohesive and frictional terms in Eq. 1. The first two terms in Eq. 2 are referred to as the Bingham shear stresses, which define the total shear stress of a debris flow in a viscous flow regime. The last term in Eq. 2 is the sum of the dispersive and turbulent shear stresses for

debris flows in the inertial flow regime. The depth-averaged form of Eq. 2 can be written as follows:

$$\tau_b = \tau_y + \frac{K\eta\bar{v}}{8h} + \frac{n^2\gamma\bar{v}^2}{h^3} \quad (3)$$

where τ_b is the total basal shear resistance opposing motion, \bar{v} is the depth-averaged flow velocity, h is the flow depth, γ is the bulk unit weight of the flow, K is a laminar resistance parameter and n is an equivalent Manning number that combines turbulent and dispersive effects. The local n -value is user-specified. The other resistance parameter values are estimated using the following relationships (FLO-2D 2004):

$$\begin{aligned} \eta &= \alpha_1 \exp(\beta_1 C_v) \\ \tau_y &= \alpha_2 \exp(\beta_2 C_v) \\ K &= 1460866n^{2.381} \quad (\text{for } 0.01 < n < 0.25) \end{aligned}$$

where α_i and β_i are empirical parameters and C_v is the volumetric sediment concentration, all of which must be specified by the user. Typical yield stress and viscosity

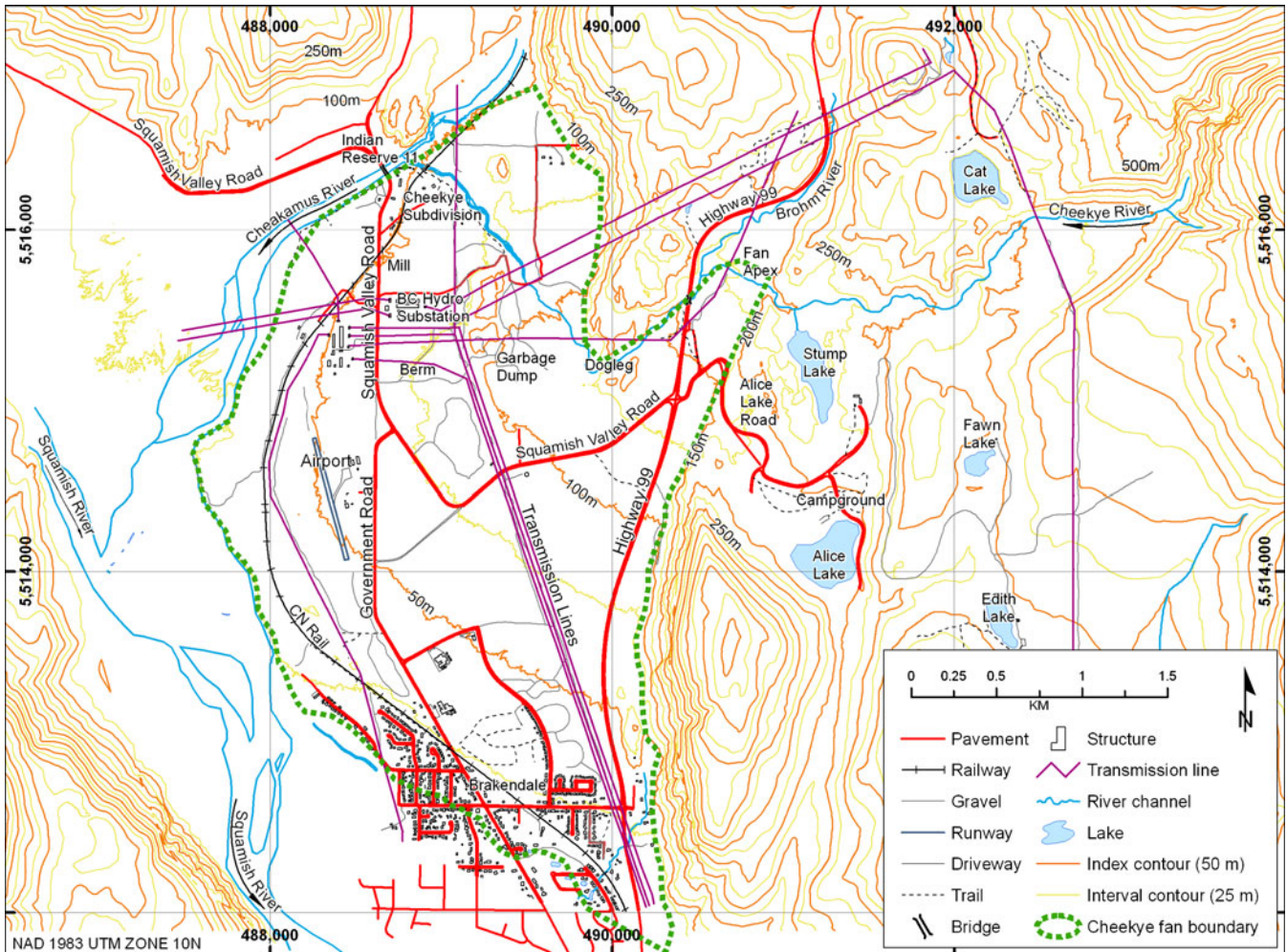


Fig. 2 Cheekye River fan with principal infrastructures and surrounding water bodies

parameter values have been estimated from laboratory experiments on samples of fine-grained mudflows in Colorado and have been supplemented with data from China (Table 9, p. 54 in FLO-2D 2004).

Results

Debris-flow model calibration

LIDAR imagery was flown in September 2006 and served as the model’s topographic input. The LIDAR points have a spacing of 1 point/m² and a relative vertical accuracy of +/-15 cm on well-reflecting surfaces. From these data, 1-m contours were interpolated and input to the FLO-2D model, and a 20-m square computational grid was generated.

Input hydrographs were based on the volume and peak discharge estimates summarized in Table 1. Hydrographs were created to match the desired volume and peak discharge based on previous frequency-magnitude analysis (BGC 2007a). Hydrographs were created with single surges (one peak) and multiple surges (several peaks) to test the sensitivity in runout distance and lateral spread. Trial runs indicated that there were no significant differences between model runs with one peak or multiple surges.

The FLO-2D manual (FLO-2D 2004) provides empirical input parameter values for flows with peak volumetric sediment concentrations up to 55 %. These data were obtained from mudflow deposits in Colorado. Volcanic debris flows may achieve higher sediment concentrations. For example, Jordan (1994) reports volumetric sediment concentrations of up to 80 % for volcanic debris flows in the Mount Meager area. Model trials with sediment concentrations exceeding 55 %, however, result in erroneous results with FLO-2D. The software developer Jim O’Brien (pers. comm., 2007) points out that sediment concentration relates to the fines (matrix) not the bulk sample. Therefore, a bulk sample measured from the flow itself would likely have a higher sediment concentration than 55 % due to the larger grain sizes. Mudflows used for calibration in the FLO-2D manual behave as Bingham fluids at low shear rates (<10s⁻¹) and are therefore unlikely to be representative of coarse non-liquefied bouldery or organic-rich surge fronts. This could imply that simulated flow velocities may be too high for some channel sections in which a coarser drained front could affect flow velocity.

Debris flows typically undergo different phases of flow during their descent, as entrainment of channel and bank materials may increase sediment concentration on the climbing limb of the

Table 1 Frequency–magnitude data for debris flows on Cheekye Fan

Return period (years)	Annual probability (1/years)	Volume (Mm ³)	Peak discharge (m ³ /s)
20	0.04	0.2	700
50	0.02	0.4	1,500
100	0.01	0.6	2,500
200	0.005	0.8	3,400
500	0.002	1.4	6,700
2,500	0.0004	2.4	12,600
10,000	0.00001	2.8	15,000

hydrograph. Decreasing sediment concentrations and hyperconcentrated afterflow are observed in the falling limb of the hydrograph once the initial surge front passes. Therefore, the debris flow will display phases with high sediment concentrations but low concentrations of fine particles (typically the initial surge) where dispersive stresses prevail, and fluid phases with dominantly turbulent stresses. FLO-2D accounts for changes in sediment concentration by allowing its specification for each unit time of the input hydrograph. In this study, sediment concentration was modelled to increase toward the peak of the hydrograph and decline on the falling limb. Maximum and minimum values of 55 to 10 % were input to the modelled hydrographs.

