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Assessment of Mitigation Alternatives for Cheekeye Fan

Final Report
April 2016
KWL Project No. 463.311

Prepared for:

SQUAMISH

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1. Introduction

1.1 Project Purpose

The Cheekeye Fan is a significant topographic feature near Brackendale, BC within the District of Squamish. The fan was formed over geologic time by debris flows originating on the flanks of Mount Garibaldi and propagating down the Cheekeye River. Over the past several decades, development has encroached onto the margins of the Cheekeye Fan. Two expert panels have concluded that the risk posed to existing development by debris flows on the Cheekeye Fan is unacceptable.

Kerr Wood Leidal Associates Ltd. (KWL) has been retained by the District of Squamish to review mitigation alternatives that could be considered to protect development and infrastructure on the Cheekeye Fan.

This report provides the following content:

- summary of relevant background information;
- identification of a broad range of mitigation alternatives that could be considered;
- discussion of local issues that may be important in selecting a mitigation alternative;
- development of a framework for evaluating mitigation alternatives;
- application of the framework to evaluate the identified mitigation alternatives;
- identification of the most promising mitigation alternatives (based on the evaluation); and
- future considerations for the District in moving forward.

The primary purpose of this report is to identify the most promising mitigation alternatives that could provide an appropriate level of protection to existing development and infrastructure, and comprise the primary components of a comprehensive mitigation plan.

Any promising mitigation alternatives identified in this report should be subjected to a greater level of investigation to confirm technical feasibility, define project components, provide construction cost estimates, develop a suitable implementation plan, and address long-term operation and maintenance issues. Subsequent investigation would also be appropriate to support a final decision to proceed with a preferred mitigation alternative.

At the time of this report, a large tract of land on the Cheekeye Fan, immediately north of Brackendale, is proposed for a major new development (“the proposed new development”) by BMS Cheekeye One Projects. This report is prepared with some knowledge that the proposed new development is contemplated, but does not constitute a “review” of the proposed new development or its associated proposal for debris flow risk mitigation.

This report does outline some future considerations for the District in moving forward with measures to appropriately mitigate the Cheekeye Fan debris flow hazard, under the scenarios of the land development project both proceeding and not proceeding.

While this assessment is focussed on debris flow hazards, some parts of the hazard area may also be affected by other natural hazards such as clear-water or debris floods on the Cheekeye River, Cheekeye River avulsion caused by sedimentation, groundwater flooding (caused by sub-surface hydraulic connectivity), and/or flooding from adjacent rivers. To be “acceptable” in the context of safe land use for communities, the total risk from all sources of hazard should be combined and considered together.

As a comprehensive mitigation plan for the Cheekeye Fan is developed, there will also be a need to ensure that any debris flow mitigation initiatives are compatible and consistent with the Squamish Integrated Flood Hazard Management Plan that is underway as of the time of this report.

1.2 Study Area

This report uses the spelling “Cheekeye” which is the traditional spelling used by the Squamish Nation. Other documents use the spelling “Cheekye”.

The Cheekeye River watershed is shown by Figure 1-1. The Cheekeye River drains a steep watershed that is approximately 64 km^2 in area.

The Cheekeye River headwaters include Mount Garibaldi and Atwell Peak. Steep slopes in the upper watershed produce periodic landslides and rock avalanches. In prolonged wet weather periods, such events may trigger large debris flows that discharge down the river to the fan. The Cheekeye River also produces debris floods and floods, and has a high rate of sediment transport.

On the fan, the Cheekeye River flows under the Highway 99 Bridge, and discharges to the Cheakamus River upstream of the Squamish Valley Road bridge. The Cheakamus River discharges to the Squamish River, which in turn discharges to Howe Sound.

The Cheekeye Fan is shown by Figure 1-2. The fan is approximately 7 km^2 in area.

Brohm River is a key tributary river, entering Cheekeye River a short distance above Highway 99. Brohm River is understood to be the most important fisheries resource area on the fan.

Dryden Creek also crosses the fan, flowing north from Alice Lake, west toward Highway 99, then south along Highway 99 to Brackendale. Outflow from Dryden Creek reaches the Squamish River at Dryden Creek pump station / floodbox.

The community of Brackendale is located at the south perimeter of the fan. The fan also transitions into the Garibaldi Estates area of the Mamquam River fan. Diking and drainage works associated with Squamish River and Mamquam River may affect the runout of Cheekeye River debris flows as well as the discharge of any debris-flow related avulsion (rapid change) of the river channel.

The fan is within the traditional territory of the Squamish Nation, which has land holdings in the area. The fan is also within the consultation area for the Tsleil-Waututh Nation.

The Cheekeye fan has been extensively studied. A partial list of references is attached.

A partial list of development and infrastructure that may be affected by Cheekeye River debris flows is provided in Table 1-1.

Table 1-1: Existing Development and Infrastructure On Cheekeye Fan

Category	Description
Residential Development	Brackendale Cheakamus I.R. No. 11 Waiwakum I.R. No. 14 Seaichem I.R. No. 16
Institutional	Brackendale Schools (2)
Regional Infrastructure	Highway 99 CN Railway Cheekeye River Bridges (Road and Rail) BC Hydro Power Lines and Substation
Municipal Infrastructure	Squamish Landfill Squamish Airport Alice Lake Reservoir
Local Roads	Squamish Valley Road Paradise Valley Road Cheakamus River (Fergie's) Bridge Depot Road (Brackendale Access) Government Road Other Local Roads
Recreational Development	Sunwolf Resort Alice Lake Park access road Various Bicycling Trails
Undeveloped IR Land	Aikwucks I.R. No. 15 Poquiosin and Skamain I.R. No. 13
Industrial	Gravel Pits and Forest Operations Sites Tree Farm Licence

1.3 Work Program

The work program undertaken in preparing this report is summarized in Table 1-2.

Table 1-2: Work Program

Task	Task Description	Identification of Sub-Tasks
1. Project Initiation		
1.1	Initial Project Scoping	Work with District of Squamish to develop initial work program
		Consider need for subsequent peer review activities
1.2	Pre-Project Meeting with District, Cornerstone and BGC	Develop understanding of each party's objectives and activities
		Confirm what information is available from BGC
		Agree on extent to which BGC work can be used by KWL and the District
		Discuss key elements of work program
1.3	Update Work Program	Update initial work program
2. Review and Assess Baseline Information		
2.1	Compile Comprehensive Reference List	Compile paper and/or digital library of key reports for purpose of project
		Produce reference list in consultation with District and BGC
2.2	Consider Hazard Scenarios and Modelling Parameters	Consider hazard scenarios from previous reports for purpose of this project
		Review modelling parameters used in BGC modelling work
		Determine whether previous hazard scenarios and modelling parameters provide an appropriate and representative description of hazard for purpose of this project
2.3	Review Current Level of Risk	Summarize current level of risk based on existing information
		Consider implications to existing development and identify key consequence areas
		Determine whether previous risk analysis provides an appropriate and representative representation of risk
2.4	Document Status of Baseline Assessments	Prepare technical memorandum to document relevance of existing information (primarily BGC reports) for this project
		Submit technical memorandum to District in draft
3. Identify and Evaluate Mitigation Alternatives		
3.1	Preliminary Identification of Structural Mitigation Alternatives	Develop a comprehensive list of all mitigation measures that have been documented by various parties in the past
		Prepare base map using 2013 LiDAR
		Identify other potential mitigation measures that have not been documented in the past, but may have merit for consideration
		Endeavour to include alternatives that have a possibility of achieving 'As Low As Reasonably Practicable' (ALARP) for the Cheekeye Fan, recognizing that this will not be confirmed until further modelling and QRA work is done
		Consider mitigation implications of ongoing fill at landfill
		Prepare sketch plans and tabular notes to document alternatives
		Prepare technical memorandum to document identification of the alternative mitigation measures
		Submit technical memorandum to District in draft

Task	Task Description	Identification of Sub-Tasks
3.2	Develop Evaluation Matrix	Identify potential evaluation criteria for alternatives
		Consult with District regarding evaluation criteria and weightings
		Work with District to create a qualitative evaluation matrix
3.3	KWL/District Workshop	Discuss priorities for protection and standard of protection
		Review preliminary compilation of alternatives
		Review proposed evaluation matrix
		Obtain feedback for completion of project
3.4	Meet with District, Cornerstone and BGC	Review KWL technical memoranda
		Discuss evaluation matrix and mitigation alternatives
		Obtain feedback for completion of project
3.5	Alternative Evaluation	Perform three independent initial evaluations the alternatives using the evaluation matrix (one each by Mike Currie, Gary Buxton and David Roulston)
		Meet with District to compare the three independent evaluations and resolve significant differences
		Develop a final evaluation matrix using average scores from the three independent evaluations
		Work with District to identify the most promising alternatives
		Consider combinations and permutations of alternatives
		Consider areas where retreat and avoid may be obvious alternatives to structural mitigation
4. Report on Mitigation Alternatives		
4.1	Report	Compile technical memoranda and alternative evaluation into a short-form report
		Identify preferred structural alternative(s)
		Discuss future considerations in the event that the proposed Cheekeye Fan development project does and does not move forward in the short term
		Comment on the subject of retreat from the highest hazard areas
		Submit report to District in draft
		Obtain District feedback, finalize report

In order to meet the District's budget constraints, several elements from the work program as originally developed were removed. This included cost estimation, council presentation, consultation with Squamish Nation, and public consultation. Discussion of future considerations was added to the original work program. Table 1-2 reflects the modified work program.

1.4 Project Team and Acknowledgements

This report was prepared by Mike V. Currie, M.Eng., P.Eng., FEC with technical review by David Roche, M.A.Sc., P.Eng.

Assistance and input on behalf of the District of Squamish was led and co-ordinated by David Roulston, P.Eng., Municipal Engineer and Gary Buxton, General Manager of Development Services & Public Works.

The authors also acknowledge the contributions of BGC Engineering, BMS Cheekeye One Projects and Squamish Nation who provided relevant background information for this project.

1.5 Limitations

This report is based on the available reports as noted and the experience and judgment of the project team. No new information was collected.

This document represents KWL's professional judgement based on the information available at the time of its completion and as appropriate for the project scope of work. Services performed in developing the content of this document have been conducted in a manner consistent with that level and skill ordinarily exercised by members of the engineering profession currently practising under similar conditions. No warranty, express or implied, is made.

This report is provided for the exclusive use and benefit of the District of Squamish. No other party is entitled to rely on any of the conclusions, data, opinions, or any other information contained in this document.

Any use that a third party makes of this report is the sole responsibility of that third party. KWL accepts no responsibility for any such use.

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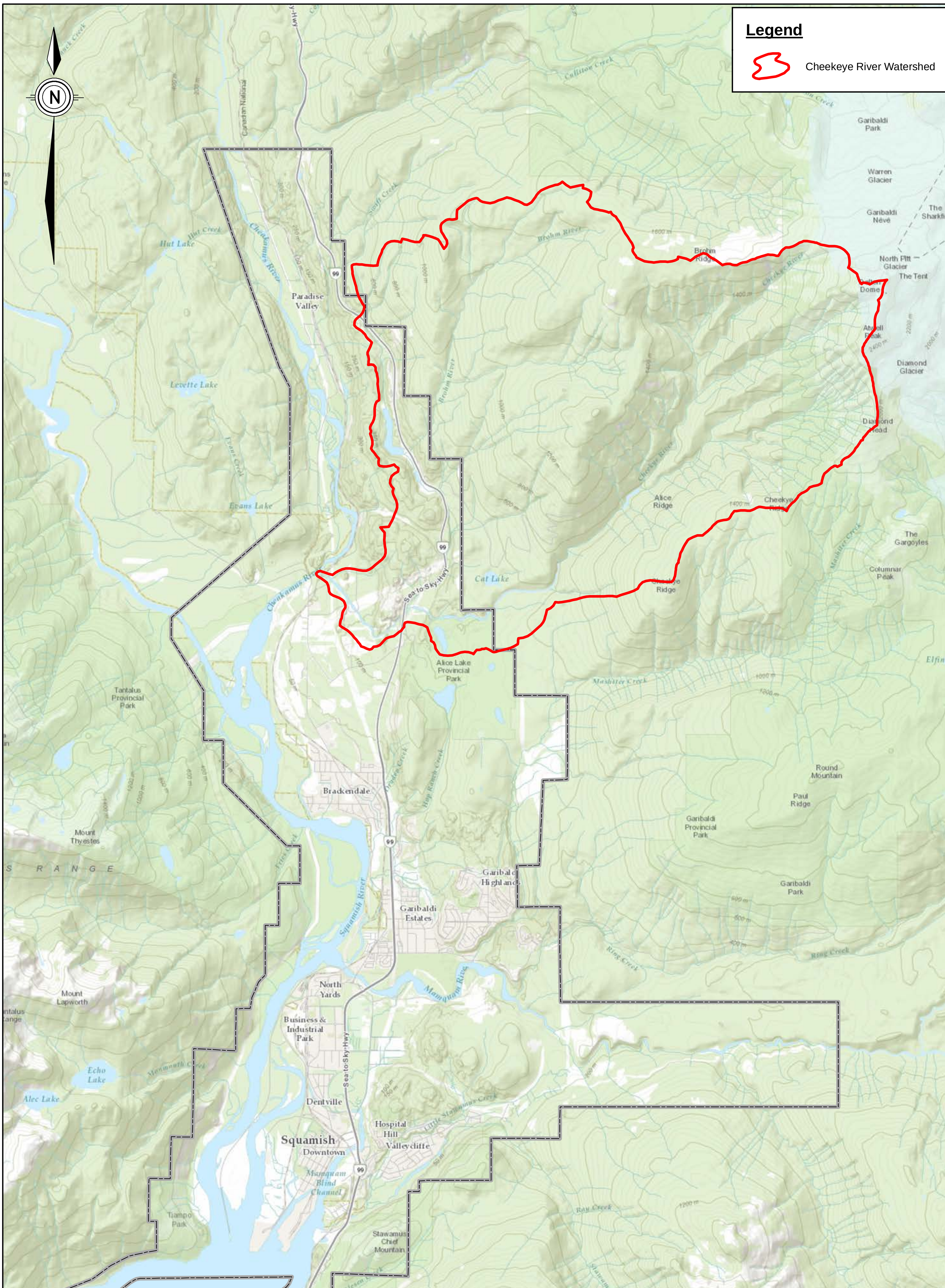
Author: RTaylor



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Assessment of Mitigation Alternatives for Cheekeye Fan

Project No.	Date
463-311	April, 2016

1,000 0 1,000
(m)

Cheekeye River Watershed

Figure 1-1

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Author: RTaylor

Reference: Orthophoto from District of Squamish, 2013.

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Assessment of Mitigation Alternatives for Cheekeye Fan

Project No.	Date
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Cheekeye Fan

Figure 1-2

2. Background Information

This section documents relevant background information from previous reports. This includes a number of reports prepared by BGC Engineering that cover the following topics:

- debris flow magnitude and frequency;
- debris flow modelling; and
- debris flow risk.

Information from several high level review reports is also included.

The purpose of this review is limited to summarizing available information to support the screening of mitigation alternatives provided herein. This review and commentary do not comprise a formal technical review or peer review of any of the previous work.

2.1 Previous Reports

A partial reference list pertaining to the Cheekeye Fan is included at the end of this report. The most relevant reports are noted in this section.

An initial set of three reports was prepared by BGC Engineering in 2007/2008:

BGC1	Cheekeye River Debris Flow Frequency and Magnitude	January 10, 2008
BGC2	Cheekeye River Debris Flow Simulations	December 14, 2007
BGC3	Cheekeye River Debris Flow Risk Assessment	October 21, 2008

Each of the above reports was reviewed and accepted by the Cheekeye Fan Geotechnical Review Board (Andy Robertson P.Eng., Dr. Oldrich Hungr P.Eng./P.Geo, and Dr. Norbert Morgenstern, P.Eng.) as documented in the following reports:

RB1	Approval of BGC1 and BGC2, and Preliminary Approval of BGC3	March 4, 2008
RB2	Approval of BGC3	October 14, 2008

The three initial BGC reports and the Review Board work were commissioned by a previous development proponent at the time (Cheekeye River Developments). The work was done specifically to support development of a mitigation strategy to protect a proposed development on the Cheekeye Fan. A potential mitigation strategy was partially developed by KWL in 2007, but was not completed as the development project was paused. A similar development project is now under consideration by a new development proponent (BMS Cheekeye One Projects), and further work has been done (as noted below).

An independent review by Golder Associates was commissioned by the BC Government:

G1	Cheekye Fan Hazard Review	March 22, 2013

Further review and input has also been obtained through two expert panel reports jointly commissioned by the BC Government, the Squamish Nation, and the District of Squamish:

EP1	Report of the Cheekye River and Fan Expert Review Panel	April 23, 2014
EP2	Cheekye River and Fan Landslide Risk Tolerance Criteria	June 8, 2015

Expert Panel #1 comprised Dr. John Clague P.Geo, Dr. Oldrich Hungr P.Eng./P.Geo, and Douglas VanDine P.Eng./P.Geo. Expert Panel #1 was directed to review all previous relevant documentation and provide opinions on the volume and frequency of future debris flows, characterize the volume of the 10,000-year return period debris flow, and comment on the possible effects of climate change. Relevant comments from EP1 are discussed in Section 2.2 below.

Expert Panel #2 included the three original members plus Dr. Norbert Morgenstern P.Eng. Expert Panel #2 was directed to provide advice with respect to four items with a focus on risk to life:

1. landslide risk tolerance criteria for existing and proposed new development on Cheekeye Fan;
2. current levels of individual and societal risk from landslides on Cheekeye Fan;
3. individual and societal risk reduction that might be achieved through mitigation, given existing and proposed new development; and
4. whether individual and societal landslide risk tolerance criteria can be applied across the District of Squamish or solely to Cheekeye Fan.

Some relevant comments from EP2 are included in Section 3.

Some of the initial BGC modelling work has recently been updated on behalf of BMS Cheekeye One Projects:

BGC4	Debris Flow Exposure Assessment	December 2, 2015
BGC5	2015 Debris Flow Modelling Summary, Cheekeye Fan (Draft)	December 23, 2015

BGC4 included some additional debris flow modelling that updates the initial work reported in BGC2. BGC5 included a more thorough update of the initial work in BGC2, superseding the work of BGC4. BGC5 therefore represents the most current debris flow modelling work for the Cheekeye Fan (but remains in draft form at the time this report was prepared).

2.2 Debris Flow Frequency and Magnitude

BGC1 provides a good assessment of debris flow frequency and magnitude, but some refinements have been made since that time.