Without repeat testing of fresh debris-flow materials, ideally, during various flow phases, rheological parameters must be estimated from empirical data or back-calculated. For this project, we used a range of empirical coefficients based on values reported in the FLO-2D manual (FLO-2D 2004; Bertolo and Wiczorek (2005)). Table 2 summarizes the input parameters used in this study to represent debris flows with high, intermediate and low viscosities.

The high-viscosity scenario is based on the research of Bertolo and Wiczorek (2005), who modelled debris flows in Yosemite Valley with FLO-2D. These values were back-calculated to obtain the best match between observed debris-flow deposition and modelled results. Yosemite Valley is known for its very coarse granitic debris flows, which are likely to be characterized by a well-developed non-liquefied bouldery front. A high-viscosity model is therefore considered a fair approximation. The low-viscosity values are based on calibration of the runout distance of the Garbage Dump debris (see next section). The intermediate values fall between the upper and lower limits.

As shown in Eq. 3, flow resistance of the turbulent and dispersive shear stress components are combined in FLO-2D into an equivalent Manning's n -value for the flow. The n -value was

estimated as 0.10 for the vegetated fan surface and varied between 0.035 and 0.06 for the channel. Paved roads had an assumed n -value of 0.025.

To calibrate the model for additional runs, we simulated the Garbage Dump debris flow. The Garbage Dump debris-flow topographic surface was artificially removed from the LIDAR topography based on deposit depths determined in BGC 2007a, and the three viscosity scenarios listed in Table 2 were run. The goal was to recreate the approximate distribution, deposition depth and runout distance as observed in the field today. The total volume of the Garbage Dump debris flow was modelled as $2.1 \times 10^6 \text{ m}^3$ with a discharge of 12,000 m³/s and peak matrix sediment concentrations of up to 55 % (volumetric).

Figure 3a–c shows the output file for the low-, intermediate- and high-viscosity runs, respectively. The low-viscosity run approximates the Garbage Dump debris flow in terms of runout distance, but overestimates area inundated. It also distributes debris more evenly than observed for the original Garbage Dump debris flow. We attribute the lack of topographic match to the impossibility of being able to accurately replicate the fan topography 900 years ago and to the fact that FLO-2D is not able to simulate highly frictional flow fronts that lead to flow diversion. Because the Garbage Dump event was not observed on the southern fan sections, this model supports the assumptions made by BGC (2007a) that the channel in the vicinity of the Highway 99 bridge was significantly more incised at the time of the event. An alternative explanation could be that the Garbage Dump debris flow could have had a much lower peak flow rate and thus longer flow duration than the one modelled.

The intermediate- and high-viscosity runs show little difference in term of runout and area inundated but display disparate maximum flow depths in the channel upstream of the fan apex. These initial calibration runs are not entirely satisfactory with regard to replication of the Garbage Dump debris flow. The single-phase bulk rheologic model that was implemented cannot simulate flow avulsions that may be caused by a high friction flow phase.

For this reason, a two-phase flow was also simulated. Rather than redefining the mechanistic underpinnings of the model (i.e. changing from a quadratic flow model to a Coulomb frictional model to simulate the highly frictional flow phase), we use the principle of equivalent fluids. In this instance, we applied the high-viscosity parameter combination (Table 2) and separate flow hydrographs to the more frictional flow phase and the low-viscosity parameter combination to the more liquid afterflow (Fig. 4). The flow volumes were split according to the distributed volumes as mapped in the field and calculated by interpolation. The same principals were applied in forward looking model runs. Table 3 summarizes the modelling assumptions.

Table 2 Empirical coefficients used for FLO-2D debris-flow modelling

Scenario	Viscosity coefficient (α_1)	Viscosity exponent (β_1)	Yield stress coefficient (α_2)	Yield stress exponent (β_2)
High viscosity	2.7	11.0	0.05	14.5
Intermediate viscosity	1.0	11.0	0.1	15.0
Low viscosity	0.13	12.0	2.7	10.4

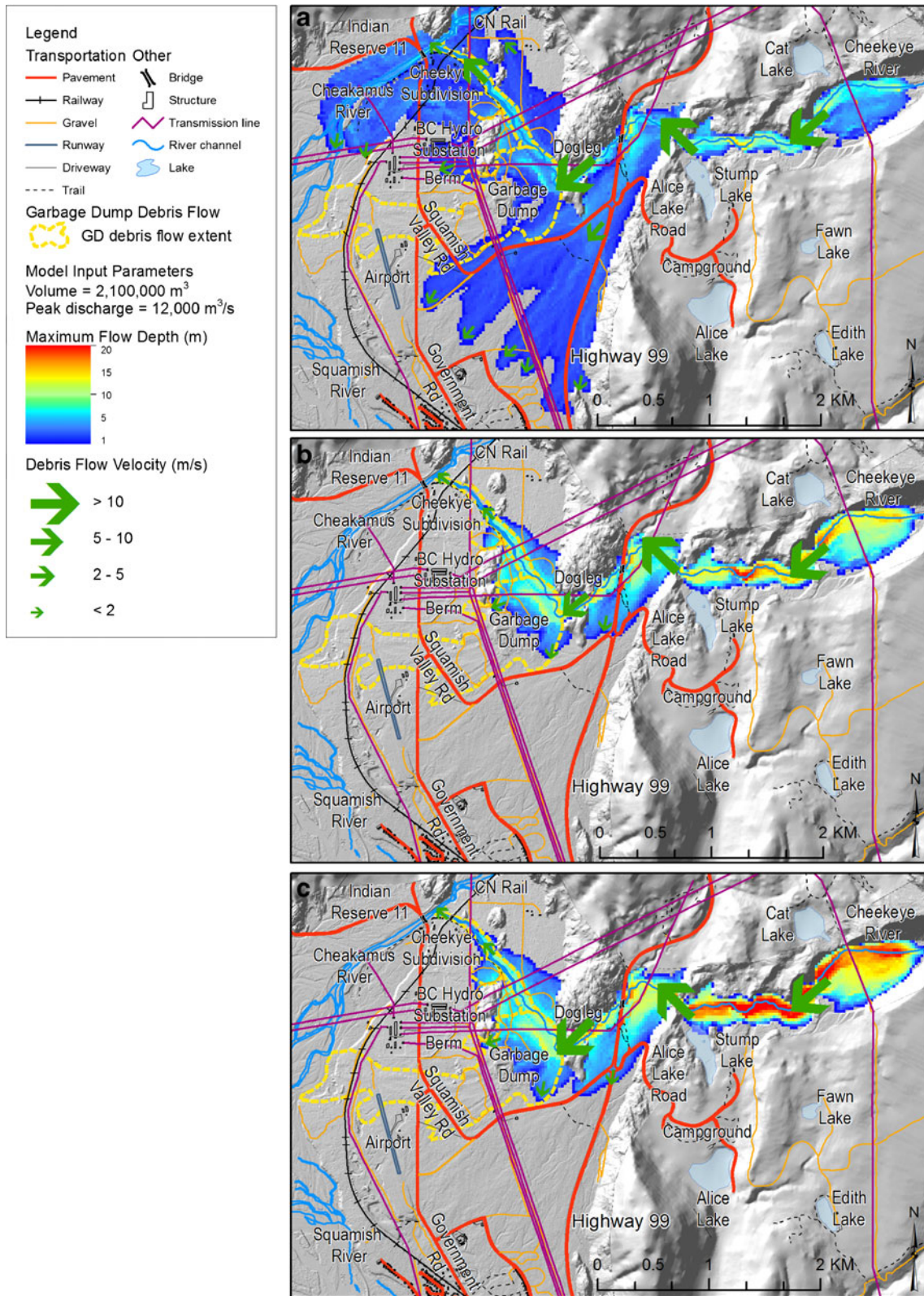
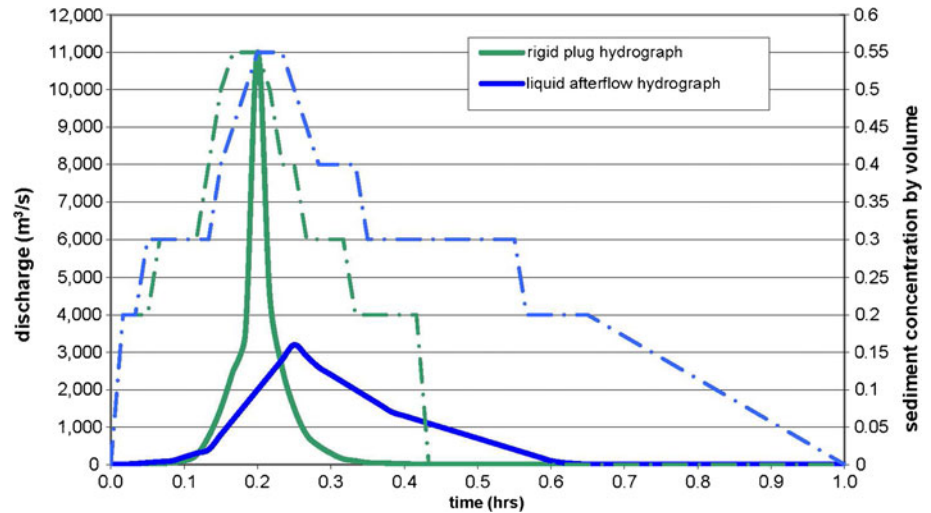


Fig. 3 Simulated low-, intermediate-, and high-viscosity debris-flow runout scenarios on Cheekye Fan for the Garbage Dump debris flow

Peak discharge for the high friction flow phase and afterflow phase of the debris flow was calculated using Eqs. 6 and 7, respectively. The former equation is applicable for bouldery debris flows found in Southern BC, while the

Fig. 4 Artificially created debris-flow hydrographs for a two-flow phase simulation of the Garbage Dump debris flow. The *solid lines* indicate the simulated peak discharge for the high-viscosity (rigid plug) and low-viscosity (liquid afterflow) phases. The *dashed line* indicates the assumed sediment concentrations for both flow phases



latter is representative of volcanic debris flows (Bovis and Jakob 1999).

$$Q_p = \left[\frac{V}{28} \right]^{0.9} \quad (6)$$

$$Q_p = \left[\frac{V}{343} \right]^{1.01} \quad (7)$$

where Q_p is peak discharge (cubic metre per second) and V is total sediment volume (cubic metres).

The volumes of the high friction flow phase and the more liquid afterflow do not sum to the total volume of 2.1 million m^3 as reported in BGC (2007a). The difference is explained by portions of the afterflow having likely descended down the existing channel of Cheekye River. This portion (estimated as 0.2 million m^3) was not modelled separately because it remained largely confined to the former channel of Cheekye River, which then spilled into Cheakamus River. The model of the high friction flow phase was started immediately upstream of the dogleg; the model for the afterflow was started southwest of the dogleg to ensure that the flow followed approximately the pre-existing topography.

Debris-flow matrix volumetric sediment concentrations ranged between 20 % and 50 % on the rising and falling limbs of the high friction flow phase hydrograph, with peak concentrations of 55 %. The shape of the hydrograph was purposely chosen to be very steep for the rising and falling limbs of the highly frictional flow phase. Based on the input parameters of Table 3, modelling results for the two-phase debris flow are shown in Fig. 5. The two-phase modelling results provide an overall better-fit to the observed depositional pattern of the Garbage Dump debris flow. The extent of inundation is greater for

the simulated flows, but it is expected that some areas would get inundated without much deposition occurring. Furthermore, it is not possible to create an exact replica of the 900-year BP fan, and some deviation in flow direction and deposition pattern are expected.

It should be recognized that the modelled Garbage Dump debris flow under the two-phase scenario may not be representative of all future flows. Depending on source area rocks, peak discharge–volume relationships and sediment concentration, flow rheology may differ substantially from the calibrated case.

Predictive model runs

The number of model runs is dictated by the objectives of the debris-flow hazard and risk assessment. In this instance, it was desirable to determine existing risk over a large spectrum of return periods, and secondly, to identify the return period range that is successfully mitigated by a range of engineered mitigation structures. Mitigation scenario, however, are not included in this paper as these are still under review. Using a low-viscosity scenario (Table 2), debris flows were simulated for the 20-, 50-, 100-, 200-, 500-, 2,500- and 10,000-year return period events using the existing fan topography. Figures 6, 7 and 8 show the model results for the 50, 500 and 10,000-year return period events. The principal interpretations from these model runs are summarized as follows:

- All events are likely to reach Cheakamus River.
- The 20-year event will likely remain fully channelized in Cheekye River until it reaches Cheakamus River. Avulsion downstream of the fan apex is possible if a high friction flow phase were to form of organic materials or coarse bouldery debris that cannot be modelled adequately (Fig. 5).
- Events including and exceeding the 50-year return period will likely spill out of the channel upstream of Highway 99 and flow toward the south (Figs. 7 and 8).

Table 3 Input parameters for the simulated two-phase Garbage Dump debris flow

Flow phase	(α_1)	(β_1)	(α_2)	(β_2)	Total volume (m^3)	Peak discharge (m^3/s)
Frictional front	2.7	11.0	0.05	14.5	900,000	11,000
Afterflow	0.13	12.0	2.7	10.4	1,000,000	3,200