EP1 provided an opinion that the magnitude of the 10,000-year return period debris flow on Cheekeye River is 5.5 million m^3, more conservative than the 2.8 million m^3 from BGC1. EP1 also included an opinion that the 10,000-year return period debris flow event is an appropriate level of hazard probability to consider for Cheekeye Fan.

The District has accepted the opinion of EP1 that the 10,000-year return period debris flow is the appropriate extreme event for estimating the largest debris flow that could affect the Cheekeye Fan.

EP1 further opined that the upper bound of the 10,000-year return period debris flow should be 5.5 million m^3, and that a debris flow event of this volume is conceptually comparable to the Maximum Credible Earthquake (MCE) or Probable Maximum Flood (PMF). G1 also had similar findings.

BGC2 used a minimum debris flow return period of 20 years. Following the occurrence of two debris flows since 2007, BGC5 uses a reduced minimum debris flow return period of 5 years.

Based on the latest work by BGC Engineering (BGC5), debris flow magnitude on the Cheekeye Fan is best estimated as in Table 2-1. This represents an update of BGC2 to reflect the expert panel findings.

Table 2-1: Cheekeye River Debris Flow Magnitude

Return Period	Debris Flow Volume	Peak Discharge
10,000 years	5,500,000 m^3 (upper limit) 2,800,000 m^3 (best estimate)	18,000 - 33,000 m^3/s
2,500 years	2,400,000 m^3	7,800 - 12,400 m^3/s
500 years	1,400,000 m^3	4,500 - 6,600 m^3/s
200 years	800,000 m^3	2,600 - 3,400 m^3/s
100 years	600,000 m^3	1,900 - 2,400 m^3/s
50 years	400,000 m^3	1,300 - 1,500 m^3/s
20 years	200,000 m^3	630 - 670 m^3/s
10 years	170,000 m^3	540 - 550 m^3/s
5 years	110,000 m^3	320 - 330 m^3/s
*All debris flow volumes below 10,000-year return period are best estimates rather than upper limits.		

The existing hazard assessment work is considered sufficient for the purposes of this screening-level assessment of mitigation options. However, it should be recognized that no hazard assessment of this nature can be exhaustive, and that the reports do not reflect every possible hazard scenario. At some point, it will be appropriate to obtain an update to BGC1 that reflects the findings of EP1, the updated work of BGC5, and any other new information that is relevant (for example, lessons learned from the 2010 Capricorn Creek debris flow near Pemberton).

2.3 Other Hazards

In addition to debris flow magnitude and frequency on the Cheekeye Fan, the project must also consider flood magnitude and frequency on the Cheekeye River, Brohm River, Cheakamus River, Squamish River and Dryden Creek. Some consideration is given to these issues in BGC5. In moving forward, it will be appropriate to further consider the complex issue of combined probability of simultaneous or successive extreme events on these rivers and creeks.

It is important to recognize that other hazards may also affect the study area, such as rockfall from high bluffs east of Highway 99.

2.4 Status of Debris Flow Modelling

BGC2 includes analysis of the garbage dump debris flow of about 800 years ago. This large event is used as a calibration event. The report also includes map products showing simulated debris flow depth and velocity for various scenarios, with return periods from 20 years to 10,000 years (the latter event having a volume of 2.8 million m^3, compared to the more conservative estimate of 5.5 million m^3 as recommended by Expert Panel#1). As noted above, BGC2 was reviewed and accepted by the initial Review Board.

BGC4 includes updated mapping, primarily to reflect extension of the model domain south to the Mamquam River dike. The range of modelled return periods is 100 years to 10,000 years. The map products show the same parameters as BGC2, namely debris flow depth and velocity. The map products also show an approximate proposed development area.

BGC5 is a draft report that may be subject to revision, and has not (yet) been subject to external review. Compared to the initial (2007) modelling work of BGC2, key changes in the modelling approach are as follows:

- the model domain was extended south to the Mamquam River dyke using 2014 Lidar data (BGC2 used 2006 Lidar data);
- the range of modelled return periods is 5 years to 10,000 years;
- a range of peak flow estimates was used to reflect varying viscosity for each return period;
- 2,500-year and 10,000-year return period debris flow model runs also incorporate a 50-year return period clear-water flood as a background condition on the Cheekeye River (lesser return periods do not);
- the model now incorporates dykes along the Squamish River and Mamquam River (along with the assumption that the floodboxes and pump stations will be inoperable during a debris flow);
- as recommended by EP1, the 10,000-year return period debris flow volume was increased from 2.8 million m^3 to 5.5 million m^3 (the peak discharge also increased from 15,000 m^3/s to an upper limit of 33,000 m^3/s);
- rather than illustrate debris flow depth and velocity in map form, BGC5 maps show debris flow "impact intensity" (which is not explicitly defined in the document but has been published previously in peer-reviewed journal articles); and
- the map products show depth only (i.e., no velocity) in areas where the impact intensity is less than 1.

Neither BGC2 nor BGC5 include modelling of post-mitigation scenarios.

The modelling work is expected to be refined in the future. Three specific issues that should be given further consideration in future modelling of debris flow runout are: the impact of the ongoing landfill development; changing forest conditions on the fan surface; and changes due to clearing and/or land development.

2.5 Commentary on Debris Flow Modelling

The modelling work for the Cheekeye Fan is comprehensive, and incorporates leading-edge tools and research. However, it is important to understand that debris flow modelling with FLO-2D remains subject to a range of general assumptions and limitations, described in Table 2-1.

Table 2-2: Limitations of FLO-2D Modelling of Debris Flows

Technological Limitations	• the model is an approximation of actual conditions, subject to input variables, uncertainty, the skill and experience of the modeller, and the possibility of human errors or "bugs" in the software • the physics of debris flows remain an area of evolving research • obtaining a good result is dependent on being able to calibrate the model based on historic event(s)

Geomorphic Limitations	• the event volume and peak discharge (water and sediment) are estimated input variables that are subject to uncertainty • the shape of the input hydrograph is estimated, and requires an assumption regarding whether to model as one surge, or multiple surges • assumptions need to be made about the magnitude, containment and direction of river flow before, during and after the modelled event • a model run will not reflect any physical changes that occur within the channel or on the fan (i.e., scour and/or deposition) during the event • the behaviour of successive surges may be affected by the deposition of their predecessors, which cannot be simulated by the runout model
Topographic Limitations	• the model includes a digital representation of topography on the fan (with one elevation for a fixed grid size, (25 m x 25 m in this case) • depending on survey and mapping methods, the representation of topography at the time of data collection may or may not be good • tree cover can be an impediment for aerial mapping techniques • the mapping may not continue to reflect the river channel or fan conditions due to ongoing geomorphic changes such as aggradation or erosion • the mapping may not continue to reflect actual conditions if there is ongoing development (especially linear fills such as roads and dykes)
Practical Limitations	• the behaviour of large log debris in a debris flow is unpredictable and hard to simulate • the actual impact of a debris flow on a given structure is subject to a large number of uncertainties and can only be expressed in probabilistic terms • changes in land use (i.e., clearing and development) on the fan may affect debris flow deposition and runout • the model shows uniform flow whereas debris flow behaviour does not tend to be uniform • the return period or probability of a given event is the probability of an event of that magnitude reaching the fan apex, whereas the probability of each alternative downstream realization is less than that of the initial event (due to compound probability associated with modelling scenarios such as blockage, and the potential for the flow to run out in unanticipated directions on the fan)

Modelling Scenarios	• it is not feasible to model every scenario or possible outcome • in order to simulate avulsion, an artificial channel blockage of assumed size and location must be added to the model (these assumptions may or may not be realistic) • assumptions may need to be made about the performance of dikes and other works during a debris flow • since the model used by BGC cannot evaluate hydraulic performance of structures, bridges and culverts need to represented as either blockages or simply removed • professional judgment is required when combining different extreme events (i.e., debris flow, river flow) and establishing boundary conditions (i.e., downstream water level)
Modelling Parameters	• the discharge and sediment volume are integrated using an estimated bulking factor to develop the inflow hydrograph • the yield stress and viscosity of the debris flow must be estimated independently and assumed to be constant over time (which may or may not be realistic) • surface roughness in the runout area must be estimated independently, and cannot vary with time, discharge, or dynamic effects of inundation or deposition.

The majority of these comments are generally applicable to any platform that simulates debris flows, and FLO-2D modelling is considered an appropriate tool to simulate debris flow runout on the Cheekeye Fan. It is nonetheless important to consider the above-noted assumptions and limitations in applying the model results for any purpose.

With respect to the review of mitigation alternatives on the Cheekeye Fan as provided by this report, some comments on the modelling work of the draft BGC5 report are as follows:

- the map products reflect the full range of return periods that should be considered;
- the map products showing debris flow impact intensity are less intuitive than debris flow depth and velocity, and potentially less directly applicable for the review of mitigation alternatives (but perhaps more directly applicable to QRA);
- debris flow impact intensity is not well defined, and its application is not explained (it is understood that these issues will be remedied in any further versions);
- the avulsion scenarios modelled by BGC and presented in the reports may not represent worst case scenarios for all hazard areas or potential mitigation alternatives on the Cheekeye Fan;
- the modelling is conservative in that it reflects continued southward flow and back-up from the river dikes (Squamish River and Mamquam River) south of Brackendale (although in practical terms, the dike may be breached and/or Cheekeye River flow quickly re-diverted as part of the District's emergency response during such an event to prevent excessive water levels);
- some of the model runs (2,500-year and 10,000-year return period) compound extreme probabilities (Cheekeye River debris flow plus 50-year return period Cheekeye River flood plus zero downstream pump capacity plus complete blockage of all outlets through the dike plus ponding behind dikes),

whereas even major debris flows are not always correlated with high river levels (as recently demonstrated by 2010 Capricorn Creek debris flow near Pemberton); and

- the model parameters have not been reviewed in detail (although this review did not identify any reason why the parameters selected by BGC would be considered inappropriate).

These comments should be addressed when BGC5 is finalized.

In using any model result, it is important to consider the discharge hydrograph in addition to the total event volume, as well as the specific avulsion assumption, to ensure that an appropriate scenario is used. Areas outside the mapped impact area are not necessarily free of hazard, since the debris flow could run out in a different manner than modelled.

In summary, the map products from BGC's debris flow modelling are useful for supporting the preparation of this report.

2.6 Potential Debris Flow Effects

The map products from debris flow modelling allow potential debris flow effect for each scenario to be described in terms of depth and velocity. Based on the scenarios of Figure 10 of BGC2 and Drawing 4 of BGC4, the effects of a 2,500-year return period debris flow are described generally in Table 2-3.

It is important to note that the relative debris flow impacts on the fan are highly dependent on the modelling scenarios, particularly avulsion and bridge blockage. The 2,500 year debris flow is presented as an example, not as the most extreme possible event. The description below is provided for illustrative purposes, and the parameters are not intended to be precise.

Table 2-3: Potential Effect of 2500-Year Return Period Debris Flow on Cheekeye Fan

Brackendale	• virtually all of Brackendale would be impacted by debris flow to some extent • debris flow generally less than 0.5 m deep in north part of Brackendale • debris flow up to 2 m deep further to south where flow impeded by dike • roads to/from Brackendale likely inoperable (from north and south) • local access roads likely inoperable
Cheekeye Confluence Area and I.R. No. 11	• most of fan area impacted by debris flow to some extent • debris flow depth highly dependent on upstream avulsion and bridge blockage assumptions, but potentially up to several metres deep • potential secondary impact from Cheakamus River blockage (likely resulting in overflow through Cheakamus I.R. No. 11) • access south to Squamish likely severed • access to north from I.R. No. 11 (e.g., Paradise Valley) may be possible
Highway 99	• 2 m to 5 m depth of debris flow across highway north of Alice Lake park access road • Cheekye River highway bridge blocked • avulsion down highway, south to Brackendale • highway likely inoperable from highway bridge to nearly Garibaldi Way

Table 2-3 underscores the fact that the potential debris flow damage at Cheekeye Fan could be severe and highly disruptive to the community.

2.7 Risk Assessment

In addition to describing debris flow impact using modelling tools as in the previous section, numerical values can be assigned to risk. This can be done through quantitative risk assessment, a tool that has been increasingly used for this purpose in BC in the past decade. It is important to recognize that the application of risk assessment methodology for natural hazards is not (yet) guided by provincial or federal legislation, regulations or guidelines. It is, however, documented in the June 2012 publication by the Association of Professional Engineers and Geoscientists of BC (APEGBC) titled “Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC” (the 2012 APEGBC Flood Guidelines”).

BGC3 provided an initial quantitative risk assessment for the Cheekeye Fan for three principal aspects:

- risk to Highway 99 users;
- risk to existing development at the Cheekeye River confluence area; and
- risk to a development area proposed at the time (similar to present proposal).

In each case, risk to individuals and groups were both rated as “unacceptable”. BGC3 notes that risk would be significantly reduced if a large debris barrier (at the time expected to contain roughly 1.4 million m^3 of debris) were to be constructed above Highway 99.

BGC3 also notes that the economic risk due to Highway 99 being severed would be in the order of $1M per day (2008 dollars).

BGC3 would require updating to provide a more definitive and current assessment. If risk assessment is to be used as a basis for major development or investment decisions, a detailed peer review of the updated risk assessment would be appropriate. As is common with engineering reports, a detailed peer review would require a depth of information beyond that presented in BGC3 to confirm the assessment structure developed for the Cheekeye Fan.

BGC4 further documents the risk exposure of existing development on the Cheekeye Fan. It includes a listing of properties (Table 3-1) that could be impacted by various return period debris flows and scenarios.

In summary, BGC4 concludes that the value of land and improvements that could be affected by a Cheekeye River debris flow could range from roughly $20M for the 100-year return period event to $900M for the 10,000-year return period event. This determination is based on existing conditions. Any mitigation works would be expected to reduce the extent of damage.

3. Identification of Alternative Approaches to Risk Mitigation

This section identifies a broad range of mitigation approaches that may be considered to mitigate risk to existing development on the Cheekeye Fan.

While the focus of this report is on protection of existing development, work associated with the proposed new development is ongoing. Mitigation measures to protect such a new development are being developed by others.

3.1 Priorities for Mitigation

In working with District staff, existing development was categorized in terms of priority for mitigating risk as shown by Table 3-1.

Table 3-1: Categorization of Existing Development for Purpose of Debris Flow Mitigation

Highest Priority Considerations	Moderate Priority Considerations	Lower Priority Considerations
Brackendale Residential Area	Aikwucks IR 15 (Limited Development)	Squamish Airport
Cheakamus IR 11 Residential Area	Paradise Valley Road (Valley Access)	Highway 99
Waiwakum IR 14 Residential Area	Cheakamus River (Fergie's) Bridge	CN Railway
Seaichem IR 16 Residential Area	Depot Road (Brackendale Access)	BC Hydro Substation
Kowtain IR 17 Residential Area		BC Hydro Transmission Lines
Confluence Residential Area		Squamish Landfill
Brackendale Schools (2)		Industrial Sites West of Airport
Garibaldi Estates Residential Area		Poquiosin & Skamain IR 13 (Non-Residential)
		Alice Lake Park Access Road

This categorization provides a basis for this initial review of alternatives.

3.2 Objectives for Hazard/Risk Mitigation

Risk Mitigation Criteria

The extent to which any natural hazard or risk will be mitigated is an important question, and can significantly impact the approach to risk mitigation as well as the type, location and scale of structural mitigative works that may be considered.

There are two basic approaches to defining acceptable mitigation:

1. a design return period approach (such as is often used for flood hazards in BC with a 200-year return period); or
2. a risk management approach where the objective is to reduce computed risk to a level acceptable to the local authority.

In some situations, it may be appropriate to integrate these two approaches.

Little direction is provided to local governments facing such decisions, although the issue is referenced in the 2004 Flood Hazard Area Land Use Guidelines. Some direction is provided to qualified professionals in the 2012 APEGBC Flood Guidelines, but is primarily focussed on new development and redevelopment. Direction for protecting existing development is particularly lacking.

Precedents in Other Parts of BC

In the early 1990's, Dr. Peter Cave developed a graduated series of risk mitigation criteria that continues to be used by the Fraser Valley Regional District (FVRD). This approach applied a "sliding scale" that facilitated minor development, but required a very low level of risk for major new development. The approach was also more stringent for more severe hazard types. For debris flows, this approach is summarized in Table 3-2.

Table 3-2: Summary of Cave Approach Used by FVRD for Debris Flows

Type of Proposed Development	Design Return Period (``Annual Return Frequency``)
rezoning for new community (major new development)	1:500-1:10,000
infill development (such as small subdivision)	1:200-1:500
build on existing lot	1:50-1:200
repair	1:50

For debris flows and major catastrophic landslides, the FVRD approach would only consider rezoning for a major new development where the debris flow hazard is naturally below, or has been mitigated to, the level of 1:500-1:10,000 annual return frequency.

Application of quantitative risk assessment techniques, as outlined in the 2012 APEGBC Flood Guidelines, goes beyond the FVRD approach by reducing the risk during the specified return period event to an acceptable level (the FVRD approach does not include specific risk criteria, but does implicitly consider risk in setting higher return period standards for higher levels of development).

The District of North Vancouver requires that subdivisions, development approvals and building permits have natural hazard risks reduced to As Low as Reasonably Practicable (ALARP). The concept of ALARP is illustrated in the diagram in Figure 3-1 (from 2012 APEGBC Flood Guidelines).