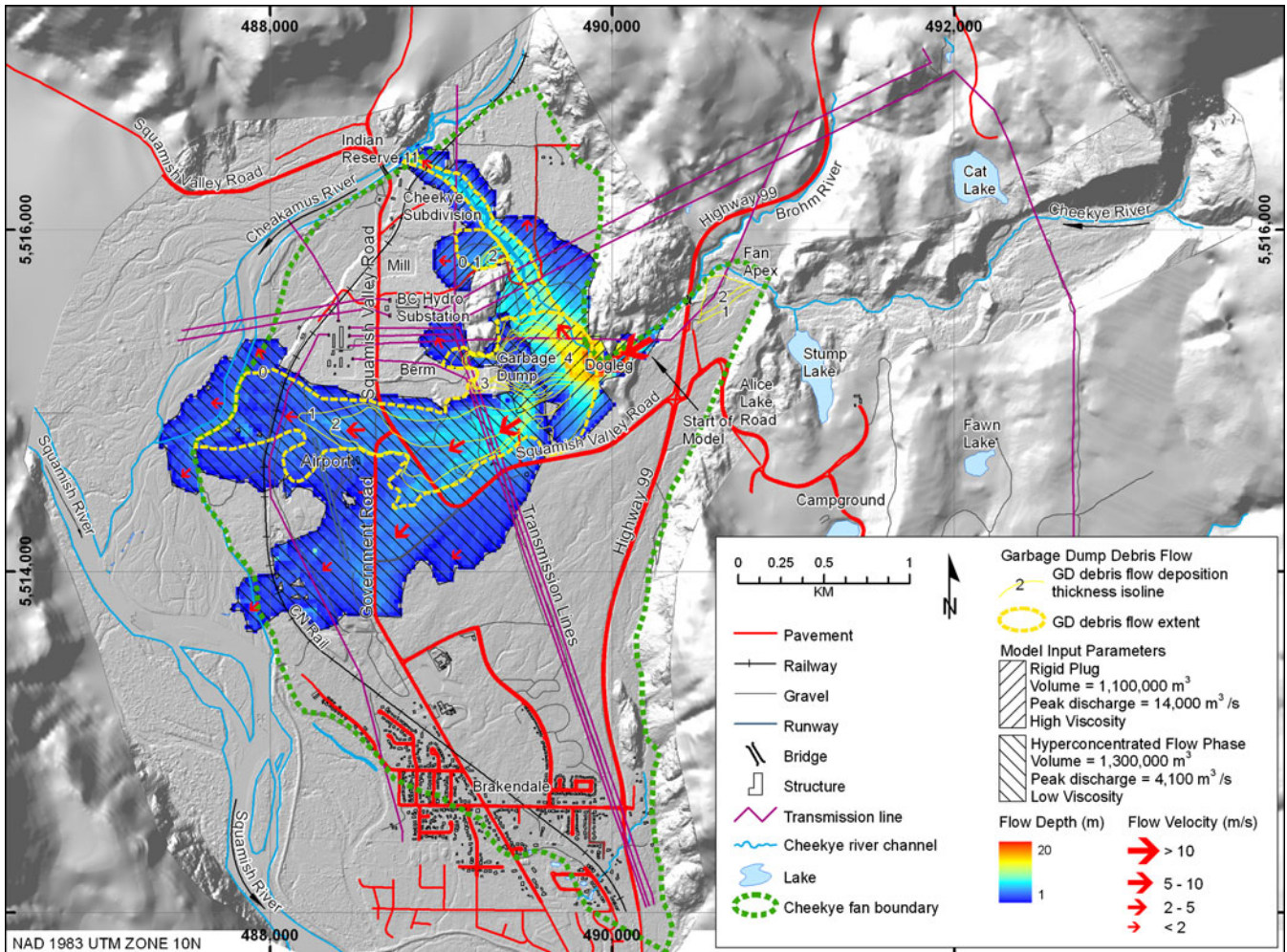


Fig. 5 Debris-flow runout modelling results for the two-phase Garbage Dump debris flow run based on pre-event topography

- Events exceeding the 50-year return period are increasingly likely to destroy the Highway 99 bridge as well as the CN Rail bridge.
- Events exceeding the 50-year return period are likely to dam Cheakamus River for periods ranging from hours to days. The landslide dam will be long in downstream direction and likely not more than 3 to 6 m deep.
- Flows exceeding and including the 500-year return period will likely affect buildings of I.R. 11 to the northwest of Cheakamus River.
- Events exceeding the 50-year return period are likely to avulse from the lower channel sections downstream of the Dogleg and impact portions of the existing Cheekye subdivision.
- For flows avulsing at the fan apex, lower flow resistance on roads will allow debris to travel down Highway 99 toward the south and Squamish Valley road toward the southwest.
- The 2,500-year and 10,000-year events are likely to impact northern portions of Brakendale, though flow depths and flow velocities may be low enough to prevent structural damage. Flow could also avulse into Alice Lake Park by the flow overwhelming the sill separating Stump Lake from the Cheekye River drainage. Water from Stump Lake could be displaced towards the south.

Four additional scenarios were modelled using the 2,500-year and 10,000-year return period events. In the first two scenarios, the 2,500-year (2.4 million m³) and 10,000-year return period events (2.8 million m³) were forced to avulse at the Highway 99 bridge, a scenario that is considered possible. A high-friction flow phase was assumed to arrest largely at the bridge flow constriction, thus forcing the afterflow to discharge onto the central and southern fan portions. Substantial flow to the north is not possible since it is uphill. The second model run allowed the debris flow to follow the channel to the Dogleg, where a high friction flow front deposited (similar to the GD debris flow). The less viscous afterflow then bypassed the deposited lobe to the south. Input parameters for these two scenarios are summarized in Tables 4 and 5.

Different viscosity and yield stress parameters were used for simulation of a high-friction flow phase forming at the fan apex than those applied to the corresponding flow phase of the Garbage Dump debris flow and the second model run for a high frictional flow front at the dogleg under existing topography. A much more viscous flow was required at this location to simulate deposition and the damming of the Highway 99 bridge. Input parameters were adjusted by trial and error to force flow towards the southern and central fan portions.

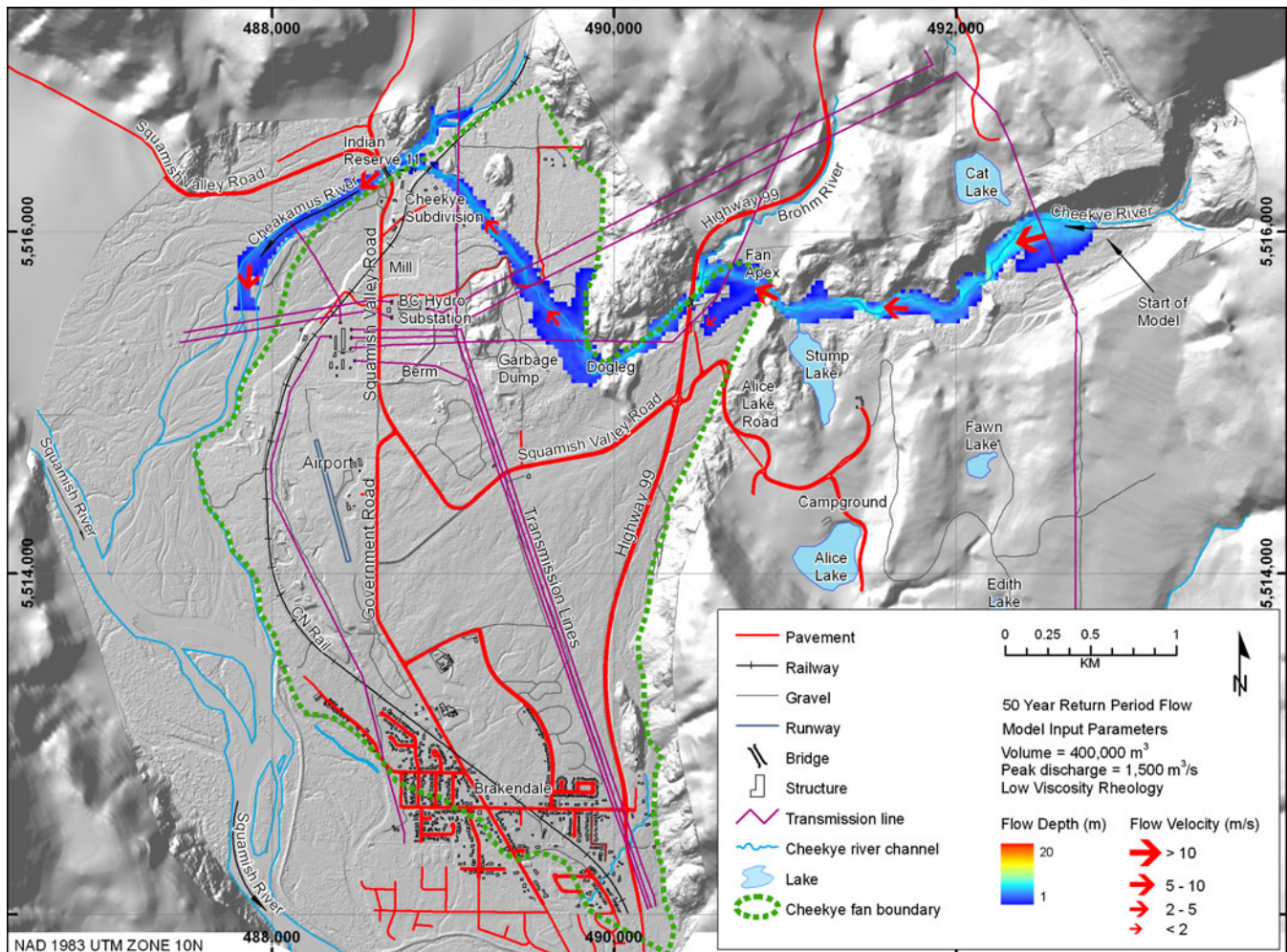


Fig. 6 Debris-flow runout modelling results for a 50-year return period debris flow. The model was stopped some 1 km downstream of the Cheekye River and Cheakamus River confluence

Model results for the avulsion-at-fan-apex scenario and avulsion-at-dogleg scenario for the 10,000-year return period debris flow are shown in Figs. 9 and 10. These scenarios are considered the most likely outcomes under existing conditions, though a large number of variations are possible. Figures 9 and 10 illustrate that, in the event of a high friction flow front forming near the fan apex and deflecting a large portion of the liquid portion of the debris toward the south and southwest, debris would likely impact large portions of Brakendale as well as inundate Highway 99 from the Cheekye River bridge to the southern fan margin and the CN Rail tracks through Brakendale. Applying some judgment and comparing the modelled flow depth to the observed deposit thickness of the Garbage Dump debris flow, inundation may range between several centimetres at the most distal portions of the runout to approximately 1 m in the inhabited portions of Brakendale, with higher flow depths in local depressions. According to the model simulations, flow velocities in the distal fan areas could range between 1 and 3 m/s.

Figure 10 shows that the high friction flow phase at the Dogleg would divert much debris towards the southwestern fan sector, but large amounts of debris would likely still reach Cheakamus River and impact the Cheekye Subdivision.

The liquid afterflow would reach the northern portions of Brakendale with some of the flow discharging into Squamish River west of the airport. The B.C. Hydro corridor, Squamish Valley Road and Government road would be inundated as shown, as well as CN Rail between Brakendale and the airport. Inundation depths and flow velocities in the inhabited area of Brakendale would likely be similar to those for the fan apex avulsion scenario.

Fans generated by debris flows are dynamic landforms in which fluid landslide hazard is likely to shift over time as some portions of the fan abruptly aggrade, while others are scoured through fluvial erosion over time. In the case of Cheekye River fan, very high return period flows may shift fan activity from the northern fan sector back to the southern fan portions. All of the predictive analyses shown here are based exclusively on the existing fan topography.

Previous sections discussed some of the uncertainties that stem from rheological considerations inherent in FLO-2D. The following section addresses additional uncertainties that are based on experience and geomorphic considerations. A discussion of these uncertainties is warranted to avert the illusion of exactness that numerical models may suggest.

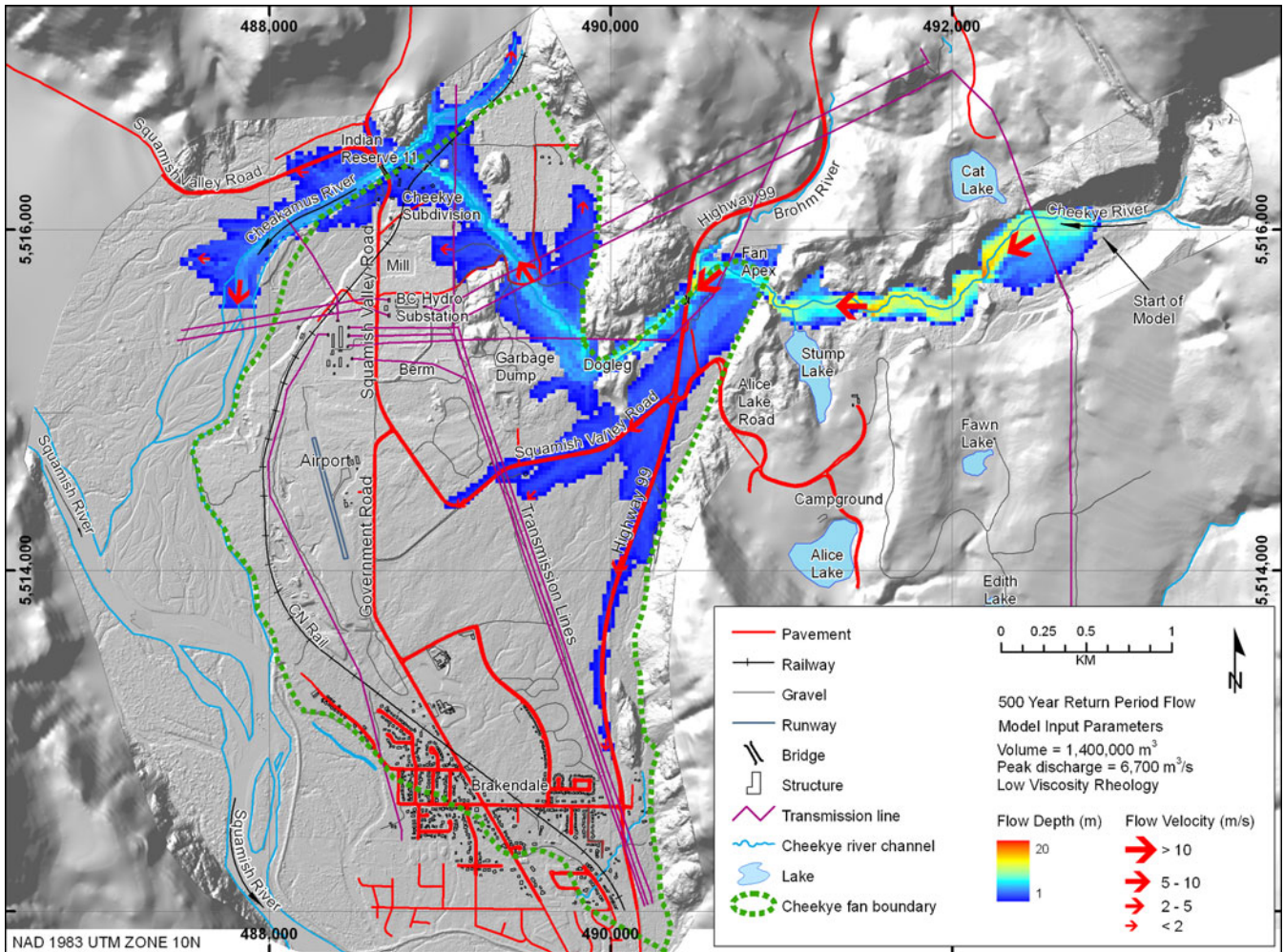


Fig. 7 Debris-flow runout modelling results for a 500-year return period debris flow

Discussion

Debris-flow modelling has been subject to ever increasing research and scrutiny over the past 10 years. While this paper does not discuss the various debris-flow models that have developed, some discussion of the validity of debris-flow models is appropriate to better understand their strengths and limitations.

Identification of an appropriate debris-flow rheology has been regarded as a key to the modelling and prediction of debris-flow characteristics and behaviour, leading to a debate on the most appropriate rheological formula (e) to be used. Contrasting this focus on a single rheological model are field observations that have proven that a single rheology cannot satisfactorily describe the range of mechanical behaviour exhibited by debris flows. Field observations and flume experiments suggest that rheologies vary temporally, spatially and exhibit feedbacks that depend on evolving debris-flow dynamics (summarized by Iverson 2003):

- Debris-flows originate from single- or multiple-source areas in which loose debris is suddenly mobilized through introduction of surface or groundwater, or due to an abrupt increase in pore water pressures through undrained loading or perhaps seismic events. Debris liquefies through loading or frictional failure

and begins to mix with water and entrain additional debris until a certain volumetric sediment balance is achieved.

- Steep surge fronts often form at the heads of debris flows and secondary surges develop behind the leading front. Coarse debris or organic debris in the form of trees and root wads accumulates at the surge front due to particle size segregation and migration, or frontal entrainment or boulders or falling trees. The surge fronts advance mostly by sliding and tumbling rather than fluid-like flow with coarse particles being lodged to the sides and upwards. The typically more fluid afterflow (hyperconcentrated flow) provides momentum to the bouldery front and also resupplies it with additional water through turbulent mixing in addition to basal streamflow entrainment.
- Lateral flow levees form along channel margins and on the fan because the coarse-grained debris at the surge front pushes sediment to the side where higher friction encourages deposition.
- Depositional lobes form where frictional resistance imposed by coarse-grained flow fronts and margins is sufficient to halt the more fluid afterflow, or where interstitial water can readily drain from unconfined flow areas.
- Fresh debris-flow deposits, particularly those with a high content in clay and silt, remain in an unstable saturated state for