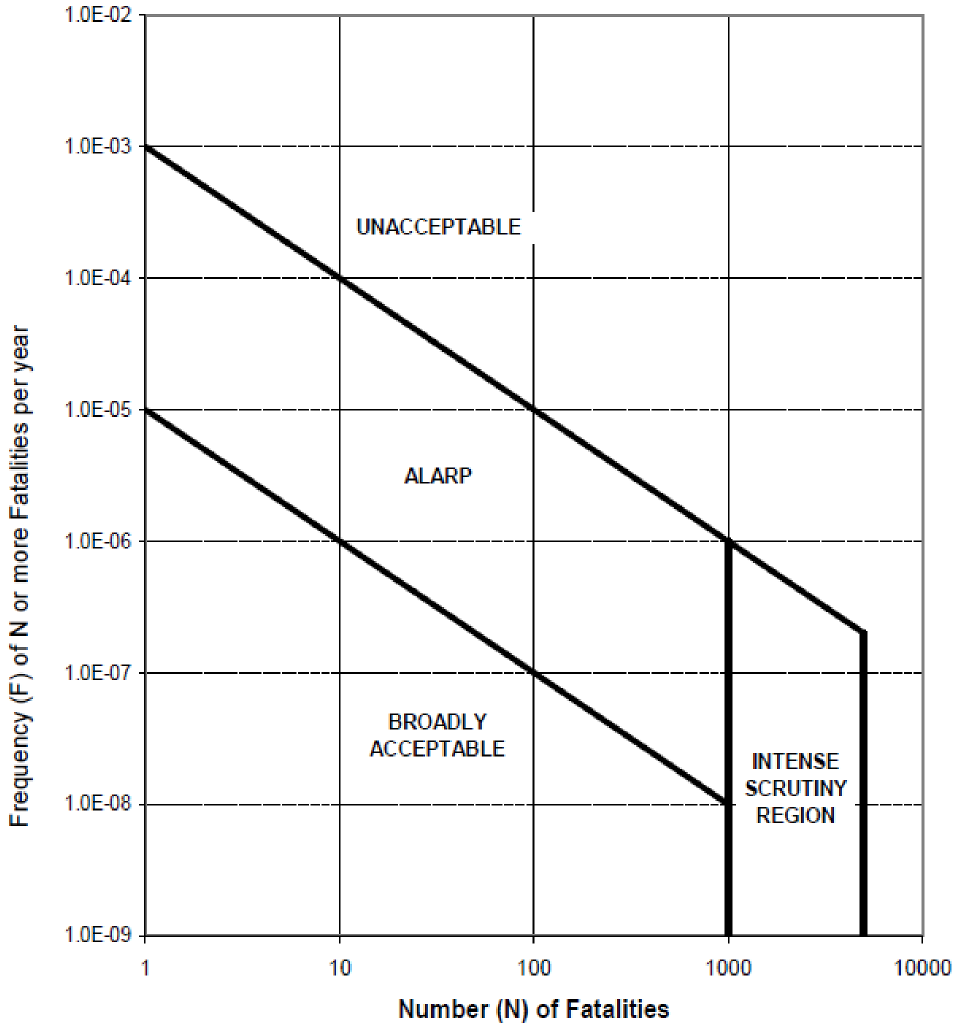

Figure 3-1: F-N Diagram From 2012 APEGBC Flood Guidelines

The F-N diagram is based on the concept of decreasing risk tolerance for increasing number of fatalities. A broadly acceptable zone is defined where risk is at or lower than that commonly accepted in society. An unacceptable zone is defined where risk is higher than that commonly accepted in society. An intermediate ALARP zone is also defined. In order to be considered ALARP, two criteria must be met:

1. the societal risk must fall within or below the ALARP zone of the F-N diagram; and
2. the cost to further mitigate the risk must be grossly disproportionate to the benefit gained, or the solution is impractical to implement.

Under the District of North Vancouver approach, in addition to ALARP, the following risk criteria need to be satisfied:

- a maximum 1:10,000 annual risk of fatality per year for redevelopments involving an increase to floor area of less than 25%;
- a maximum 1:100,000 annual risk of fatality per year for new developments and redevelopments involving an increase to floor area of more than 25%; and
- maintenance, would have to be examined and considered.

Natural hazards issues are a hot topic in BC at present, partly as a result of climate change considerations, and new precedents are likely to surface.

Guidance from Cheekeye Expert Panel #2

Cheekeye Expert Panel #2 made some relevant general comments:

- jurisdictional decision-makers ultimately have to select, by means of an appropriate public process, appropriate risk evaluation parameters (hazard probability and landslide volume and/or peak discharge) for a particular situation or jurisdiction; and
- once landslide risk tolerance criteria have been established and appropriate risk evaluation parameters have been selected, communities can choose a number of options to meet the criteria.

Cheekeye Expert Panel #2 also made some specific comments pertaining to the Cheekeye Fan:

- landslide risk assessment should rely on quantitative risk assessment;
- the Hong Kong landslide risk tolerance criteria (F-N diagram) should be adopted for Cheekeye Fan;
- individual risk tolerance should be less than 1:10,000 for existing development, and less than 1:100,000 for new development;
- societal annual risk tolerance should fall within the ALARP zone of the F-N diagram, and meet the qualitative "reasonably practicable" criteria; and
- final determination of risk evaluation parameters should be made by stakeholders and decision-makers.

EP2 further suggests the following three suites of hazard probability options be considered for further quantitative risk assessment on the Cheekeye Fan:

- up to and including 500-year return period;
- up to and including 2500-year return period; and
- up to and including 10,000-year return period.

The District has not (yet) selected one of these options. In so doing, there will be a need to confirm that this is an appropriate way to proceed (further discussed below).

Regarding mitigation measures on the Cheekeye Fan, Cheekeye Expert Panel #2 made the following points:

- landslide risks to existing development should be mitigated whether or not there is any future development on Cheekeye Fan (a reiteration from Expert Panel#1);

- in terms of protecting existing development and possibly allowing some new development on Cheekeye Fan, all forms of mitigation, singly or in combination, should be considered and carefully evaluated;
- individual and societal risk reduction to existing and proposed new development could be achieved with some form of engineered structural mitigation, singly or in combination; and
- the technical feasibility of such structural mitigation including an examination of detailed designs and operation and maintenance, would have to be examined and considered.

It is understood that the District has adopted the recommendations from Cheekeye Expert Panel #2.

Commentary on the Application of QRA for the Cheekeye Fan

Quantitative Risk Assessment for the Cheekeye Fan can be effective for the following purposes:

- to assist in the comparison between risk mitigation alternatives;
- to confirm that a risk mitigation alternative can meet the level of risk that the community is willing to accept; and
- to determine the scale of mitigation works required.

In moving forward, there will be a need to update previous quantitative risk assessment work. This should include the following general considerations:

- confirm tolerable and broadly acceptable levels of risk for individuals and groups, for both proposed and existing development;
- consider the suggestion of Expert Panel #2 to select one of the three suites of hazard probability options (further discussed below);
- update the hazard assessment and modelling work to an appropriate degree;
- determine what the results of the quantitative risk assessment will be used for, and conduct an appropriate level of peer review; and
- convey the quantitative risk assessment results to key third parties such that they can consider appropriate actions.

If risk assessment is to be used as the primary tool to determine the scale of structural mitigation works, it would be prudent to update the baseline risk assessment prior to any further design work.

The recommendations from Expert Panel #2 provide a good platform from which to proceed with further QRA work for the Cheekeye Fan, however, there are some points that merit further consideration.

It is important to recognize that two of the three hazard probability options suggested by Expert Panel #2 would exclude large events from the QRA (to different degrees). This would significantly affect the results of the QRA. In each case, an additional (indeterminate) risk of death from larger events would be implicitly accepted.

The potential variation in QRA results that can result from excluding large events is illustrated by Figure 3-2 using a generic QRA example and the above F-N diagram. While the actual risk level of the community would not change, the computed risk level would change significantly. One interpretation indicates that the risk would be unacceptable, while another shows that the risk would be negligible.

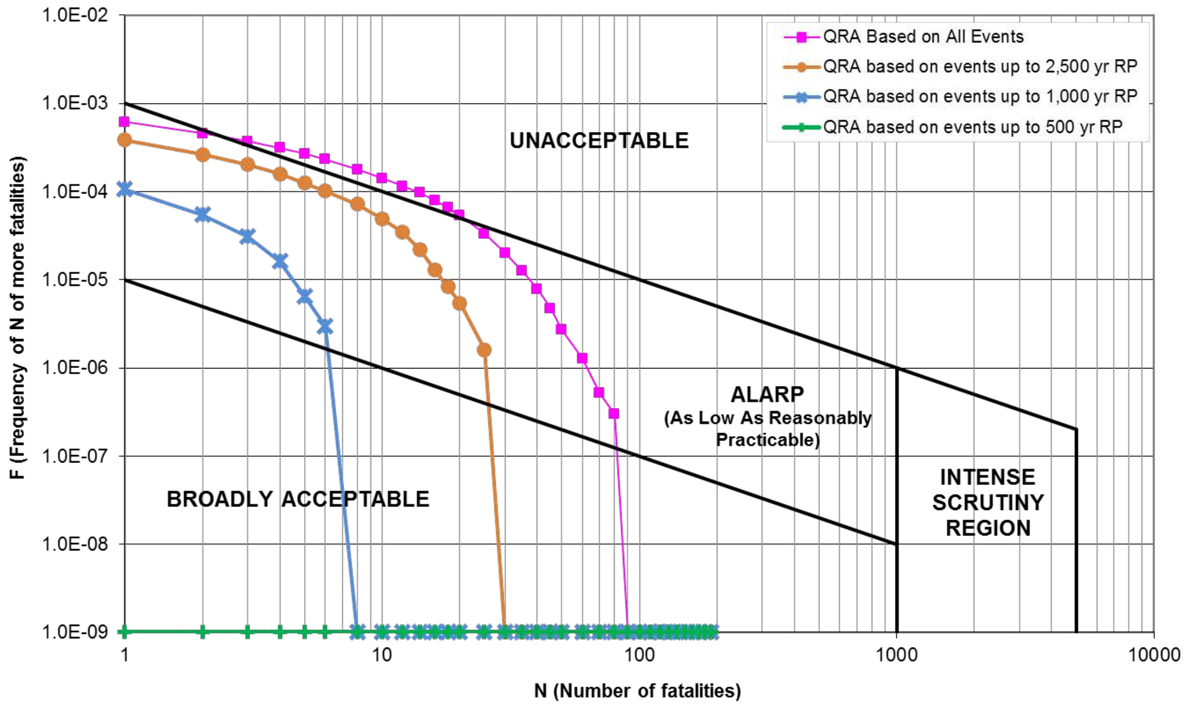

Figure 3-2: QRA Example to Illustrate the Importance of Selecting a Hazard Probability Option

The example in Figure 3-2 illustrates why the District should carefully consider the selection of a hazard probability option prior to further QRA work being performed. QRA assumptions for Cheekeye Fan should be consistent with those used to derive the acceptable risk criteria (i.e. the limits and zones shown on the F-N diagram). Arbitrarily selecting a hazard probability option could invalidate the acceptable risk comparison. Previous QRA work done by BGC Engineering on the Cheekeye Fan has incorporated events up to, and including, the maximum credible event. This seems appropriate since the QRA would then consider events up to and including the point where larger, less likely hazards no longer affect the consequence calculations.

Alternatively, if the community is prepared to accept an indeterminate level of residual risk, a QRA offers little benefit over the simpler, well-established and more cost-effective practice of hazard-based design (which adopts a negligible threshold for acceptable risk under design conditions, and accepts an indeterminate level of risk during more extreme events).

Commentary on ALARP Risk Mitigation for the Cheekeye Fan

As previously defined, two criteria must be satisfied for risk mitigation to be considered ALARP:

1. the societal risk must fall within or below the ALARP zone of the F-N diagram; and
2. the cost to further mitigate the risk must be grossly disproportionate to the benefit gained, or the solution is impractical to implement.

Achieving the first ALARP criteria (i.e., plotting within the ALARP zone on the F-N diagram) does not itself demonstrate that the level of mitigation is ALARP. It merely suggests that the second ALARP criteria may then be applied to determine when an appropriate level of mitigation is achieved.

The second ALARP criteria is inherently subjective, and has been found to be legally problematic in some jurisdictions (Robinson, May 2014). It is reasonable to expect that the courts, acting with the benefit of hindsight in a post-disaster scenario, would apply a fairly conservative interpretation of the term "disproportionate" under the second criteria.

In particular, ALARP risk mitigation for the Cheekeye Fan could create difficulties for any future development proposal not included in the initial QRA. Subsequent development proposals could elevate the risk level above the second ALARP criteria (since at that point there is essentially no cost to maintaining the status-quo level of risk). The District should therefore consider the ultimate level of desired development in determining whether any risk mitigation proposal achieves the ALARP standard.

3.3 Mitigation Strategies for Debris Flow Risk

A wide range of flood risk mitigation strategies has been documented as part of the ongoing Integrated Flood Hazard Management Plan (IFHMP) project for Squamish. This work is reproduced in Table 3-3 with slight modifications in the examples to suit debris flow situations.

Table 3-3: Debris Flow Risk Mitigation Strategies

Strategy	Description	Examples
Protect	Protect existing development in its current form and location, balancing costs and increasing vulnerability against societal cost and risk associated with other strategies.	• Construct structural mitigation works (e.g., a debris barrier or deflection berm). • • Ensure appropriate long-term operation and maintenance of the works
Accommodate	Accommodate the potential consequences of ongoing changes by changing human activities and/or infrastructure to increase resilience.	• Raise land elevation and structures with structural fill • Consider appropriate land use that favours lower-consequence development (e.g. non-residential)
Retreat	Manage Retreat by gradually withdrawing potentially-vulnerable infrastructure and services from hazard areas in recognition of their increasing vulnerability.	• Reclaim developed area to natural state as a community amenity
Avoid	Avoid increasing the presence or density of potentially-vulnerable populations, infrastructure or services within hazard areas.	• Particularly high hazard areas • Areas where development could exacerbate hazards or risk for others

In addition to the four key strategies outlined in the table above, the concept of **Accept** is implicit in all discussions. An accept strategy may endorse the status quo level of mitigation (i.e., if existing risk is considered acceptable), but is more frequently an implied as part of a more comprehensive strategy that is focussed on defining and advancing the concept of "safe enough". Guidance as to what might constitute "safe enough" has been provided in the preceding discussion.

Another type of strategy, **Attack**, involves reclaiming land from an existing natural hazard area. This strategy is most often considered in countries and regions where severe land constraints, very high population densities, and skyrocketing land values justify the substantial costs, risks, and environmental impacts. The proposed new development is considered an "Attack" strategy that may be justifiable as a mechanism to fund the substantial works required to mitigate the existing risk to an acceptable level.

3.4 Typical Mitigation Measures to Mitigate Debris Flow Risk

Within the range of strategies summarized in Table 3-3, a wide range of specific mitigative measures may be considered to mitigate debris flow risk. Table 3-4 summarizes a range of measures that are typically considered to mitigate debris flow risks.

Table 3-4: Typical Mitigation Measures to Mitigate Debris Flow Risk

Category		Objective	Comments
1. Land Use and Site-Specific Measures			
1.1	Land Use Planning	Locate development in safe areas.	Primarily applicable before development occurs.
1.2	Secondary Floodproofing	Elevate buildings above grade, provide emergency flow path.	Best applied during initial development, but can sometimes be retrofitted. Not always popular with residents.
1.3	Property Acquisition	Remove development from hazardous areas.	Is usually an economic and policy issue. Some residents may not want to leave.
2. Watershed and River Management			
2.1	Watershed Stabilization	Stabilize watershed to decrease debris flow frequency and/or magnitude.	Does not normally provide sufficient mitigation on its own since geologic processes can't be reversed. However, can be effective in addressing site-specific problems.
2.2	Channel Maintenance	Inspect creek channels and manage debris accumulation.	Does not provide sufficient mitigation on its own, but is good management practice to reduce blockages during creek events.
2.3	Bridge Upgrading	Provide larger waterway openings to facilitate debris passage.	Does not usually provide sufficient mitigation on its own, but is good management practice, and may be considered in a package with other measures.
3. Structural Protection Works			
3.1	Check Dams	Stabilize channel to reduce debris production.	Does not normally provide sufficient mitigation on its own, but can be effective in mitigating site-specific problem areas.
3.2	Deflection Berm	Deflect debris away from critical area.	Requires an undeveloped area to deflect debris to. May result in a transfer of risk from one area to another on the fan.
3.3	Channelization	Funnel debris through critical area.	Most applicable for small steep fans near the sea. May involve costly concrete channel works.
3.4	Debris Basin/Barrier	Concrete/steel structure to arrest and store debris above critical area.	Requires a favourable construction site near the fan apex. Often favoured since it normally provides a universal reduction in risk. May be costly. May be sized for a portion of the anticipated event volume in a package with other measures.

Category		Objective	Comments
4. Emergency Planning			
4.1	Warning	Provide warning of event in progress.	Not usually favoured for debris flow hazards due to infrequent occurrence and short duration. False alarms may occur.
4.2	Emergency Response	Have systems in place to respond effectively to an emergency situation.	An important part of any comprehensive mitigation approach.
5. Other Mitigation Measures			
5.1	Risk Acceptance	Take no mitigative measures, advise residents of affected area and live with risk.	Political acceptability depends on level of risk. May only be acceptable if risk is low. Financial constraints may dictate this option.
5.2	Insurance	Insurance policy to provide compensation after a damaging event.	Is available for commercial and other interests in BC, and is now being introduced for homeowners.
5.3	Public Outreach and Education	Increase awareness of hazard conditions, need for mitigation, and operation of mitigation measures.	A useful part of a comprehensive mitigation approach.

In most situations where a comprehensive mitigation strategy is desired, a combination of strategies (Table 3-3) and specific measures (Table 3-4) are integrated into an overall approach (comprehensive mitigation plan) that is tailored to a specific situation.

Many of the mitigation measures in Table 3-4 are worthy of consideration at Cheekeye Fan. The focus of this report is on structural measures, although many of the non-structural measures would also be appropriate and should be incorporated into the final mitigation plan.

The structural mitigation measures listed in Section 3 of Table 3-4 provide a starting point for identification of primary protective measures for Cheekeye Fan. These are discussed further in Section 3.5.

3.5 Primary Debris Flow Mitigation Alternatives for Cheekeye Fan

A range of structural mitigation measures that could be considered as primary debris flow mitigation works on the Cheekeye Fan are generally summarized in Table 3-5, along with some pertinent comments.

The selection of the structural measures listed in Table 3-5 assumes that "protect" is the primary mitigation strategy. For some options, strategy components of "retreat", "avoid" and "attack" are also inherent. The strategy of "accept" is always part of a solution. Continuing consideration of mitigation strategy should be ongoing through to final selection of an alternative for implementation.

In total, 8 structural alternatives are identified plus the option of large-scale retreat. The structural alternatives include 5 debris basin/barrier alternatives, 2 berm alternatives, and 1 channelization option.

Combinations of options have not been considered at this stage. Some of the individual options have been previously evaluated and described as technically feasible by others. Other options have not been previously evaluated and technical feasibility is less certain. In the end, a combination of measures is likely to provide the most effective protection.

Section 4 provides a discussion of local issues that may be relevant to selecting an approach to mitigation. Section 5 provides a comparative evaluation of the options identified in Table 3-5.