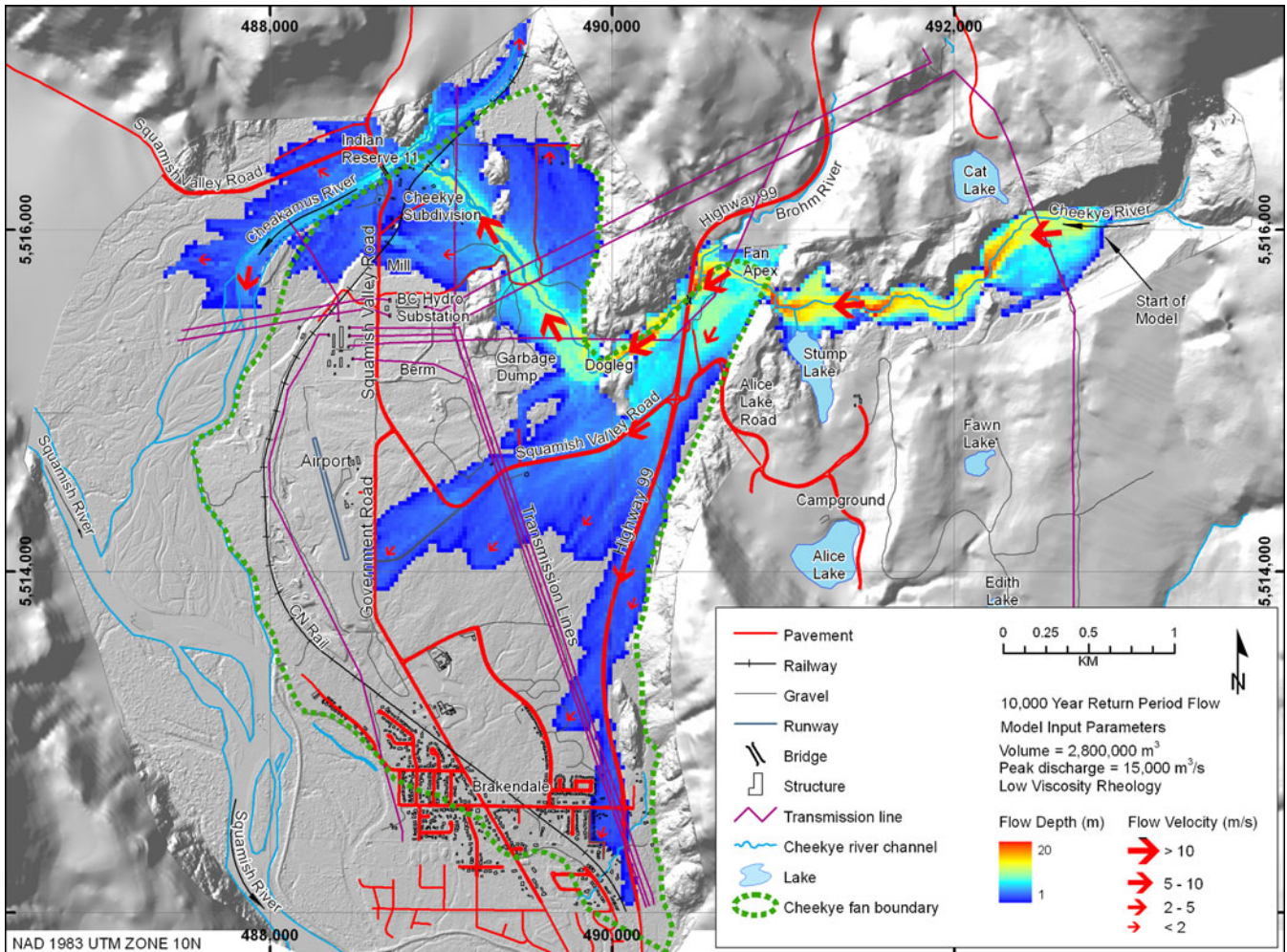


Fig. 8 Debris-flow runout modelling results for a 10,000-year return period debris flow

some time after which they consolidate through progressive pore water loss.

In addition to field observations during and after debris-flows flume experiments (Iverson 1997), it can be stated that:

- Basal pore-fluid pressure nearly equal to the basal total normal stress persists during motion and deposition suggesting full liquefaction. Liquefaction commences due to sudden contraction of water-filled pores during debris-flow initiation.
- The high porosities and permeability of debris-flow surge fronts allows dissipation of pore pressures below those necessary for liquefaction. The flow separation into liquefied and

unliquefied portions thus precludes specification of a single rheological model.

- High fine content promotes greater debris-flow runout distance, as it inhibits pore pressure dissipation and allows transient liquefaction to persist longer than for coarse-grained debris flows.
- Pore fluid pressure and grain agitation (“granular temperature”) influence the apparent rheology of debris (Iverson and Vallance 2001).

All of the above observations indicate that a single rheologic model is unattainable because non-hydrostatic forces cannot exist in steady states. More advanced models, such as the Coulomb

Table 4 Input parameters for the simulated two-phase 2,500-year return period debris flow (2.4 Mm³)

Scenario	Flow phase	(α_1)	(β_1)	(α_2)	(β_2)	Volume (Mm ³)	Peak discharge (m ³ /s)
Fan apex avulsion	High friction	2.0	17.0	0.0345	24.0	1.1	14,000
	Afterflow	0.13	12.0	2.7	10.4	1.3	4,100
Dogleg avulsion	High friction	2.7	11.0	0.05	14.5	1.1	14,000
	Afterflow	0.13	12.0	2.7	10.4	1.3	4,100

Table 5 Input parameters for the simulated two-phase 10,000-year return period debris flow (2.8 Mm³)

Scenario	Flow phase	(α_1)	(β_1)	(α_2)	(β_2)	Volume (Mm ³)	Peak discharge (m ³ /s)
Fan apex avulsion	High friction	2.0	17.0	0.0345	24.0	1.2	15,000
	Afterflow	0.13	12.0	2.7	10.4	1.6	5,100
Dogleg avulsion	High friction	2.7	11.0	0.05	14.5	1.2	15,000
	Afterflow	0.13	12.0	2.7	10.4	1.6	5,100

mixture theory (Iverson 1997), strive to account for unsteady flow behaviour. While it is realized that the mathematical representation of rheology is likely inadequate, finding a reasonably realistic representation of the underlying flow physics lies at the heart of modelling complex geophysical processes, at least until such time as better formulated alternatives are available to practitioners.

Yield strength

Yield strength is an important input parameter in debris-flow models including FLO-2D. Reported yield strength values have focused on

the fine-grained “matrix” component of debris flows, which can readily be sampled (e.g. Kang and Zhang 1980; O’Brien and Julien 1988; Phillips and Davies 1991; Major and Pierson 1992; Coussot and Piau 1995; Locat 1997; Parsons et al. 2001). Yield strength varied between 10 and 400 Pa in these studies. However, these published values are not consistent with the governing equations of debris-flow models. For example, using a one-dimensional static limit-equilibrium equation ($\tau = \rho g h \sin \Theta$) on slopes $> 5^\circ$ indicates that debris thickness should be less than 0.2 m for the published yield strength values (Iverson 2003). In contrast, debris-flow deposits in excess of 5 m are observed on the Cheekye Fan. Back-calculating yield strength for typical values

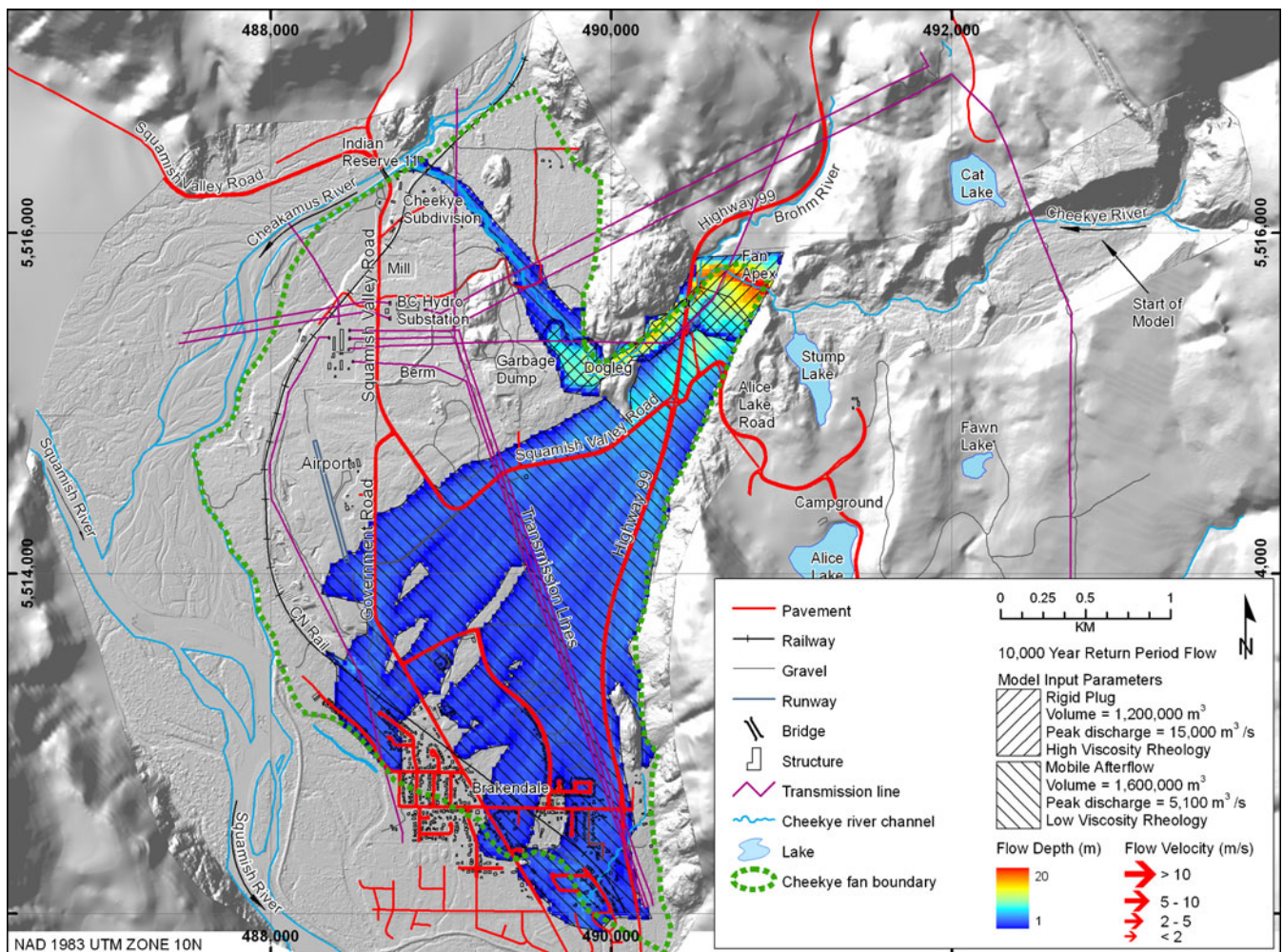


Fig. 9 Debris-flow runout modelling results for a 10,000-year return period debris flow artificially avulsed near the fan’s apex

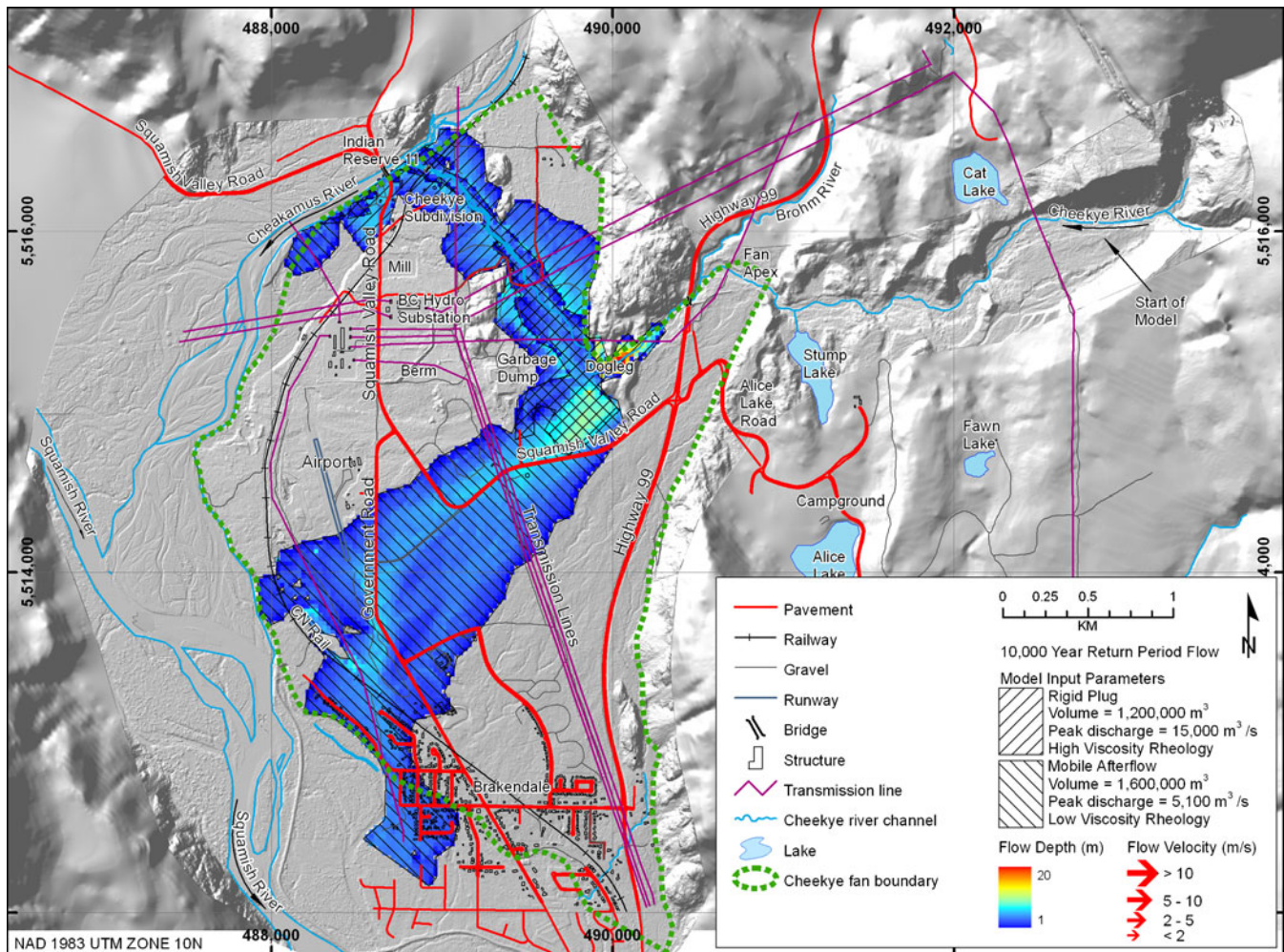


Fig. 10 Model results for the avulsion-at-dogleg scenario for the 10,000-year return period debris flow

on the Cheekye Fan ($\rho=2000 \text{ kg/m}^3$, $h=1-5 \text{ m}$, $\theta=1-5^\circ$), results in a range of 340 to 8,500 Pa.

Criticisms of debris-flow models have also focused on the use of fixed-yield strength values, which place limitations on debris-flow rheology. The issue lies with the temporal and spatial transience of influencing factors such as pore water pressures. Poorly or unsorted debris-flow materials gain most of their strength from intergranular friction proportional to intergranular normal stress and not from yield strength as a rheological property. Therefore, yield strength varies as debris-flow thickness, and particle size varies in time and space during flow. A fixed yield strength value would only be valid if a debris-flow consisted of a homogeneous liquefied sediment mixture. The central question to rheologically based modelling is therefore whether the temporal and spatial-dependency of yield strength can be ignored, or if its transiency will render modelling results useless.

Viscous stress and rate dependency

Debris-flow models such as FLO-2D often include a static functional relationship between shear resistance and shear rate. The Bingham model assumes a linear relation between shear stress and shear rate. Bingham models fitted to muddy slurries typically yield

viscosities between 0.1 and 50 Pas. If such viscosities are multiplied with typical debris-flow shear rates ($<10 \text{ s}^{-1}$), resulting resisting stresses are in the order of 500 Pa. The implication is that shear stresses at the largely drained, highly frictional front of a debris flow may be an order of magnitude higher than the liquefied debris mass following the coarse debris-flow front. It is then of interest how this flow front exerts influence on the rest of the debris flow. To answer this question, it is worth examining an observed case. This comparison may allow a conclusion as to whether differences in shear stress between the flow front and the trailing flow can be ignored or if their neglect could lead to significantly different model outcomes.