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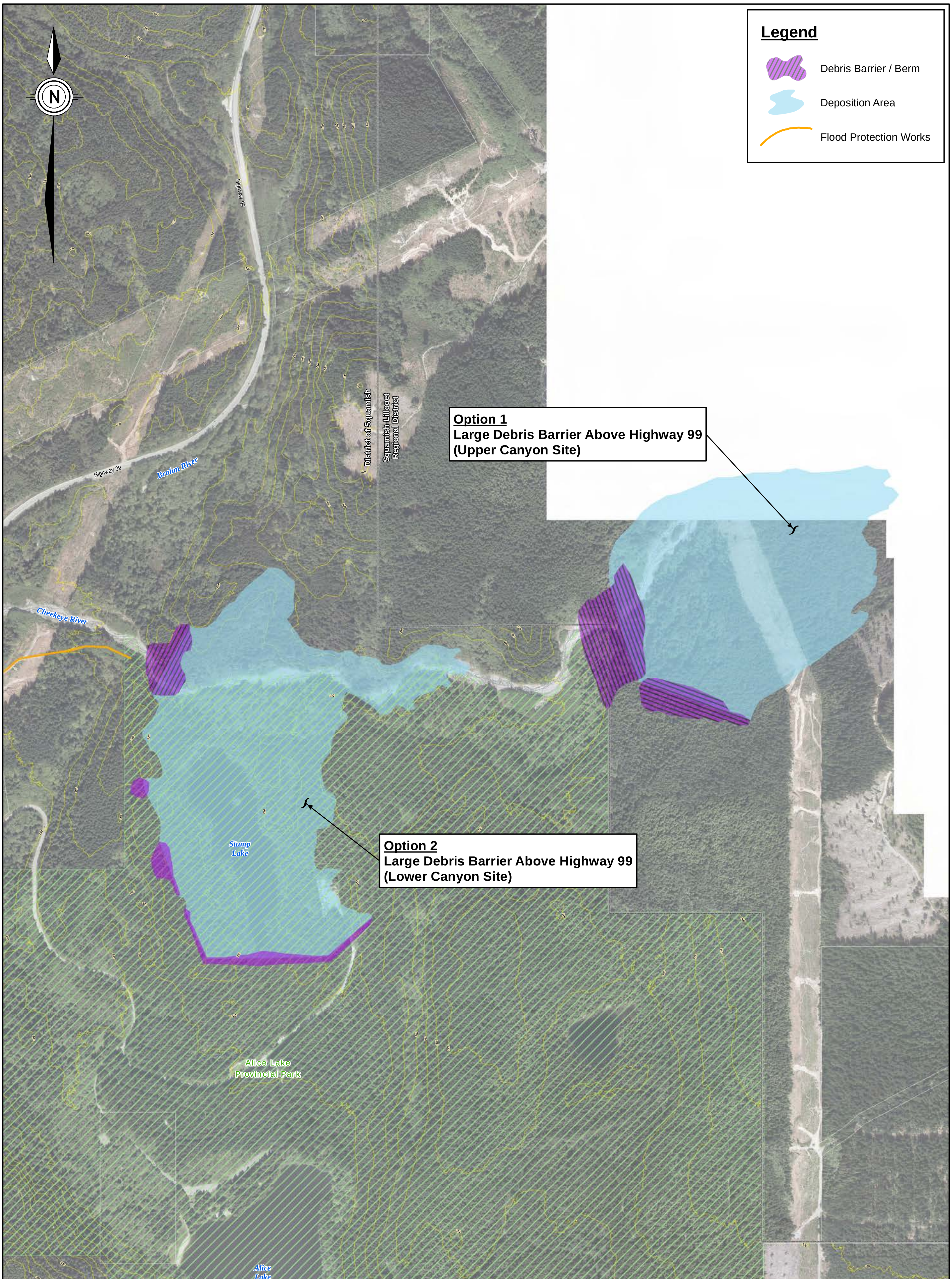

Note: Proposed works based on BGC Engineering Draft Project Memorandum dated November 24, 2015.

Reference: Orthophoto from District of Squamish, 2013.

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consulting engineers

Assessment of Mitigation Alternatives for Cheekeye Fan

Project No.	Date
463-311	April, 2016

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(m)

Debris Barrier Alternatives Above Highway 99

Figure 3-3

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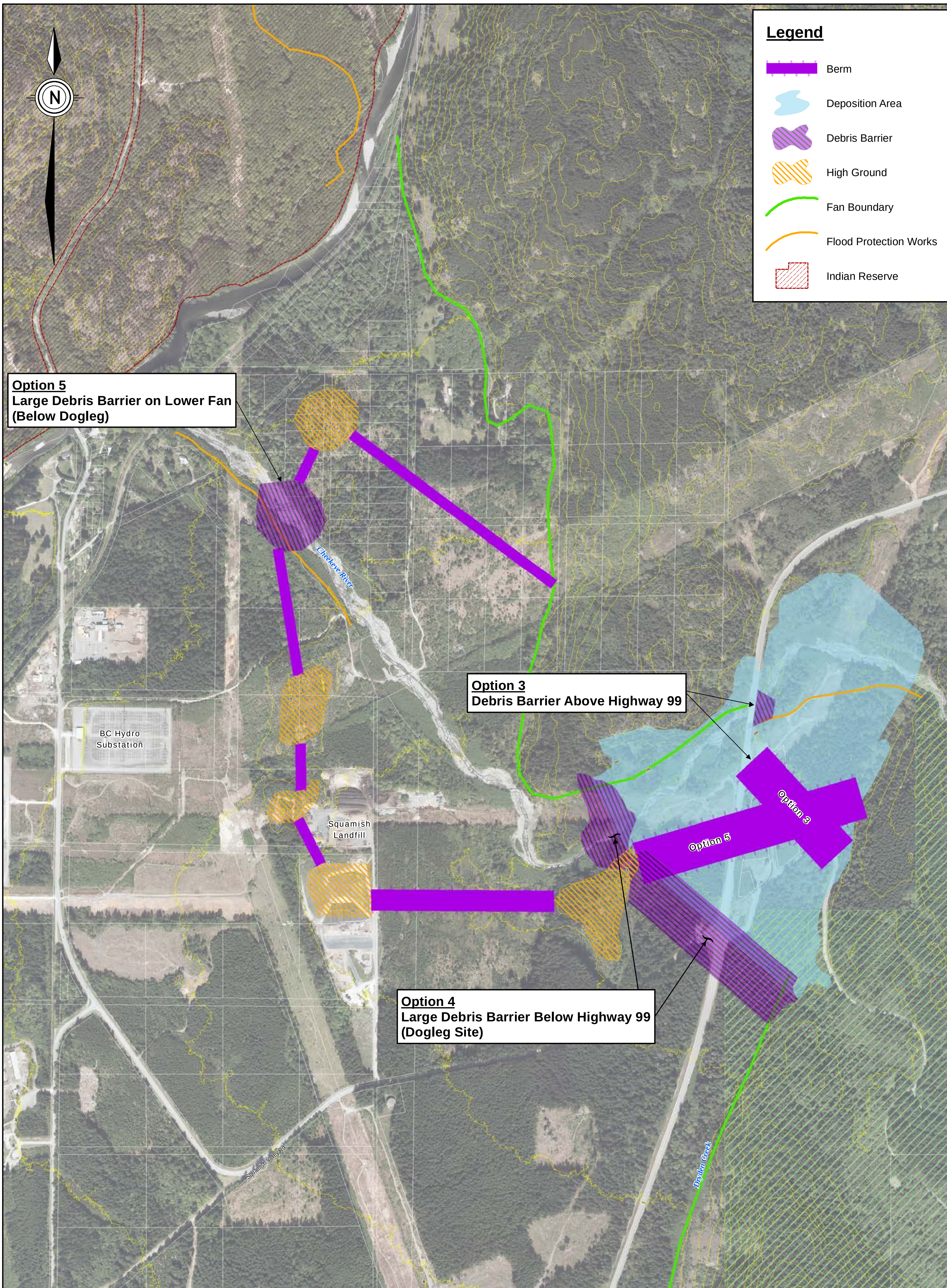

Note: Option 4 works based on BGC Engineering Draft Project Memorandum dated November 24, 2015.

Reference: Orthophoto from District of Squamish, 2013.

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Assessment of Mitigation Alternatives for Cheekeye Fan

Project No.	Date
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Debris Barrier Alternatives 4, 5 and 6

Figure 3-4

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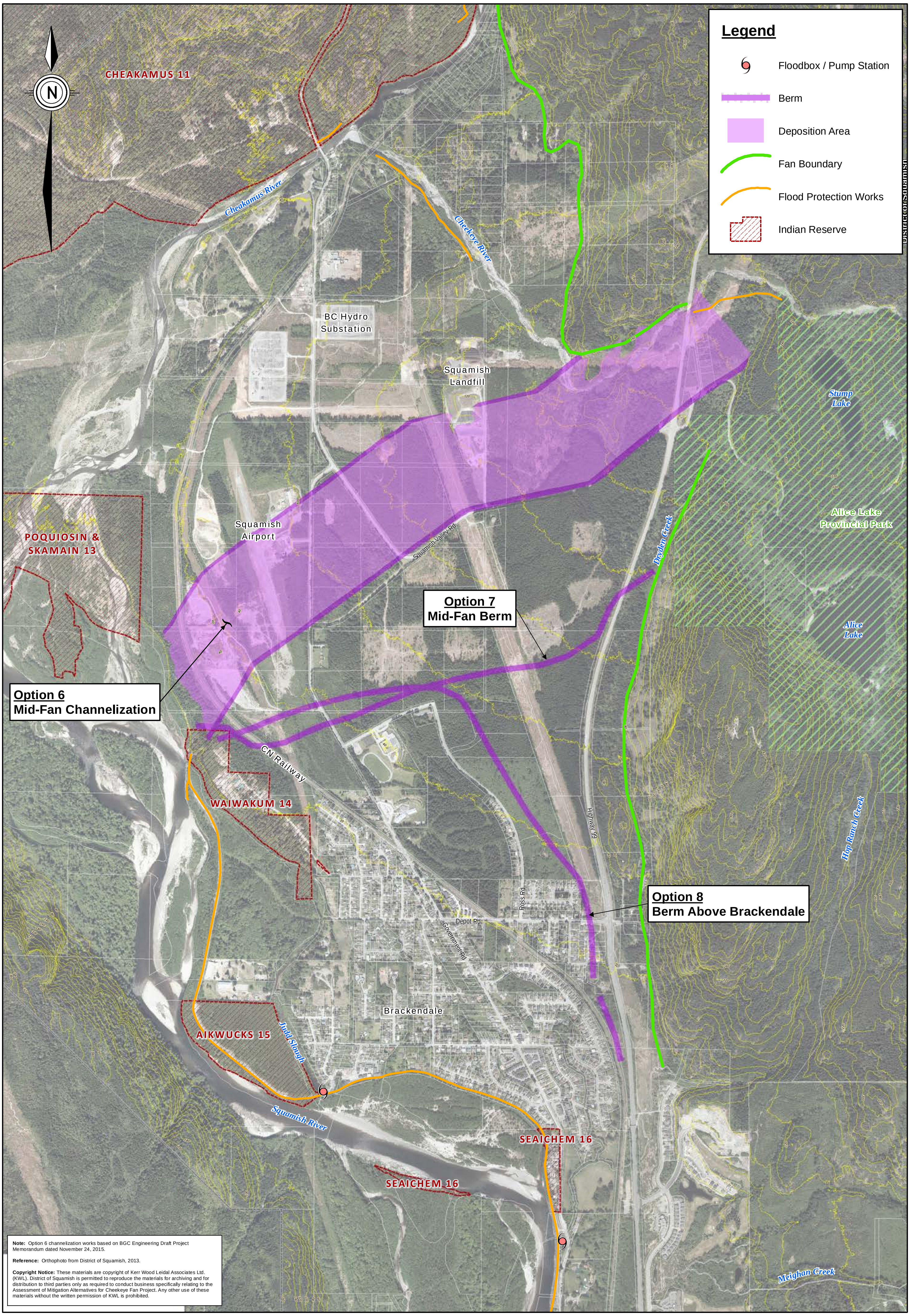

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Assessment of Mitigation Alternatives for Cheekeye Fan

Project No.	Date
463-311	April, 2016

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Berm and Channelization Alternatives

Figure 3-5

Table 3-5: Primary Debris Flow Mitigation Alternatives for Cheekeye Fan

Reference	Description	Commentary
1. Large Debris Barrier Above Highway 99 – Upper Canyon Site 2. Large Debris Barrier Above Highway 99 – Lower Canyon Site	Two sites have been identified where a (very) large debris barrier having up to 5.5M m^3 could be constructed. These alternatives have been investigated to a conceptual level by BGC Engineering. Either site would likely involve a dam-like earthen structure (with concrete and steel components) in a canyon, allowing deposition within a natural basin upstream. Some berming on the flanks of the basin areas would be needed to prevent side outflow. Either site could also be built with a smaller volume as part of a multiple barrier approach.	With such a barrier, the debris flow hazard would be significantly mitigated upstream of Highway 99 to the benefit of all of the District's mitigation priorities. Highway 99 would be protected in its current location and alignment. Such a barrier could adequately mitigate the debris flow hazard to all areas of the fan. As debris would be contained upstream, there would be no transfer of risk from one area to another. The sites are partly (lower canyon site) or fully (upper canyon site) within Alice Lake Provincial Park. The upper canyon site is also significantly outside of the District boundary, within SLRD. During a large debris flow, debris retained at the lower canyon site would infill Stump Lake. Some additional (complex and undefined) works would be required in the highway vicinity (perhaps berms and additional conveyance capacity under highway), and along the creek corridor (to be determined).
3. Debris Basin Above Highway 99	A large debris basin could be constructed immediately above Highway 99 through a combination of berming and excavation. The work would need to avoid impacting fish access to Brohm River. A small outlet structure would likely still be required. The upper limit of storage volume has not been considered. This alternative may not be able to achieve 5.5M m^3 storage volume. A range of volumes could be considered as one component of a multiple barrier approach. At a small scale, this alternative could simply be a sediment basin.	This alternative would avoid Highway 99 modification or relocation. The power line crossing above Highway 99 would pass through the basin and may be an issue.
4. Large Debris Barrier Below Highway 99 – Dogleg Site	A large debris barrier could be constructed below the Highway 99 bridge. This would involve a barrier structure at the dogleg and a berm to high ground extending across Highway 99 near the Alice Lake access road. This site could also be built with a smaller volume as part of a multiple approach. This alternative was not investigated in detail for this report.	Highway 99 would have to be regraded to go over the berm, or be relocated on the upper fan with a new bridge upstream of the existing crossing. The Highway intersection with Alice Lake access road / Squamish Valley Road may also need to be modified or relocated. These roadwork issues could be significant, and would fall under provincial jurisdiction. The existing Highway 99 bridge area would remain vulnerable to closure. The power line crossing below Highway 99 would pass through the basin and may be an issue. Fish access to Brohm River would need to be preserved.
5. Large Debris Basin on Lower Fan – Below Dogleg	A debris barrier could be built below the dogleg, with berms to high ground on either side. Unless work is done in the vicinity of Highway 99 to prevent debris flow avulsion down the highway, this barrier would only be effective as a downstream component of a multiple barrier approach. This alternative was not investigated in detail for this report.	The multiple berm sections required under this alternative would be spread over a considerable distance, potentially resulting in an operational difficulty. This alternative would be aided by expansion of the District landfill to the east (the landfill would act as a berm). Fish access to Brohm River would need to be preserved.
6. Mid-Fan Channelization (to Squamish River)	Channelization of the Cheekeye River (as either realignment of the existing mainstem or, more likely, as an overflow channel) could be achieved through some combination of channel excavation and berm construction. The objective would be to deflect debris flows away from Brackendale toward Squamish River. There may be a variation to commence the channelization works at the dogleg rather than above Highway 99. This alternative was not investigated in detail for this report.	Highway 99 would have to be regraded to go over the berm, or be relocated on the upper fan with a new bridge upstream of the existing crossing. The Highway intersection with Alice Lake access road / Squamish Valley Road may also need to be modified or relocated. These roadwork issues could be significant, and would fall under provincial jurisdiction. The existing Highway 99 bridge area would remain vulnerable to closure. The works would cross a BC Hydro transmission line, Squamish Valley Road, and Government Road. Issues would have to be addressed in each case. In the absence of other measures, this alternative would not significantly protect Cheakamus I.R. No, 11 or the confluence residential development. The works would direct debris flow toward the Squamish Airport. These works would direct debris flow toward Squamish River above a major river constriction, which may lead to hydraulic complications. Transfer of risk is a significant concern of this alternative.
7. Mid-Fan Berm (to Squamish River)	This option would involve a series of large berms across the fan, commencing at high ground east of Highway 99, crossing the highway and terminating north of IR 14. Significant variations in alignment could be accommodated. A number of supplemental berms could be constructed for specific purposes, if desired. This alternative was previously investigated to a preliminary design level by KWL in 2003.	Highway 99 would have to be regraded to go over the berm. The Highway 99 bridge area would remain vulnerable to closure. The works would cross a BC Hydro transmission line and Government Road. Issues would have to be addressed in each case. In the absence of other measures, this alternative would not benefit Cheakamus I.R. No. 11 or other development at the Cheekeye River / Cheakamus River confluence. The works would direct debris flow toward the Squamish Airport and a section of railway between the airport and IR 14. These works would direct debris flow toward Squamish River above a major river constriction, which may lead to hydraulic complications. Transfer of risk is a possible concern for this alternative.
8. Berm Above Brackendale	This alternative would involve a berm around upper Brackendale. Significant variation in alignment could be accommodated. A number of supplemental berms could be constructed for specific purposes, if desired. This alternative was not been investigated in detail for this report.	On the west side of Brackendale, this alternative would need to address (to some extent) the issues noted above for Alternatives 6 and 7 at Government Road and CP Railway, as well as the hydraulic issue with Squamish River. On the east side of Brackendale, this alternative would need to address issues associated with proximity to Highway 99 and crossing Depot Road (primary access to Brackendale). It would also require integration with diking, floodplain and drainage issues on lower Dryden Creek to the pump station. Some property acquisition might be considered in order to improve the berm alignment.
9. Large-Scale Retreat	Acquire sufficient lands on the fan to reduce the overall risk to ALARP. This may include isolated developments as well as a significant portion of Brackendale. Areas that are not acquired would need to be appropriately protected.	The extent and cost of this alternative would be significant but cannot be assessed in detail without further risk assessment work. Implementation could be phased over a multi-decadal timescale. Small-scale managed retreat may be combined with several of the other alternatives as part of a comprehensive mitigation plan.

4. Discussion of Local Issues

This section provides commentary on many local issues that should be considered in developing and implementing a mitigation alternative for the Cheekeye Fan. This list of issues is not considered to be comprehensive. Additional issues may be identified following further work with the District of Squamish and other parties.

4.1 Engineering Issues

Some key engineering issues are identified and discussed below.

- **Large Debris Barriers:** The largest debris barrier constructed to date in BC has a debris storage capacity (volume) of less than 100,000 m^3. It should be recognized that the large structures being contemplated for the Cheekeye Fan would be an order of magnitude larger and would be among the largest of this type in the world. As such, the technology may not be considered to be "tested and proven" for coarse debris flows such as may occur on the Cheekeye River. Despite the different characteristics, some lessons may be learned from the large lahar (fine volcanic debris flow) retention works on the North Fork Toutle River in Washington State (downstream of Mount St. Helens).
- **Multiple Barrier Approach**: It is generally accepted that a multiple barrier approach to mitigation will provide more effective mitigation for debris flow situations than a single-barrier approach. Reducing reliance on any single structure increases the overall system reliability and redundancy. For the Cheekeye Fan, the best technical solution may be a combination of different structural measures.
- **Consideration of "Small" Debris Flows:** Depending on how they are designed, large barriers may pass "small" debris flows up to perhaps the 100-year return period. This will present a residual hazard to that would require further consideration to provide appropriate protection to downstream areas (particularly along the river corridor).
- **Sediment Management:** Ongoing sediment transport and management issues need to be addressed for any structural mitigation option. Sediment transported by the "normal" clear-water flow regime may either be passed through the structure or retained. Retention can result in changes to the downstream channel and create challenges with regard to reserve capacity (discussed below). Sediment management may be aided through establishing a sediment basin (a site above Brohm River confluence has been proposed previously, this would be good from a fisheries perspective). Sediment management efforts downstream of Brohm River would need to address fisheries issues. Some relevant background infraction on sediment management on the Cheekeye River is provided in Appendix C in the forum of a 2014 KWL Technical Memorandum.
- **Reserve Capacity:** For any mitigation scheme that is sized for a specified event volume, consideration should be given to adding an appropriate reserve capacity to allow for deposition of material that has not been able to be removed on a timely basis, particularly "small" debris flows and routine sediment transport. Increasing the reserve capacity may reduce the frequency of sediment removal.
- **Area Protected:** Different types and locations of mitigation structures will protect different portions of the fan. For example, large debris barriers at/above Highway 99 will reduce the risk to the whole fan. In contrast, alternatives involving a mid-fan berm would reduce the risk to the Brackendale

area, but would leave the upper fan and other areas outside the berm alignment largely unprotected.

- **Transfer of Risk:** It is important that a mitigative approach not inappropriately transfer risk from one area to another. In this regard, debris barrier alternatives are generally considered preferable to berming alternatives (at least some portion of the volume will be stored, rather than deflected). For example, a mid-fan berm may reduce the risk to Brackendale by redirecting a debris flow toward another at-risk area.
- **ALARP Principle:** In order to meet the ALARP principle, not only must the computed risk be within the ALARP zone of an F-N diagram, but it needs to be established that the cost to further mitigate the risk would be grossly disproportionate to the benefit gained, or that the solution is impractical to implement. No specific guidance is available as to how "grossly disproportionate" should be defined in the context of Cheekeye Fan debris flow risk mitigation.
- **Cheakamus River**: Options that "funnel" debris flows down the Cheekeye River may result in massive sediment input to the Cheakamus River at the mouth of the Cheekeye River. This area is a critical hydraulic reach. Such an occurrence could obstruct the Cheakamus River, increasing upstream flood levels. It would also increase the risk of a river avulsion toward IR 11. In addition, private works such as the existing left bank dike downstream of the Cheakamus River (Fergie's) Bridge may have the unanticipated consequence of exacerbating debris flow risks.
- **Squamish River**: Large debris flows on the Cheekeye Fan would convey debris flow material to Squamish River at or upstream of a critical "bottleneck" in the Squamish River (at Aikwucks I.R. No. 15). This may increase the probability of a dike breach that may impact the above-noted south Brackendale floodway area. Options that involve channelization and/or berming could further increase this risk.Land and Infrastructure Development Issues

4.2 Land and Infrastructure Development Issues

Some key issues associated with land and infrastructure development are identified and discussed below.

- **South Brackendale**: Approximately half of Brackendale at the base of the Cheekeye Fan is also within the Squamish River secondary floodway (i.e. in the event of a dike breach). This area has been flagged for special attention in the IFHMP. It may be appropriate to integrate floodplain management and debris flow mitigation considerations for this area.
- **Cheekeye River / Cheakamus River Confluence:** The Cheekeye River / Cheakamus River confluence encompasses a low-lying area of the Cheakamus River floodplain at and opposite the mouth of the Cheekeye River. Development includes the Cheekeye community on Cheakamus I.R. No. 11 as well as Sunwolf Resort and other private development. The area is subject to hazards from both the Cheakamus River and the Cheekeye River, which may occur at the same time or as independent events. A private dike has been previously constructed on the left bank of the Cheakamus River downstream of the Squamish Valley Road (Fergie's) bridge and may have created a transfer of risk. A costly protective dike proposed for the Cheekeye community may encounter similar issues, as well as challenges associated with accommodating relief flow in the event of a bridge blockage. Any reduction in the magnitude of Cheekeye River debris flow magnitude at the river confluence would reduce the hazard to this community. Any "funneling" of debris flow material down the Cheekeye River would increase the hazard to this community. The IFHMP recommends that local-scale issues at the Cheekeye River / Cheakamus River confluence

be addressed once both the IFHMP River Flood Risk Mitigation Report and this report on Cheekeye Fan debris flow mitigation options are complete.

- **Isolated Developments**: There are other isolated developments on the lower fan in the vicinity of the CN Railway bridge, above the Cheakamus River floodplain. These would be difficult to protect, especially if cost-effectiveness is a consideration.
- **Garibaldi Estates:** The finer, more mobile fraction of debris flow runout material could extend beyond the base of the Cheekeye Fan into parts of the Garibaldi Estates community on the Mamquam River fan.
- **Land Use Potential:** Options that protect a greater portion of the mid to upper fan may allow consideration of a greater range of future land uses and community development.
- **Retreat:** Various degrees of retreat could be considered to mitigate areas of particularly high risk. Large-scale retreat could be considered as an alternative to major mitigation structures. Smaller-scale managed retreat (i.e., a staged process targeting specific blocks or buildings) may be appropriate as a supplemental measure under any of the structural mitigation alternatives.. Managed retreat may be most applicable in areas where the hazard is particularly severe, and/or where the incremental cost to protect the development is greater than the cost to retreat (i.e., near the Cheekeye River / Cheakamus River confluence).
- **SLRD Territory:** The upper Cheekeye Fan is beyond the District of Squamish boundary, within SLRD territory. The upper canyon debris barrier would extend into this territory and would need to address any resultant issues.
- **Other Interests:** Some issues associated with lands held by the BC Ministry of Transportation and Infrastructure, Indian and Northern Affairs Canada, CN Rail, and BC Hydro are outside District's jurisidcation. These stakeholders have not (yet) been directly consulted on the contents of this assessment. Interests associated with specific infrastructure owned or operated by these parties are addressed in Section 5.

4.3 Existing Infrastructure Issues

Some key issues associated with existing infrastructure on the fan are identified and discussed below.

- **Highway 99:** The current configuration of Highway 99 near the fan apex could allow a debris flow to follow the highway corridor into the heart of Brackendale. To be effective, most structural alternatives would require at least some modification of Highway 99 to mitigate this possibility. Modifications could involve regrading the highway to incorporate a berm crossing, adding flow-through provision under the highway, or complete relocation of the highway to a higher-elevation alignment (likely with a new bridge over the river). Some of these provisions could be very costly, complex and disruptive. Road intersections with Squamish Valley Road and the Alice Lake access road may also require modification.
- **Economic Impacts**: It has been estimated that the economic cost of a Highway 99 closure may be in the order of $1M per day. The effects of a highway (or railway) closure would extend throughout the Sea to Sky corridor. Other local economic impacts would include infrastructure damage, general disruption, loss of employment, emergency response, and building recovery.
- **Primary and Secondary Road Access:** Under any alternative, it is important that access into various residential areas be preserved and reasonably protected. Squamish Valley Road (including

Fergie's bridge) is the only access to the Squamish Valley and Paradise Valley. Brackendale is accessed via Government Road (north and south) and Depot Road.

- **Dikes:** Cheekeye River debris flows that reach the lower fan would back up behind the existing dyke system along Judd Slough, Squamish River, Harris Slough and Mamquam River. This may impact the dike.
- **Pump Stations:** Downstream pump stations and floodboxes are likely to suffer from sedimentation during and after a debris flow event. This may result in ongoing operational problems.
- **Squamish Landfill:** The ongoing landfill development could be integrated into some barrier and berm options to effectively provide low-cost fill. This may give rise to some long-term options.
- **Squamish Airport:** The airport is not intended to be a focus for mitigation, but would require consideration under certain options (berm and channelization in particular) to ensure compatibility.
- **CN Railway:** The railway traverses the lower fan and crosses the Cheekeye River just above the confluence. The railway bridge has been frequently impacted by floods and sedimentation events, with periodic service disruptions. The railway would benefit from reduced hazard in the bridge vicinity.
- **Industrial Areas:** There are some scattered industrial developments along the lower Cheekeye Fan, upland of the CN Railway. These are not intended to be a focus for mitigation, but would also require consideration under certain options (berm and channelization in particular) to ensure compatibility.

In evaluation of alternatives, it should be recognized that some alternatives have the advantage of protecting more infrastructure than other alternatives.

4.4 Environmental and Community Issues

Some key environmental and community issues are identified and discussed below.

- **Aquatic Habitat Impacts**: Instream structures can impact fish access along a creek or river. In this region, this issue is most critical for migrating salmon. Maintaining salmon access from Cheakamus River to Brohm River via Cheekeye River is considered a critical issue for any proposed structure on Cheekeye River. Some options would involve a berm across Dryden Creek, for which it would be critical to address fisheries issues as well. Changes in the sediment transport regime can also affect aquatic habitat and productivity.
- **Terrestrial Habitat Impacts**: Some structural mitigation options may disrupt wildlife movement along certain corridors, such as along the Cheekeye River.
- **Overall Environmental Impact**: Any approach must include a broad assessment and mitigation of environmental impacts (fish, wildlife, sensitive habitats, etc.). A common guideline is "no net loss".
- **Regulatory Challenges**: Some options may trigger formal environmental impact assessment processes. Virtually all options would require approvals pursuant to the Water Act and Dike Maintenance Act.
- **Social and Community Impacts:** There is no known work to date on the subject of social vulnerability or social risk fromo Cheekeye Fan debris flow hazards (e.g., issues associated with displacement and sheltering of vulnerable populations, loss of employment, or interruption of key community services).

- **Recreation/Trail Impacts:** There are many trails through the Cheekeye Fan area that are popular for hiking, wildlife viewing and mountain biking. It is important to minimize/mitigate impacts to the trail system.
- **Aesthetics:** While aesthetics do not usually govern the choice of a structural mitigation option, it is important to recognize that some options will have a more substantial visual impact for residents and travellers (e.g., along Highway 99) than others.
- **Alice Lake Park**: Options that are within the park, or could impact park land or use, would require review and approval by BC Parks.

4.5 Operational Issues

Key operational issues are identified and discussed below.

- **Public Safety:** Debris barriers invariably include high vertical structures that result in a significant fall hazard. Careful attention to design, fencing and signage issues is needed to maintain an appropriate level of public safety (and worker safety) and reduce liability of involved parties.
- **Financial Considerations:** Large-scale mitigative works, such as are being considered for the Cheekeye Fan, are expensive to construct, operate, maintain, restore after an event and (eventually) decommission or replace. A key cost component will be regular removal of accumulated sediment. Operation and maintenance costs are of critical importance as they constitute the long-term costs to the community after the mitigation works are built.There needs to be an appropriate long-term funding mechanism to cover the full range of life-cycle costs.
- **Operation and Maintenance Logistics:** Any works constructed need to have land tenure and equipment access. A maintenance authority needs to be established (most likely the District of Squamish in this case). The maintenance authority will likely be obligated to provide regular inspection reports to a regulator such as the Ministry of Forests, Lands and Natural Resource Operations' Dam Safety Section or the provincial Inspector of Dikes.
- **Post-Event Recovery:** An approach must be identified to safely access, assess, and restore the structural mitigation works after a large event. This should include consideration of whether protection will be restored by removing infilled debris, or by constructing more structures. The role, if any, of senior government disaster relief financial assistance should be considered.

5. Evaluation of Primary Debris Flow Mitigation Alternatives

This section describes the development of a matrix tool used to perform an initial qualitative evaluation of primary debris flow mitigation alternatives for Cheekeye Fan. Use of the word 'primary' implies that the measures evaluated would be the most significant – but not the only – element(s) in a 'comprehensive mitigation plan'. Various supplemental measures would be required for each alternative.

For the purpose of comparison and discussion, the matrix also includes the non-structural alternative of large-scale retreat.

This section also describes the application of the matrix to evaluate the identified alternatives and identifies preferred mitigation alternatives.

5.1 Development of Evaluation Matrix

The list of issues in Section 4 was refined in consultation with District staff and Council to generate preliminary evaluation criteria and corresponding weighting factors. The criteria and weighting factors are focussed on the primary objective of protecting major existing development areas.

The evaluation criteria and weighting factors are listed below.

Evaluation Criteria		Weight
Economic	Capital Cost	5
	Capital Cost Sharing Potential	3
	Operation and Maintenance Costs	5
	Post-Event Recovery Costs	4
Environmental	Fish Impacts	4
	Disturbed Area	3
	Wildlife Corridor Impacts	1
	Sensitive Habitat Disturbance	3
Social – Risk	Risk Reduction	5
	Unmitigated Risk Transfer	4
	Land Use Potential	4
	Economic Risk Reduction	3
	Additional Assets Protected	2
Social – Design	Design Confidence	4
	Post Event Restoration Options	4
	Infrastructure Impacts	3
	Regulatory Challenges	3
Social – Other	Aesthetics	1
	Cultural / Archeological Impacts	2
	Recreation / Trail Impacts	1

Weighting Factors	
5	extremely important
4	very important
3	somewhat important
2	minor importance
1	negligible importance

A blank copy of an evaluation matrix incorporating these criteria and weighting factors is provided in Appendix A. The matrix sheet includes more detailed descriptions of the evaluation criteria and scoring system (on a scale of 1 to 3 for each criteria). The matrix has been developed under a triple bottom line concept in that it incorporates economic, environmental and social aspects.

In applying the evaluation matrix, it is important to recognize that results are integrated across all criteria to provide an overall score. The weighting factors give appropriate emphasis to the most important criteria; however, there may still be circumstances where it is appropriate to compare scores for individual criteria.

5.2 Evaluation of Primary Debris Flow Mitigation Alternatives

Appendix B includes a copy of the completed evaluation matrix, with the scores shown being the average of the three independent scores (Mike Currie, Gary Buxton, David Roulston). Some effort was made to resolve scores having a significant variation from the three individual scores, particularly for the highest ranking alternatives. The matrix results are considered inexact in that some criteria have not been researched in detail (i.e., environmental impacts, archaeological impacts, etc.), and economic criteria have only been considered qualitatively.

The matrix evaluations were rounded to the nearest even number, recognizing the inexact nature of this type of analysis. Of the primary debris flow mitigation alternatives, the matrix evaluation divides the alternatives into three groups having similar scores as follows:

- **highest ranking:** two debris barrier sites above highway, mid-fan berm, Brackendale berm;
- **middle ranking:** two debris basin sites below highway; and
- **lowest ranking:** mid-fan channelization.

An evaluation matrix is an appropriate screening method to identify the most promising primary debris flow mitigation measures for Cheekeye Fan. However, it is important to note that the outcome is dependent on the selected criteria, weightings, scoring system, and the subjective opinion of those assigned to complete the scoring. Other methods of screening may also be valid, and may produce slightly different results.

Table 5-1 provides high-level commentary on the results of the evaluation matrix for each primary mitigation alternative. Further discussion of the highest-ranking alternatives is provided in Section 5.3.

Table 5-1: Commentary on Evaluation Matrix Results

Alternative	Rank (Out of 9)	Discussion	Summary Comment
1. Large Debris Barrier Above Highway 99 – Upper Canyon Site	3(T)	The debris barrier sites above Highway 99 rate quite high. They provide the greatest level of risk reduction (in fact, protect all areas downstream), do not transfer risk, could allow for community development, provide cost-sharing opportunities, and have virtually no infrastructure impacts. The most significant drawback is cost (for construction, O&M, and post-event restoration). There may also be some regulatory challenges.	Debris barriers above Highway 99 are considered promising alternatives based on current criteria. The upper canyon site appears most promising of the two.
2. Large Debris Barrier Above Highway 99 – Lower Canyon Site	5(T)		
3. Debris Basin Above Highway 99	2	While this measure ranks high, it would not easily provide sufficient protection on its own to be considered as a primary measure. To provide a debris basin of sufficient size would essentially require the incorporation of Alternative 1 or 2.	This measure may be best applied as part of a package of measures, possibly in the form of a sediment basin.
4. Large Debris Barrier Below Highway 99 – Dogleg Site	7	Debris barrier sites below Highway 99 appear less effective than the sites above Highway 99. In comparison, they have greater environmental impacts, do not protect Highway 99, and would be more visible.	Barrier options below Highway 99 are considered less favourable alternatives based on current criteria. Debris barrier sites above Highway 99 are more favourable.
5. Large Debris Basin on Lower Fan – Below Dogleg	8		
6. Mid-Fan Channelization (to Squamish River)	9	This measure has many challenges, including high cost (for construction, O&M, and post-event restoration), a high level of disturbance, design confidence, regulatory challenges, infrastructure impacts, aesthetics and trail impacts. Delivery of debris directly to the Squamish River above a key river constriction would also transfer risk.	This option is considered less favourable based on current criteria.
7. Mid-Fan Berm (to Squamish River)	3(T)	These two berm alternatives rank high. The mid fan berm ranks higher as it has fewer conflicts with existing development and infrastructure, could allow for some community growth, and has some cost-sharing potential. The mid fan berm would have to address challenges with crossing Highway 99 and Dryden Creek. Neither berm scenario would protect infrastructure on the upper fan, nor protect the confluence area including IR 11. Land acquisition may be a challenge with both berm scenarios.	The mid fan berm is considered a promising alternative based on current criteria. The exact berm alignment is highly flexible. Lower berm options toward Brackendale may be considered as a variation if there is an interest in proceeding with a berm.
8. Berm Above Brackendale	5(T)		
9. Large-Scale Retreat	1	Shows that large-scale retreat would be effective as mitigation. Given that the necessary degree of retreat is not known, the cost of property acquisition cannot be assessed, but would be significant. There is no apparent potential for cost-sharing. It would not allow for community growth, nor protect existing infrastructure. On the positive side, there would be minimal technical issues and significant areas could be reclaimed to their natural state for less-intensive land use (e.g., recreation and resource applications).	This alternative appears to be technically favourable but cost-sensitive. The extent of retreat should be assessed before making a final decision. Unless there is strong support and funding for large-scale retreat, this measure may be best applied on a small scale as part of a package of measures.