Observed flow behaviour

With regard to modelling, hazard and risk analysis, the large (lower return period) flows become increasingly important as they yield a higher damage potential. Therefore, the Garbage Dump debris flow may serve as a good example of whether spatial and temporal fluxes in flow rheology affect flow behaviour and thus may affect modelling results.

The distribution of sediments on the Cheekye Fn is discussed in Jakob and Friele (2010), including the areal extent of the Garbage Dump debris flow. We assume that the principal channel at

the time of this debris flow followed the main depositional lobe. Evidence for this assumption includes older channel deposits observed along this alignment. The GD debris flow appears to have occurred in at least two stages. The first stage appears to have been a coarse primary surge with a significant number of trees and large boulders. These elements were observed in abundance during a test pitting program conducted in 2006. This surge is likely responsible for the large well-defined lobe that is up to 6 m thick below the Dogleg (Fig. 2). The lobe thins abruptly on its margins except for the principal tongue that can be traced to Squamish River. It is presumed that this first surge front was highly frictional due to a higher concentration of boulders and trees in an area where flow confinement was suddenly lost (the Dogleg). At this moment, the front may be best described by a Coulomb friction model with high resisting stresses. This surge front likely blocked portions of the modern channel, which may have been a minor branch of the main channel. Deposition of the surge front also diverted the liquefied afterflow toward the central fan portion (Fig. 2). This liquefied afterflow would likely have significantly lower resisting stresses. Typical grain sizes found in this tongue are less than 200 mm in diameter. As the deposit further thinned, yield strength values may have dropped below 100 Pa. At this stage, grains were typically less than 100 mm in diameter and were suspended in a muddy matrix. This deposit was traced to Squamish River where it was likely quickly entrained by streamflow.

This example illustrates the temporal and spatial variability of debris-flow behaviour, which will affect model outcomes. In particular, it is impossible to predict where and when a coarser organic debris lobe may deposit and divert the hyperconcentrated afterflow because of some randomness in the spatial and temporal flow behaviour as well as the potentially changing channel geometry during the flow. Irrespective of the numerical model used, these developments cannot be reliably simulated, and geoscientific judgment must be applied in anticipating these changes in flow behaviour. With respect to debris-flow mitigation, sudden deposition of a coarse bouldery and/or organic-rich flow front should be anticipated, unless mitigation aims towards stopping the initial surge or surges, which lowers the probability of sudden changes in flow direction.

Several additional sources of uncertainties exist that cannot readily be modelled. They are discussed to understand the repercussions and effects on flow behaviour. Brohm River, which joins the Cheekye River from the right bank near the fan apex, would be temporarily backed up or completely dammed by most modelled debris flows. Debris flows with return periods of 20 to 500 years would likely occur during very wet weather, as it is presumed that those events are triggered by prolonged heavy rain, and thus would occur at a time of high discharge on Brohm River. Blockage would likely be limited to higher return period flows (>200 years) and to less than 1 h since the Brohm River drainage upstream of the confluence is steep and only about 30,000 m³ water could be stored. As the temporary debris dam is overtopped or fails, debris-flow material deposited in the Cheekye River channel would likely be re-entrained, perhaps leading to a series of secondary hyperconcentrated flow surges. This process is difficult to model but could lead to additional hazard in the form of surge waves overrunning deposited debris along the channel, thus increasing the likelihood of avulsions and extending the runout distances in some downstream fan sectors.

For scenarios where debris flows do not dam Brohm River (likely for return periods <200 years), Brohm River could add significant water volumes to Cheekye River debris flows. This process of flow dilution towards a lower sediment concentration could change flow behaviour from mostly laminar to increasingly turbulent. This effect could slow the flow or, if the sediment concentration of the debris flow was very high, could accelerate the flow by adding mobility. The high water discharge would also aid in mobilizing or incising into channel debris during the falling limb of the debris-flow hydrograph. A complete blockage of the area near the confluence is conceivable if the narrow bedrock canyon at the Highway 99 bridge is blocked by large trees that are likely to be introduced when channel banks are undercut and collapse into the channel. In this case, it is conceivable that water from Brohm River could be diverted across the deposit and towards the south.

Conclusions

This work attempted to simulate past and future debris flows on a large fan complex in southern British Columbia for return periods from 20 to 10,000 years. This work was completed to provide debris-flow intensity parameters for future flows that can then be entered into a quantitative risk assessment for loss-of-life. A key issue to be considered in the reliance of the simulations for risk assessments and ultimately development planning is whether a rheological model, such as the model used in FLO-2D, can be regarded as an equivalent fluid to the actual debris flows. The question arises if the debris flow can be treated as a continuously liquefied slurry if gravitational normal stresses affecting friction in unliquefied parts dominate or affect flow behaviour. Spatial and temporal fluxes in shear stress and yield strength are likely, and a single rheological model is considered inadequate to represent the entire spectrum of mechanics during a debris flow. Alternative approaches such as presented by Hutter et al. (1996) and Iverson (1997) use Coulomb mixture theory that describes the behaviour of debris-flow mixtures from the onset of motion through deposition and post-depositional consolidation. However, Iverson (2009) points out that even those models fall short of allowing for particle segregation, a well-known characteristic of bouldery debris flows. In the absence of commercially available models that have mastered multiphase flow, a single-rheology model can still yield usable results, but only if the model has been well calibrated and the model output compared with evidence encountered and documented in the field. This includes runout distance of debris flows, deposit thickness and rheology as discerned by observation of the deposit's grain size distribution and flow spread. Ultimately, the exact mathematical representation of flow behaviour is perhaps less important than a realistic and replicable representation of observed or back-calculated flow runout and deposition characteristics.

Given the high flow depths of higher return period flows and the typically high fines content of volcanic debris flows (which limits shear stresses due to frictional effects), we assume that the quadratic model is an adequate bulk rheological representation of flows on Cheekye Fan. Recent work has confirmed that the quadratic shear stress model used in FLO-2D appears to be a reasonable approximation for observed debris flows elsewhere (Bertolo and Wiczorek 2005; Cetina, et al. 2006).

Deviations from modelled flows can occur due to temporary dam formations, blockage by log jams or sudden scour of unconsolidated debris-flow deposits during further debris-flow surges. Irrespective of the rheological model used or other advanced

approaches, these events are largely random and cannot be modelled. Geoscientific judgment is required to incorporate these scenarios into an overall hazard assessment.

The well-studied Garbage Dump debris flow was simulated to obtain a well-calibrated base model that yields variables that can be used for modelling over a wide range of magnitudes. The Garbage Dump debris flow appears to have occurred as a two-phase flow with a high friction flow front consisting of a higher boulder concentration and a higher concentration of trees being followed by a more fluid afterflow that was diverted by the earlier deposition of the plug. This flow behaviour may be characteristic of future flows, and the two flow phases were thus modelled separately. Uniting the two model runs demonstrates good agreement between the observed Garbage Dump debris-flow extent and the modelling results. To account for the high friction front behaviour identified in the Garbage Dump debris flow, we also modelled two additional two-phase scenarios for the 2500- and 10,000-year return period debris flows with high friction flow fronts forming at the fan apex and at the Dogleg under existing topographic conditions. More fluid afterflow was then allowed to flow south past the flow constriction. These results are instructive to assess current hazard on Cheekye Fan but are unlikely to be representative of flows under mitigated scenarios when the highly frictional flow phase would be captured by proposed mitigation measures.

Debris flows were modelled for return periods of 20 to 10,000 years using low viscosity variables for the hyperconcentrated afterflow phase. Flows exceeding the 50-year return periods will likely avulse and lead to damage in existing subdivisions, avulse onto Highway 99 and will affect CN Rail. Flows with return periods of several thousand years could affect the existing community of Brakendale. The model's output variables in the form of flow velocity, area inundated and flow depths were used in subsequent quantitative risk assessments (BGC 2007c).

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