5.3 Comparison of Most Promising Primary Mitigation Alternatives

The evaluation process highlighted two structural alternatives as the most promising primary mitigation measures: the mid fan berm and the upper canyon debris barrier. These two alternatives are compared in Table 5-2, with the advantages shown for each. As noted above, this comparison is considered inexact in that some criteria have not been researched in detail.

Table 5-2: Advantages for Mid Fan Berm and Upper Canyon Debris Barrier

Criteria	Mid Fan Berm	Upper Canyon Debris Barrier
Economic	• anticipated lower capital cost (to be confirmed) • anticipated lower O&M costs (to be confirmed) • lower post-event recovery costs • may be possible to phase implementation over time	• greater cost-sharing potential
Environmental	• less fisheries impacts • less wildlife corridor impact • less sensitive habitat disturbance • less disruption of natural river processes	• less total disturbed area (or “footprint”)
Social - Risk		• greater overall level of risk reduction • minimal transfer of risk • allows for community development (land use) • significant economic risk reduction • protects significant additional assets
Social – Design	• traditional technology resulting in more reliable design confidence • easier post-event restoration • less regulatory challenges	• minimal impacts for existing infrastructure
Social – Other		• less aesthetic impact • smaller footprint avoids conflicts with cultural sites and recreational trails

Commentary on Mid-Fan Berm

In summary, the mid fan berm has a significant advantage in the economic criteria, and lesser advantages in the environmental, and social-design criteria. Of the assets identified as high priority in Section 3, the mid fan berm would protect Brackendale, Waiwakum I.R. No. 14, Seaichem I.R. No. 16, Kowtain IR 17, and Garibaldi Estates.

Some limitations, challenges and/or disadvantages of the mid fan berm compared to the upper canyon debris barrier are noted as follows:

- Cheakamus I.R. No. 11 and the confluence residential area would not be protected;
- other important assets would also not be protected, including Highway 99, CN Railway, Squamish Airport, Squamish Valley Road and Squamish landfill;
- undeveloped lands north of the berm would remain unprotected, and not suitable for development;
- extending the berm alignment across Highway 99, Dryden Creek, Government Road and the CN Railway would present significant technical challenges; and
- the berm may transfer risk by redirecting debris flows that would otherwise reach Brackendale toward the airport area.

The mid-fan berm concept allows for some flexibility in alignment. The structure could be shifted south, possibly as far as the "berm above Brackendale" option.

The mid fan berm would require relatively few complementary structural measures to develop a comprehensive mitigation plan (such works would likely comprise channel works and sediment management works along the river corridor).

The mid fan berm is not compatible with the proposed new development as presently conceived. It may be compatible with a smaller or reconfigured proposed development limited to the Ross Road area.

Commentary on Upper Canyon Debris Barrier

The upper canyon debris barrier has a significant advantage in the social-risk criteria, and a slight advantage in the social-other criteria. It would offer significant and equal protection for all of the assets identified as high, medium and low priority in Section 3.

Some limitations, challenges and/or disadvantages of the upper canyon debris barrier compared to the mid fan berm are noted as follows:

- challenges associated with being in SLRD territory and requiring work within Alice Lake Provincial Park would need to be addressed;
- Cheakamus I.R. No. 11 and the Cheekeye River / Cheakamus River confluence would be significantly protected against large Cheekeye River debris flows, but may remain vulnerable to smaller debris flows that pass through the debris barrier (these areas would also remain vulnerable to flooding and erosion from Cheakamus River under all mitigation scenarios);
- environmental approval requirements are not well known, and may result in a significant challenge;
- post-event restoration would primarily involve instream work to clear the debris barrier (costly, challenging and environmentally-sensitive);

- the complex and unprecedented design may be expected to add cost and time to the design, review and approval processes; and
- a debris barrier structure does not easily lend itself to phased construction over a period of years.

While this screening-level evaluation considers only a single large debris barrier above the fan, it may ultimately be preferable to construct multiple smaller structures. This is discussed further in Section 6.

The upper canyon debris barrier would require significant complementary structural measures to develop a comprehensive mitigation plan (possibly including sediment basin, berm above highway, works in highway bridge area, berms below highway, and channel works).

BMS Cheekeye One Projects has indicated that it is willing to pay the capital cost for the upper canyon debris barrier, and work with the District to establish a funding mechanism in the proposed new development area to cover operation and maintenance costs. This demonstrates that the proposed new development is also compatible with the debris barrier. If the financial arrangement suggested by BMS Cheekeye One Projects is confirmed, it may be possible to implement the upper canyon debris barrier alternative at minimal up-front cost to the District.

While the cost-sharing opportunity suggested by BMS Cheekeye One Projects could cover up-front capital costs (and potentially operation and maintenance costs), the District would presumably be responsible for any major response, post-event recovery, and/or future reconstruction costs. Because both existing and new development would remain in place in perpetuity, the District may wish to incorporate structural design life and any potential costs for decommissioning and replacement into its decision framework.

5.4 Commentary on Large-Scale Retreat

Large-scale retreat does not lend itself to easy comparison with the structural mitigation options. As suggested by its high score in the evaluation matrix, large-scale retreat has many positive aspects, and is probably the most effective long-term approach to reducing risk on the Cheekeye Fan. However, the economic and social costs of large-scale retreat may be prohibitive, and full implementation would likely span several decades.

The District may wish to investigate the scope, scale, cost and implications of risk mitigation through large-scale retreat more fully before selecting an approach for the Cheekeye Fan. Recent discussions with council related to the IFHMP suggest that the District's constrained land base will be a significant consideration in any debate that involves gradual but certain retreat from existing developed areas. The District may be forced to choose between densifying less vulnerable floodplain areas versus the Cheekeye Fan.

Small-scale managed retreat may play a targeted role in a comprehensive plan built around any of the primary mitigation measures noted above.

6. Future Considerations

This section provides some information to assist the District in moving forward.

The District is understood to have accepted the recommendation from Cheekeye Expert Panel #2 to use quantitative risk assessment based on the F-N diagram as a basis for determining tolerable risk, and the scale of mitigation measures. Ultimately, it will need to be determined whether to supplement the risk criteria with a design return period approach for the creek corridor. It also needs to be determined how to apply the qualitative component of ALARP (the cost to further mitigate the risk would be grossly disproportionate to the benefit gained, or the solution is impractical to implement). These aspects will be important in building a comprehensive mitigation plan that is based on a primary mitigation alternative.

This report does not provide a recommendation as to whether the proposed new development should be approved or not approved. However, one objective of this report is to assist decision-makers and stakeholders in making this important decision.

The proposed new development would be compatible with, and could financially support implementation of, the upper canyon debris barrier. As proposed, the new development is not compatible with the mid-fan berm or large-scale retreat. The development decision therefore becomes inseparable from the decision on risk mitigation.

Section 6.1 provides information that the District should consider when responding to the proposed new development.

Section 6.2 addresses the scenario of the proposed new development proceeding in the short term. Presumably this would incorporate a large debris barrier above the fan as noted in the previous section.

Section 6.3 addresses the scenario of the proposed new development not proceeding in the short term.

Section 6.4 identifies some other implications that the District may wish to consider.

6.1 Response to Proposed New Development

As noted in Section 5, BMS Cheekeye One Projects has proposed that its new development could cover the capital cost of a large debris barrier. BMS Cheekeye One Projects has also indicated that is willing to work with the District to implement a funding mechanism to cover ongoing operation and maintenance costs. This would be a major advantage to the District in the following respects:

- there would be no significant capital costs incurred by the District for initial construction (presuming that all the components needed to develop a comprehensive mitigation plan are included);
- all existing development and infrastructure would be significantly protected without transferring risk from one area to another;
- an appropriate level of community redevelopment could be considered in and around Brackendale (subject to District planning considerations, as well as Squamish River flood constraints and evaluation as part of the final Cheekeye Fan QRA); and
- a mechanism for financing long-term operation and maintenance could be provided.

The evaluation of primary mitigation alternatives in Section 5 identified that the large debris barrier alternative was one of the most promising measures. While the mid fan berm alternative ranked slightly higher in the evaluation matrix, the modest technical advantages are offset by the cost-sharing potential.

It would be appropriate for the District to continue its work with BMS Cheekeye One Projects to further investigate and refine this alternative. Primary objectives should include confirming the preliminary findings and resolving questions raised in this report with respect to the upper canyon debris barrier, as well as seeking a more complete understanding of the long-term implications to the District.

Further investigating the large debris barrier option in conjunction with the proposed new development should be contingent on the District accepting the following principles:

- the location, concept, and scale of the proposed new development are potentially acceptable from the perspectives of land use planning and community development;
- the concept of large-scale retreat is not favoured by the District at this time;
- quantitative risk assessment is accepted by the District as the primary tool for assessing the safety of the proposed development;
- the details of a clear and defensible approach to implementing, peer reviewing, and comparing the results of the QRA against acceptable risk criteria will be established and agreed in advance with BMS Cheekeye One Projects;
- the District would be willing to accept a large debris barrier above the fan as the primary mitigation measure; and
- the District is willing to accept long-term operation and maintenance responsibility for all works to be constructed, including any unanticipated and unfunded costs for repair, cleanout or reconstruction.

The District may also wish to consider in advance whether funding of the operation and maintenance program would extend from the proposed new development to other existing development or redevelopment areas that also would benefit from the mitigation works.

Further to the above, the District must understand that, even if a fully-funded mechanism for long-term operation and maintenance is implemented, a large debris flow could occur before the fund builds to a level capable of covering the costs of restoring and rehabilitating the structural mitigation works. Once the new development is in place, the District would have little choice but to complete the works and cover any temporary funding shortfall. A plan to address this issue should be developed to ensure that the District will be able to restore the intended level of protection without incurring a disproportionate financial burden. It is not known whether there would be any possibility of emergency management funding from senior governments.

It should also be recognized that a large debris barrier may not adequately protect all existing development and infrastructure. It may prove more cost-effective to pursue managed retreat in some areas, while implementing complementary protection in others (e.g., the Cheekeye community on Cheakamus I.R. No. 11). These considerations (and others such as emergency planning) would need to be defined as part of a comprehensive mitigation plan that could then be incorporated into District policy and guidelines.

6.2 Considerations if Proposed New Development Proceeds

If the proposed new development proceeds in the short term, some key steps related to debris flow mitigation are suggested below (not necessarily in order). Some of these are known to be at least partially completed at present.

Planning Considerations

1. Ensure that the approach for the Cheekeye Fan is compatible with the direction taken in the Squamish IFHMP that is nearing completion, and is reflected in any policy updates.
2. Initiate preliminary discussions with regulators and other stakeholders identified herein to ensure that any potential concerns are identified and addressed early in the process.
3. Develop an approach to future land use that is appropriate in view of both natural hazard and community development issues. The approach must include, but may not necessarily be limited to, the proposed new development.
4. Ensure that the ultimate vision for future land use is considered when evaluating the results of an updated quantitative risk assessment against acceptable risk or ALARP mitigation criteria.
5. Develop a framework to continue to achieve tolerable levels of risk as development evolves and is rebuilt over time. This may include implementation tools such as restrictive covenants.

Risk Assessment and Design Criteria

6. Prepare a consolidated hazard assessment report. This work is essentially complete, but the documentation should be updated to incorporate the most recent work.
7. Confirm a target risk level for the proposed new development that is acceptable to the District. Expert Panel #2 recommended an individual risk of 1:100,000, and a societal risk of ALARP. Whether such risk should be ALARP or “broadly acceptable” may require further consideration, as might the question of how to apply the ALARP principle of disproportionate costs and benefits.
8. Determine whether there should be a target level of risk (reduction) for existing development to be achieved in parallel with the proposed new development. For existing development, Expert Panel #2 recommended an individual risk of 1:10,000, and a societal risk of ALARP for the fan as a whole.
9. From the three suites of options recommended by Expert Panel #2, select the landslide hazard probability option that is most consistent with the acceptable risk criteria to be applied, and determine whether and how more extreme events will be included in the risk assessment.
10. Update previous QRA work to incorporate new data and confirm the debris storage volume that would be needed to achieve the target risk level(s).
11. Undertake peer review of the QRA work to a level appropriate in view of the degree to which the QRA work is used as a basis for major development and/or investment decisions.
12. Determine whether there should be a minimum return period for design of works within the Cheekeye River corridor, independent of the QRA. For example, specific design return periods could be selected for flood and debris flow works along the river corridor (e.g., to maintain more frequent events within a designated primary floodway, and ensuring that only more extreme events would overflow onto the fan). This approach could also help clarify the question of possible retreat from the highest hazard areas, which would become part of the primary floodway.

Approach to Debris Barrier Design

13. Refine the canyon debris barrier concept based on the following considerations:
    - consider whether it would be best to proceed with multiple smaller debris barriers versus one large debris barrier;
    - identify what other structural mitigation works may need to be combined with the debris barrier(s) as part of a comprehensive mitigation plan;
    - coordinate with regulators and District operations to confirm an appropriate target for reserve storage;
    - size the debris barrier(s) to meet the risk acceptability criteria, accounting for reserve storage;
    - ensure that there are no "show stoppers" (SLRD jurisdiction, park issues, environmental issues, regulatory challenges, etc.);
    - develop structural, geotechnical and hydrotechnical design criteria for the barrier(s);
    - develop a suitable debris barrier design concept that can satisfy the impact design criteria and accommodate overflow during an extreme event; and
    - compare the proposed structure with any similar structures elsewhere in the world in order to learn from previous experience and understand the degree to which new ground is being broken.
14. Perform debris flow modelling to quantify the residual risk to development on the fan in the event that the structural mitigation works are overwhelmed.
15. Obtain and review updated cost estimates for capital construction costs, operation and maintenance costs, and event recovery costs. Confirm that these costs remain compatible with the cost-sharing proposal suggested by BMS Cheekeye One Projects.

Operation and Maintenance

16. Confirm that the District is willing to be the maintenance authority for the debris barrier(s) subject to understanding the anticipated costs and having an acceptable long-term funding mechanism.
17. Also confirm that the District is willing to be the maintenance authority for other structural mitigation works and the sediment management plan.
18. Consider whether existing development areas (such as Brackendale) should participate in the funding mechanism for long-term operation and maintenance.

Comprehensive Mitigation Plan

19. Confirm complementary elements, in addition to the debris barrier(s) that would be needed as part of a comprehensive mitigation plan. In addition to the debris barrier(s), this may include:
    - sediment management measures, potentially including a sediment basin above Highway 99;
    - a training berm above Highway 99;
    - modifications at Highway 99 (possibly to include underflow capacity and/or highway regrading);
    - river works to contain design return period flood and debris flow;
    - channel stabilization works;
    - training berms at low areas on the south bank of the Cheekeye River below Highway 99;

- watershed management measures to monitor conditions in debris source areas and undertake appropriate rehabilitation work if/as needed;
- appropriate secondary measures (e.g., land use and floodproofing measures described elsewhere in this section);
- site-specific measures such as managed retreat or additional structural protection (diking) in focus areas such as the Cheekeye River / Cheakamus River confluence;
- integration of hazard-specific warning, emergency planning, and emergency response considerations into an appropriate annex to the District's Comprehensive Emergency Management Plan (CEMP); and
- a communication strategy to achieve public and stakeholder acceptance of the existing risks and District mitigation decisions.

20. Perform studies as appropriate to confirm that the proposed mitigation strategy:
    - would achieve the design and risk tolerance criteria;
    - would not result in any unacceptable environmental or social impacts;
    - is feasible and approvable in all respects;
    - would not transfer risk from one part of the fan to another; and
    - would achieve the ALARP principle (the effort to further reduce risk would be grossly disproportionate to the level of incremental risk reduction achieved).
21. Update debris flow modelling to better understand the residual risk with the proposed mitigation works in place.
22. Consider managed retreat for areas of high residual risk after the proposed mitigation measures are in place.

Sediment Management

23. Prepare a sediment budget to estimate sediment delivery to the fan during flood events from mean annual to (for example) the 500-year return period. This should include consideration of sediment/debris passage provisions at the debris barrier.
24. Prepare a sediment management plan that may include a sediment basin above Highway 99. Estimate the frequency, volume and cost of future sediment removal. The method of sediment removal and possible destinations for the excavated sediment should be identified. Acceptance of environmental agencies should be sought to at least ensure that they will not prevent the plan from being implemented.
25. Identify any alternatives that could support a more natural sediment management regime (e.g., managed retreat from a primary floodway corridor).

Floodproofing Measures

26. Identify floodproofing measures for the proposed new development. These may include:
    - site grading and floodways to route shallow flow through the development area in the event of the protective works being overtopped;
    - elevation of buildings above surrounding finished grade; and
    - building design features that are resistant to erosion;

27. design requirements for debris impact (e.g., loads, siting, and orientation) for any structures that remain within the potential runout zone of large debris flow associated.
28. Implement appropriate regulatory land use provisions for long-term development control in both the proposed new development area and existing development areas.
29. Work with Squamish Nation and senior governments regarding a plan for flood protection at the Cheekeye River / Cheakamus River confluence, including but not limited to the Cheekeye community on Cheakamus I.R. No. 11.

Implementation

30. Determine the order of implementation for the proposed new development and the debris flow structural mitigation works.
31. Undertake engineering design of all proposed mitigation works included in the final comprehensive mitigation strategy. This may be done under the lead of the District, BMS Cheekeye One Projects and/or Squamish Nation. This should include peer review and environmental review and assessment as required.
32. Make appropriate arrangements for construction, operation and maintenance of proposed mitigation works (including financial considerations).
33. Develop a comprehensive operation and maintenance manual for the mitigation works.

6.3 Considerations if Proposed New Development Does Not Proceed

If the proposed development does not proceed in the short term, it would be appropriate for the District to step back and re-evaluate the best way to proceed. A compatible combination of land use and protection should be developed, with a focus on protecting existing development. This should include reconsideration of the berm alternatives, and various combinations of other measures including managed retreat. The evaluation criteria may be updated for this purpose. This work should be coordinated with the Squamish Nation in an effort to integrate protective measures and maximize the protection afforded to both District and Nation lands.

6.4 Operation and Maintenance Considerations

The District will almost certainly need to be the long-term maintenance authority for any structural mitigation works constructed on the Cheekeye Fan (unless some other government agency would be willing). The implications of assuming this role for the District include the following:

- formal land tenure will be needed for all structural mitigation works;
- an operation and maintenance manual will need to be prepared that documents requirements for annual inspection of the works, periodic specialist inspection of the works, periodic watershed inspection, routine maintenance work, periodic repair work, and post-event restoration;
- the requirements of the operation and maintenance manual will need to be undertaken in perpetuity;
- an appropriate funding mechanism needs to be developed that considers the unpredictability of the timing and magnitude of future debris flow events, as well as the unpredictable costs for post-event repairs and possibly the eventual costs of future reconstruction;

- arrangements may need to be made for funding major repairs and post-event restoration in times when insufficient funds are available through the established funding mechanism (the availability of senior government disaster financial assistance could be investigated);
- the sediment management plan will need to be implemented in perpetuity; and
- other forms of monitoring (i.e. environmental, hydrologic etc.) may need to be undertaken.

To support emergency operations, the District may wish to consider installation of some form of debris flow warning or monitoring system. A warning system would indicate when a debris flow is likely to occur. A monitoring system would indicate when a debris flow is or has just occurred.

Unlike floods on the local rivers, debris flows can occur without warning and do not allow enough time for an active response. Rather than a broad-scale public warning system, it may be preferable to have an internal real-time monitoring system whereby the District's first responders could be advised of a debris flow striking the uppermost debris barrier.

The District should keep in mind that a very large debris barrier on the Cheekeye Fan would be significant on a world scale. Long term operation and maintenance activities may need to address some unexpected issues. The structure(s) may also attract a higher level of media attention. Liability concerns should be carefully evaluated for the possible outcome that the works do not perform as intended during a large debris flow.

7. Summary

This report provides the District with information to support key decisions on implementing debris flow mitigation measures on the Cheekeye Fan, and possibly approving a proposed new development on the Cheekeye Fan.

Relevant background information is identified and summarized.

A broad range of alternative approaches to risk mitigation are identified. Local issues that would be important considerations in selecting an appropriate mitigation alternative are identified and discussed. Primary debris flow mitigation alternatives are evaluated using a matrix screening tool that was developed for this project.

As a result of the evaluation of alternatives, two types of primary mitigation measures were identified as the most promising:

- a mid fan berm to prevent debris from entering developed areas; and
- a large debris barrier above the fan.

A mid fan berm has a significant advantage in economic criteria, and some advantage in environmental and social-design criteria. It would protect many existing development areas, but not all existing development areas. Cheakamus I.R. No. 11 would not be protected in this alternative, nor would other assets such as Highway 99, CN Railway, Squamish Airport, Squamish landfill and Squamish Valley Road.

A large debris barrier above the fan has a significant advantage in social-risk criteria, and some advantage in other social criteria. This alternative would need to address challenges with being in SLRD territory and requiring work in Alice Lake Provincial Park. While I.R. No. 11 would be protected against large Cheekeye River debris flows, it may remain vulnerable to small debris flows, and would remain vulnerable to flooding and erosion from Cheakamus River. Environmental approval requirements are not well known, and may result in a significant challenge.

The alternative of large scale retreat (removal of development from hazard areas) was identified as having merit, and may be the most effective long-term approach to reducing risk on the Cheekeye Fan. This alternative, however, does not lend itself to easy comparison with the structural mitigation options. Furthermore, the cost and likely extent of retreat that would be necessary to achieve a satisfactory level of risk reduction is not known. The District may wish to consider the option of retreat more fully before selecting a mitigation approach for the Cheekeye Fan. Small-scale retreat may have a part in a comprehensive plan with any of the primary mitigation measures identified.

Section 6.1 provides information that the District may wish to consider in responding to the proposed new development. The fact that the proposed new development may be able to cover initial capital costs associated with a large debris barrier, and provide an opportunity to create a funding mechanism for long-term operation and maintenance would be major advantages to the District. On this basis, and since the large debris barrier alternatives were identified as promising, it is considered appropriate for the District to work with BMS Cheekeye One Projects to further investigate and refine this alternative, confirm the preliminary findings of this report with respect to this alternative, and more fully understand the long-term implications to the District.

Further investigation of the debris barrier alternative in conjunction with the proposed new development should be contingent on the District accepting a number of key principles that are identified. The District should further ensure that the proposed funding mechanism would not overly burden the District financially in the event that a large debris flow occurs before the fund has built to a point that can cover all restoration and reconstruction costs.

Section 6.2 identifies a broad range of issues that would need to be addressed in the event that the proposed new development proceeds in the short term with a large debris barrier. Ultimately, a comprehensive mitigation plan needs to be developed that would meet the stated objectives.

Section 6.3 addresses the scenario of the proposed new development not proceeding in the short term. In short, in this scenario it is suggested that the District step back and re-evaluate the best way to proceed.

Under any alternative, it appears inevitable that the District accept long-term operation and maintenance responsibility for all works constructed. This is a significant obligation that requires much further attention in the future. Section 6.4 identifies relevant operation and maintenance considerations.

Prior to further QRA work being conducted, it will be necessary for the District to give careful consideration to the suggestion of Expert Panel #2 that one of three suites of hazard probability options be selected. This is a critical decision that may have a bearing on the scale of any mitigation works, as well as land use planning.

The District should keep in mind that a very large debris barrier on the Cheekeye Fan would be significant on a world scale. Long term operation and maintenance activities may need to address some unexpected issues. Liability concerns should be carefully evaluated for the possible outcome that the works do not perform as intended during a large debris flow.

Report Submission

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Statement of Limitations

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This document represents KWL's professional judgement based on the information available at the time of its completion and as appropriate for the project scope of work. Services performed in developing the content of this document have been conducted in a manner consistent with that level and skill ordinarily exercised by members of the engineering profession currently practising under similar conditions. No warranty, express or implied, is made.

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Revision History

Revision	Date	Status	Revision	Author
A	March 31, 2016	Draft	Preliminary Draft for District Review – Not for Circulation	MVC
B	April 12, 2016	Final Draft	Incorporates District Comments	MVC
C	April 20, 2016	Final	Incorporates Final Review Comments from District and KWL	MVC

OQM | Organizational Quality Management Program

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Appendix A

Blank Evaluation Matrix for Cheekeye Fan Debris Flow Mitigation Alternatives

Maximum Score = 192

Description		Economic					Environmental					Social													Scoring	
												Risk					Design				Other					
		Capital Cost	Capital Cost Sharing Potential	O&M Costs	Post-Event Recovery Costs	Sub-Total Max points =	Fish Impacts	Disturbed Area	Wildlife Corridor Impacts	Sensitive Habitat Disturbance	Sub-total Max Points =	Risk Reduction	Unmitigated Risk Transfer	Land Use Potential	Economic Risk Reduction	Addt'l Assets Protected	Design Confidence	Post Event Restoration Options	Infrastructure Impacts	Regulatory Challenges	Aesthetics	Cultural/ Archeological Impacts	Recreation/ Trail Impacts	Sub-Total Max points =	Total Score	Rank
	Weight	5	3	5	4	51	4	3	1	3	33	5	4	4	3	2	4	4	3	3	1	2	1	108		
Option 1	Upper Canyon Debris Barrier					0					0													0	0	
Option 2	Lower Canyon Debris Barrier					0					0													0	0	
Option 3	Debris Basin Above Highway					0					0													0	0	
Option 4	Debris Barrier Below Highway					0					0													0	0	
Option 5	Debris Basin Below Dogleg					0					0													0	0	
Option 6	Mid-Fan Channelization					0					0													0	0	
Option 7	Mid-Fan Berm					0					0													0	0	
Option 8	Berm Above Brackendale					0					0													0	0	
Option 9	Large-Scale Retreat					0					0													0	0	

Economic Criteria

Capital Cost
3 = low (<$10 M)
2 = moderate ($ 10-50 M)
1 = high (> $ 50 M)

Capital Cost Sharing Potential
3 = high
2 = moderate
1 = low

O&M Costs
3 = low maintenance costs (<$50,000 annually)
2 = moderate costs ($50k to $ 100k annually)
1 = high maintenance costs (>$100k annually)

Post-Event Recovery Costs
3 = low (< $10M) costs to recover existing land/infrastructure AND structural mitigation
2 = moderate ($10-50M)
1 = high (> $50M)

Economic Risk Reduction (building recovery, disruptions, highway shutdown)
3 = reduces all economic risk to existing/future development/infrastructure
2 = reduces some risk to existing/future development/infrastructure
1 = doesn't reduce risk to existing/future development/infrastructure

Weight	
	5=extremely important 4=very important 3= somewhat important 2= minor importance 1=negligible importance

Environmental Criteria

Fish Impacts
3 = low
2 = moderate
1 = high

Disturbed Area
3 = low
2 = moderate
1 = high

Wildlife Corridor Impacts
3 = low
2 = moderate
1 = high

Sensitive Habitat Disturbance
3 = low
2 = moderate
1 = high

Social Criteria (Risk, Design, Other)

Risk Reduction
3 = high
2 = medium
1 = low

Unmitigated Risk Transfer
3 = negligible or no risk transfer
2 = risk transfer requires mitigation (retreat, protect, etc)
1 = risk transfer can't be mitigated

Land Use Potential
3 = will allow new, desired future uses anywhere on fan
2 = will allow limited future development on fan (seasonal, recreational, heavy industrial)
1 = will allow very limited land use (resource, park, community forest, open space, agriculture, infill of Brackendale)

Economic Risk Reduction (building recovery, disruptions, highway shutdown)
3 = reduces all economic risk to existing/future development/infrastructure
2 = reduces some risk to existing/future development/infrastructure
1 = doesn't reduce risk to existing/future development/infrastructure

Addt'l Assets Protected
3 = protects all other infrastructure (Highway, Hydro, CN Rail, District infrastructure)
2 = protects some (Highway, Hydro, CN Rail, District infrastructure)
1 = protects minimal(Highway, Hydro, CN Rail, District infrastructure)

Design Confidence
3 = very confident that design will work as anticipated
2 = reasonable confidence that design will work as anticipated
1 = poor confidence that design will work as anticipated

Post-Event
3 = restoration plan requires 1/3 of large event deposition to be off-hauled
2 = restoration plan requires 2/3 of large event deposition to be off-hauled
1 = event deposition to be off-hauled to restore protection

Infrastructure Impacts
3 = no or negligible impacts to existing infrastructure
2 = some impacts (moving roads, moving buried linear infrastructure, hydropower poles)
1 = severe impacts (closing airport, moving BC hydro substation etc.)

Regulatory Challenges
3 = minimal regulatory challenges
2 = moderate regulatory requirements (Water Act, Dike Maintenance Act, Riparian Area Regulation)
1 = significant regulatory requirements (boundary expansion, park access/encroachment, Environmental Assessment reqmt, etc)

Aesthetics
3 = good looking OR mostly hidden from public view
2 = neutral looking, some visual exposure to public
1 = visually unappealling OR large visual exposure to public

Cultural / Archaeological Impacts
3 = low
2 = medium
1 = high

Recreation / Trail impacts
3 = no trails impacted
2 = limited trail closures required
1 = major trail closures required

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Appendix B

Completed Evaluation Matrix for Cheekeye Fan Debris Flow Mitigation Alternatives

Maximum Score = 192

Description		Economic					Environmental				
		Capital Cost	Capital Cost Sharing Potential	O&M Costs	Post-Event Recovery Costs	Sub-Total Max points =	Fish Impacts	Disturbed Area	Wildlife Corridor Impacts	Sensitive Habitat Disturbance	Sub-total Max Points =
	Weight	5	3	5	4	51	4	3	1	3	33
Option 1	Upper Canyon Debris Barrier	1.0	3.0	1.0	1.0	23	2.2	2.0	2.0	1.7	22
Option 2	Lower Canyon Debris Barrier	1.0	3.0	1.0	1.0	23	2.2	2.0	2.0	1.7	22
Option 3	Debris Basin Above Highway	2.0	2.3	2.3	2.3	38	2.2	1.5	2.3	1.7	21
Option 4	Debris Barrier Below Highway	1.3	2.2	1.0	1.2	23	1.7	1.5	1.8	1.7	18
Option 5	Debris Basin Below Dogleg	1.3	2.2	1.0	1.2	23	1.7	1.3	1.8	1.8	18
Option 6	Mid-Fan Channelization	1.3	1.7	1.3	1.2	23	2.0	1.0	1.3	1.3	16
Option 7	Mid-Fan Berm	2.0	2.0	2.0	2.0	34	2.8	1.8	2.5	2.0	25
Option 8	Berm Above Brackendale	2.0	1.3	2.0	2.3	33	2.8	2.0	2.5	2.2	26
Option 9	Large-Scale Retreat	1.0	1.0	3.0	3.0	35	3.0	3.0	3.0	3.0	33

Description	Social													Scoring	
	Risk					Design				Other					
	Risk Reduction	Unmitigated Risk Transfer	Land Use Potential	Economic Risk Reduction	Addt'l Assets Protected	Design Confidence	Post Event Restoration Options	Infrastructure Impacts	Regulatory Challenges	Aesthetics	Cultural/ Archeological Impacts	Recreation/ Trail Impacts	Sub-Total Max points =	Total Score	Rank
Weight	5	4	4	3	2	4	4	3	3	1	2	1	108		
Option 1	2.8	3.0	3.0	3.0	3.0	2.0	1.0	3.0	1.2	2.7	2.2	2.3	87	132	3
Option 2	2.8	2.8	3.0	3.0	3.0	2.0	1.0	3.0	1.2	2.0	2.2	1.7	85	130	5
Option 3	1.5	3.0	2.3	2.0	1.3	2.0	2.3	2.5	1.7	1.7	2.0	2.0	75	133	2
Option 4	2.3	2.7	2.7	2.0	2.0	2.0	1.3	2.0	1.7	1.3	2.0	2.0	75	116	7
Option 5	2.3	3.0	2.3	1.7	2.0	2.0	1.3	1.5	2.0	1.7	2.0	2.0	73	114	8
Option 6	2.5	2.3	2.0	2.0	2.3	1.7	1.3	1.0	1.0	1.0	1.7	1.3	64	103	9
Option 7	2.3	2.0	1.7	1.5	1.0	2.5	2.7	1.5	2.0	2.0	2.3	2.3	73	132	3
Option 8	2.2	2.0	1.3	1.2	1.0	2.0	2.7	2.2	2.3	2.0	2.0	2.3	70	130	5
Option 9	2.7	3.0	0.7	1.3	0.7	2.7	3.0	3.0	1.7	3.0	1.3	3.0	79	147	1

Economic Criteria

Capital Cost	3 = low (<$10 M) 2 = moderate ($ 10-50 M) 1 = high (> $ 50 M)
Capital Cost Sharing Potential	3 = high 2 = moderate 1 = low
O&M Costs	3 = low maintenance costs (<$50,000 annually) 2 = moderate costs ($50k to $ 100k annually) 1 = high maintenance costs (>$100k annually)
Post-Event Recovery Costs	3 = low (< $10M) costs to recover existing land/infrastructure AND structural mitigation 2 = moderate ($10-50M) 1 = high (> $50M)
Economic Risk Reduction	(building recovery, disruptions, highway shutdown) 3 = reduces all economic risk to existing/future development/infrastructure 2 = reduces some risk to existing/future development/infrastructure 1 = doesn't reduce risk to existing/future development/infrastructure

Weight	
Weight	5=extremely important 4=very important 3= somewhat important 2= minor importance 1=negligible importance

Environmental Criteria

Fish Impacts	3 = low 2 = moderate 1 = high
Disturbed Area	3 = low 2 = moderate 1 = high
Wildlife Corridor Impacts	3 = low 2 = moderate 1 = high
Sensitive Habitat Disturbance	3 = low 2 = moderate 1 = high

Social Criteria (Risk, Design, Other)

Risk Reduction	3 = high 2 = medium 1 = low
Unmitigated Risk Transfer	3 = negligible or no risk transfer 2 = risk transfer requires mitigation (retreat, protect, etc) 1 = risk transfer can't be mitigated
Land Use Potential	3 = will allow new, desired future uses anywhere on fan 2 = will allow limited future development on fan (seasonal, recreational, heavy industrial) 1 = will allow very limited land use (resource, park, community forest, open space, agriculture, infill of Brackendale)
Economic Risk Reduction	(building recovery, disruptions, highway shutdown) 3 = reduces all economic risk to existing/future development/infrastructure 2 = reduces some risk to existing/future development/infrastructure 1 = doesn't reduce risk to existing/future development/infrastructure
Addt'l Assets Protected	3 = protects all other infrastructure (Highway, Hydro, CN Rail, District infrastructure) 2 = protects some (Highway, Hydro, CN Rail, District infrastructure) 1 = protects minimal(Highway, Hydro, CN Rail, District infrastructure)
Design Confidence	3 = very confident that design will work as anticipated 2 = reasonable confidence that design will work as anticipated 1 = poor confidence that design will work as anticipated
Post-Event	3 = restoration plan requires 1/3 of large event deposition to be off-hauled 2 = restoration plan requires 2/3 of large event deposition to be off-hauled 1 = event deposition to be off-hauled to restore protection
Infrastructure Impacts	3 = no or negligible impacts to existing infrastructure 2 = some impacts (moving roads, moving buried linear infrastructure, hydropower poles) 1 = severe impacts (closing airport, moving BC hydro substation etc.)
Regulatory Challenges	3 = minimal regulatory challenges 2 = moderate regulatory requirements (Water Act, Dike Maintenance Act, Riparian Area Regulation) 1 = significant regulatory requirements (boundary expansion, park access/encroachment, Environmental Assessment reqmt, etc)
Aesthetics	3 = good looking OR mostly hidden from public view 2 = neutral looking, some visual exposure to public 1 = visually unappealling OR large visual exposure to public
Cultural / Archaeological Impacts	3 = low 2 = medium 1 = high
Recreation / Trail impacts	3 = no trails impacted 2 = limited trail closures required 1 = major trail closures required

KERR WOOD LEIDAL
consulting engineers

Appendix C

Cheekeye River Sediment Management Considerations
(2014 Technical Memorandum)

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Technical Memorandum

DATE: March 12, 2014

TO: Matt Simmons, District of Squamish

FROM: Erica Ellis, M.Sc., P.Geo.
David Roche, M.A.Sc., P.Eng.

RE: **DISTRICT OF SQUAMISH FLOOD HAZARD MANAGEMENT**
Cheekye River Sediment Management Considerations (PO #34521)
Our File 0463.302-300

1. Introduction

The District of Squamish is subject to a range of flood hazards from Howe Sound and five different river systems: Squamish River, Cheakamus River, Mamquam River, Stawamus River and Cheekye River.

The Cheekye River is unique among the District's rivers, being subject to periodic large debris flow events as well as more modest, annual rainfall- and snowmelt-generated floods. The channel gradient is very steep in the Cheekye River headwaters and declines with distance downstream. This causes the river to lose energy as it travels, which in turn causes the river to deposit sediment and debris brought down from the upper watershed. Over time, deposition fills in the river channel. Periodically, a larger flood or small debris flow will result in a larger deposit of sediment accumulating in the downstream reaches of the channel. This on-going channel aggradation increases the flood hazard to adjacent properties. Historically, aggradation impacts on flood hazard have been mitigated to some degree by in-channel sediment removals, most recently in 2012.

The District of Squamish (the District) has retained Kerr Wood Leidal Associates (KWL) to provide a high-level assessment of sediment management in Cheekye River. This memo summarizes KWL's assessment and associated considerations.

1.1 Previous Work

The Cheekye River fan has been the focus of much previous work and research. The majority of work has concentrated on historical behaviour of, and potential risks associated with, large debris flows. Pertinent background reports include:

- "*Cheekye River Terrain Hazard and Land Use Study*" (March 1993). Report prepared by Thurber Engineering Ltd. and Golder Associates Ltd. for the BC Ministry of Environment Lands and Parks.
- "*Preliminary Design Report for Cheekye Fan Deflection Berms*" (June 2003). Report prepared by KWL for the District of Squamish.
- "*Cheekye River Debris Flow Frequency and Magnitude*" (January 2008). One of three reports prepared by BGC Engineering Inc. for KWL as background for a local development application, subsequently released by the developer for District review.

- "*Cheekye Confluence Sediment Management*" (February 2013). Construction Completion Report prepared by KWL for the District of Squamish.

Peer-reviewed literature on the Cheekye River includes:

- Friele, P.E., Ekes, C. and Hickin, E.J. (1999). Evolution of Cheekye fan, Squamish, British Columbia: Holocene sedimentation and implications for hazard assessment. *Canadian Journal of Earth Sciences* **36**, 2023-2031.
- Ékes, C. and Hickin, E.J. (2001). Ground penetrating radar facies of the paraglacial Cheekye Fan, southwestern British Columbia, Canada. *Sedimentary Geology* **143**, 199-217.
- Friele, P.A. and Clague, J.J. (2002). Younger Dryas readvance in Squamish River valley, southern Coast mountains, British Columbia. *Quaternary Science Reviews* **21**, 1925-1933.
- Clague, J.J., Friele, P.A. and Hutchinson, I. (2003). Chronology and Hazards of Large Debris Flows in the Cheekye River Basin, British Columbia, Canada. *Environmental & Engineering Geoscience* **9**(2), 99-115.
- Jakob, M. and Friele, P. (2010). Frequency and magnitude of debris flows on Cheekye River, British Columbia. *Geomorphology* **114**, 382-395.
- Jakob, M., Macdougall, S., Weatherly, H. and Ripley, N. (2013). Debris-flow simulations on Cheekye River, British Columbia. *Landslides* **10**, 685-699.

Building on the above reports and papers, KWL understands that there is a panel-based expert review currently underway. The review is expected to produce a definitive opinion based on all work completed to date.

2. Background

2.1 Watershed Setting

The Cheekye River is located in the Coast Mountains at the north end of Howe Sound, close to the confluence of the Squamish River and Cheakamus River. The total Cheekye River watershed area is about 58 km², including one major tributary, Brohm River, which flows into the Cheekye River just upstream of the Highway 99 crossing.

The highest elevations of the watershed include the slopes of Mt. Garibaldi (2,670 m elevation), while the ground elevation near the Cheakamus River is about 25 m. The steep slopes in the upper watershed, including the slopes draining Mt. Garibaldi, Dalton Dome and Diamond Head, are relict volcanoes dating from the Quaternary age.

The Cheekye River has built a large fan deposit below approximately elevation 600 m, composed of Quaternary glacial deposits, slope failure deposits, and alluvial (river-transported) sediment.

Previous research has established that the Cheekye River is subject to a range of geohazards, including periodic very large debris flow events initiating from slope failures in the upper watersheds.

2.2 Watercourse Hazards

Cheekye River is subject to both a "typical" flood regime (generated by intense rainfall, rain-on-snow or snowmelt) and to periodic, larger debris flow events. Floods, debris floods (or sediment floods) and debris flows are all part of a continuum of natural hazards distinguished by an increasing sediment concentration (Figure 2-1). Steep river gradients are required to support debris flows and other processes associated with high sediment concentrations.

Debris flows may be thought of as 'channelized landslides': they have very high sediment concentrations that alter the physics of the flow. Debris flows are associated with very rapid flow velocity and the ability to transport large boulders. A series of debris flows along the Sea-to-Sky corridor in the 1980s resulted in fatalities and the subsequent construction of substantial hazard mitigation works.

Factors that govern whether a given event on the Cheekye River becomes a flood, debris flood or debris flow include the amount of sediment available for entrainment (e.g. was there a landslide into the channel, or did the event simply entrain ravelled material stored in upper watershed gullies?) and the runoff intensity (e.g. the rainfall and/or snowmelt associated with the event).

The largest debris flows originate as landslides in the upper watershed. Smaller events may be generated simply due to rainfall in the upper watershed falling after a sustained dry period (P. Friele, pers comm., 2014). Prolonged dry weather reduces the stability of the bedrock in the upper watershed promoting increased rates of ravelling of material that accumulates in the gullies. This material can be relatively easily mobilized during the first rainfall, potentially resulting in a small debris flow. This mechanism is thought to have resulted in the 2013 Cheekye River debris flow (ibid.).

Peak discharge for debris flows and debris floods can significantly exceed that of the equivalent return period 'clear water' flood. For example, the 200-year return period flood for the Cheekye River has been estimated as high as 300 m^3/s (Thurber and Golder, 1993); in comparison, the estimated 200-year return period debris flow has a peak discharge of 3,400 m^3/s (BGC 2008).

A debris flow event can transport and deposit material that may not normally be transported during moderate clear-water flood events. This material is larger in size and may not be remobilized until the next significant flood or debris flood event. As such, it is possible for material transported and deposited by a debris flow to remain in place for an extended period of time (i.e., years to decades or longer).

A large debris flow could also result in an avulsion. Avulsion is a process where the river channel experiences extreme and rapid change, with high discharge, sediment deposition, and subsequent erosion frequently leading to the formation of a new river channel. River avulsions can be extremely damaging, disruptive, and dangerous.

This technical memorandum focusses on local-scale flood hazards typically associated with more frequent flood events, and generally leaves consideration of the larger range of debris flow hazards to more detailed studies.

2.3 Overview of Sediment Sources and Sediment Transport

The steep slopes in the upper Cheekye River watershed provide an abundant source of sediment. The channel is generally wide and braided, with exposed bar deposits that are large in comparison to the wetted width. This morphology is indicative of a river that has a sediment supply in excess of its transport capacity: this kind of river is often noted to be "transport limited" (i.e. more sediment would be transported if more transport capacity was available).

Given the availability of sediment, bedload transport can be expected whenever the discharge is large enough to mobilize the size of sediment exposed on the bed. For fine sediment (e.g. sands and finer), transport may occur even at modest flows. Larger sediment (gravel, cobble and boulder) requires a larger flow to mobilize. However, previous estimates of bed mobility indicate that the Cheekye River bed may become mobile even during very small floods (Thurber and Golder, 1993), implying that bedload transport of coarse sediment may occur in most years' annual flood.

Once entrained, bedload will be transported downstream until the stream power is no longer sufficient to keep the sediment moving. The transported sediment begins to deposit as the gradient decreases. Larger sediment is typically deposited first, with progressively smaller sediment is deposited further downstream. These processes typically form a fan deposit at the river outlet.

In the case of Cheekye River, the lower fan deposit starts about 600 m upstream of Highway 99, where the river emerges from a bedrock canyon. The northern limit of the Cheekye fan extends to the confluence with the Cheakamus River, a total distance of approximately 3.5 km. The southern limit of the Cheekye fan is located in the District community of Brackendale.

A secondary fan apex is located about 1.7 km upstream of the Cheakamus River, near a bend in the Cheekye River sometimes referred to as "the dogleg".

The lower reach of the Cheekye River is shown in Figure 6-1 from KWL's 2006 / 2007 Dike Inspection Report (figure appended to this report for ease of reference). The downstream-most 750 m of Cheekye River have historically been targeted for sediment management.

2.4 Historic Floods, Debris Floods and Debris Flows

Major Cheekye River debris flows, debris floods or floods have occurred in 1921, 1940, 1958, 1984, 1990 (2 events) and 1991 (Thurber and Golder, 1993). The 1991 flood was a regionally-significant event, also triggering debris floods on Fitzsimmons Creek and Britannia Creek. Thurber and Golder (ibid.) indicate that in most cases, observed rainfall for these events was not necessarily severe, with the exception of the 1921 and 1991 events. The authors speculate that the local, short-duration rainfall experienced in the Cheekye River watershed may have been more severe and/or augmented by snowmelt.

Extremely large debris flow events are known to have occurred on the Cheekye River fan; however, these events generally occurred thousands of years ago during the earlier stages of deglaciation. A sediment budget for the Cheekye River fan indicates that 90% of the material stored in the lower fan was deposited prior to about 6,000 years ago (Friele et al., 1999).

One large debris flow event is known to have occurred more recently: the "Garbage Dump" debris flow occurred about 700 to 800 years ago and has an estimated associated volume of 2.1 million m^3 (Jakob and Friele, 2010).

A frequency-magnitude relationship has been developed for Cheekye River debris flows (BGC, 2008) and is presented in Table 3-1.

Table 3-1: Estimated Cheekye River Debris Flow Frequency-Magnitude Summary (BGC 2008)

Return Period (years)	Debris Flow Peak Discharge (m^3/s)	Debris Flow Volume (m^3)
20	700	200,000
50	1,500	400,000
100	2,500	600,000
200	3,400	800,000
500	6,700	1,400,000
2,500	12,600	2,400,000
10,000	15,000	2,800,000

The debris flow peak flows and associated volumes in Table 3-1 are for the Cheekye River watershed as a whole. Such estimates are often made at the fan apex, and do not necessarily represent the peak flow or deposition that might be expected at the confluence with the Cheakamus River.

The volume associated with the 10,000-year return period event in Table 3-1 represents the lowest 10,000-year volume estimate among all studies completed to date. It is reasonable to expect that the frequency-magnitude estimates will be a key focus of the on-going expert panel review.

3. Sediment Management History

Background reports document a history of sediment removals from the downstream-most reaches of the Cheekye River, from the mouth to about 650 m upstream of the BC Rail bridge.

Removals in the 1980s and 1991 were triggered by a series of large flood/debris flow events that resulted in aggradation of the Cheekye River channel. On Cheekye River, the 1991 flood resulted in about 2.5 m of deposition in the lower reaches of the channel.

3.1 Historic Sediment Management Activites

Documented removals are summarized in the following table.

Table 3-2: Documented Lower Cheekye River Sediment Removals

Year	Removal Volume (m^3)	Notes
1981-1985	Few thousand	• Material removed between river mouth and BC Rail bridge.
1985	35,000	• Material removed over 650 m reach upstream of BC Rail bridge. • Material bulldozed to stockpiles along both banks (not removed from channel?).
1991	22,000	• Material removed upstream of BC Rail bridge. • Material used for fill, etc. Channel returned more or less to post-1985 condition.
2012	5,625	• Removal in response to 2009 debris flow deposition at mouth of Cheekye River.

According to observations reported by C. Robert Bland, P.Eng.[1], the 1991 debris flow event deposited about 28,000 m³ of gravel over a 600 m long reach of channel upstream of the CN Rail bridge. In his report, Bland provides recommendations on sediment management following the 1991 event[2,3]. In particular, Bland notes over 3 m of aggradation on the Cheakamus River at Paradise Valley Road bridge (Fergie's Bridge). However, he also reports that the bed level following the 1991 flood was similar to the level shown on bridge drawings dating from 1926 and 1958. Ultimately, Bland concludes that a continuous long-term gravel removal program would be necessary for sediment management to be effective as a means of flood control at this site.

With regard to the Cheekye River channel, Bland[2] concludes that the 1991 gravel removals provided sufficient freeboard (± 1 m) for a 400 m long reach upstream of Fernwood Road, but that additional gravel removals over a 900 m long reach further upstream would be beneficial.

KWL is not aware of any Cheekye River gravel removals occurring between the 1991 event response and the 2012 project at the Cheakamus River confluence.

3.2 2009 Debris Flow and Response

In the evening of July 25, 2009 an intense rain storm passed over the Cheekye River watershed and triggered a debris flow which temporarily blocked the Cheakamus River and then breached causing a 2 m flood wave downstream[4]. By the following morning, the remaining debris flow deposit still blocked about 80 percent of the Cheakamus River.

The Provincial Emergency Program (PEP) opened a response file with the District shortly after the event. Some of the deposited material was excavated from the Cheakamus channel and stockpiled on the adjacent gravel deposit. The typical size of debris excavated stockpiled on the bank was significantly larger than the typical gravel-sized material mobilized as bedload by the Cheakamus River. Some 60% to 70% of the channel width was still obstructed as of July 31, 2009 when the District retained KWL to assist with the recovery.

On August 4, 2009, KWL walked the Cheekye River channel from the Cheakamus River confluence to about 200 m upstream of the Highway 99 bridge.

KWL's site assessment identified an increase in flood risk for areas downstream of the CN Rail bridge (referred to as "Reach 1" in an August 2009 letter from KWL to DFO). The primary flood risk was a reduction in channel capacity of the Cheakamus River, which could exacerbate inundation of Squamish Nation Cheakamus I.R. No. 11, the Sunwolf recreation property, and other nearby properties. Additional risk was posed by further floods or debris flows on the Cheekye River. Sediment management in Reach 1 was recommended as the first priority of a larger sediment management response effort.

KWL also recommended targeted sediment management for selected locations in "Reach 2", which extended about 1.5 km upstream from the CN Rail bridge to the Cheekye River secondary fan apex. This recommendation was based on the KWL site assessment's findings of significant deposition, reduced

[1] C. Robert Bland, 1992. Report on Cheekye River Investigations and Berm Design. Report prepared for BC Environment Water Management Division. File No. 55.4804. OIC 1298 – August 1991 Squamish Area Flood. 7pp. plus drawings.

[2] Technical Memorandum prepared by C. Robert Bland, P.Eng. for Water Management Division OIC 1298 Re: August 1991 Squamish Area Flood – Cheekye River gravel removal 100 m d/s to 500 m u/s of Fernwood Road. 30 June 1992. 5pp. plus figures and drawings.

[3] Technical Memorandum prepared by C. Robert Bland, P.Eng., for Water Management Division OIC 1298 Re: August 1991 Squamish Area Flood – Cheakamus River at Paradise Valley Bridge, Review of gravel deposition.

[4] Ministry of the Environment (J. Pattle), 'Cheekye / Cheakamus Debris Blockage: Situation Report', Email Correspondence

conveyance (i.e., increased hazard to adjacent riparian properties), reduced sediment storage capacity for future events, and increased potential for remobilization of material which could exacerbate the deposition issues in Reach 1.

No sediment management was recommended for areas upstream of Reach 2.

KWL understands that the District's 2009 response activities were suspended indefinitely by the withdrawal of provincial emergency response funding in August 2009. At the time, excavation of debris from the Cheakamus River had accomplished little in terms of mitigating the flood hazard. The excavated material was left in stockpiles along the edge of the Cheakamus River channel, and no material was removed from the confluence.

Subsequent attempts to secure Indian and Northern Affairs Canada (now Aboriginal Affairs and Northern Development Canada, AANDC) funding to complete the Reach 1 sediment management works were unsuccessful.

The scope of work KWL originally proposed for Reach 1 was completed by the District in 2012. The work was completed with funding assistance from Emergency Management BC (EMBC) and as part of the much larger "Tier 3" strategic sediment management / flood protection project on the Squamish River.

3.3 Current Conditions

Following the 2012 removal, another small debris flow occurred in 2013. A comparison of 2012 and 2013 topographic surveys found that the 2013 event deposited about 9,900 m³ of new material downstream of the CN Rail bridge. This volume is approximately 75% greater than the volume of sediment and debris removed in 2012.

To KWL's knowledge, no site assessment of Cheekye River above the CN Rail bridge was carried out following the 2013 event, and the benefits of sediment management within the upper reach (relative to the confluence) have not been established.

4. Flood Hazard and Mitigation Options

4.1 Flood Hazard

Infrastructure and development potentially vulnerable to the Cheekye River / lower Cheakamus River flood hazard include:

- bridge crossings (Highway 99, railway, Paradise Valley Road),
- properties located on the Cheekye River fan (e.g. Sunwolf, residential properties),
- other properties located near the confluence of the Cheekye and Cheakamus Rivers (e.g. Cheakamus IR 11).

The topography of the Cheekye fan means that overbank flows could spread across the fan and/or occupy one or more old relict channels. The topographically-sensitive behaviour of overbank flooding on the Cheekye fan makes it difficult to provide a qualitative assessment of site-specific impacts for a given location and hazard scenario.

Over the long term, channel aggradation will continue to raise the Cheekye River flood profile. This leads to an increased likelihood of overland flooding and avulsion on the Cheekye fan. In addition, material transported into the Cheakamus River will continue to contribute to the long-term increase in the flood profile of the Cheakamus River. Short-term increases in the Cheakamus River flood profile can also result from temporary channel blockages.

There is insufficient background information available at present to quantify the average annual rate of sediment deposition in the lower Cheekye River, or in the Cheakamus River near the confluence. It may be possible to quantify a multi-decadal net change in aggradation for select reaches by collecting new channel surveys and comparing them to as-constructed drawings for the 1991 gravel removal project.

4.2 Existing Flood Hazard Mitigation Works

Sediment management activities are often undertaken in parallel with, and to preserve the capacity of, pre-existing structural flood protection works (e.g., dikes and training berms) rather than as a primary means of flood hazard mitigation.

Records held by the Pronvincial Inspector of Dikes (IoD) identify two flood protection structures on the Cheekye River:

- the Cheekye Berm, total length 1.17 km and administered by the District; and
- the Fernwood Road berm, reported as 550 m of "remnant emergency works" with no designated maintenance authority.

KWL's 2006/2007 dike inspection report also identifies two structures, but with different extents, including:

- a well-defined but poorly-maintained berm upstream of Highway 99 with a length of about 500 m; and
- a poorly-defined, heavily-vegetated possible structure in the vicinity of Fernwood Road with a length of about 650 m.

The total combined length of these structures is approximately 1.15 km.

The apparent discrepancy between IoD records and KWL field observations can be explained by referencing reports prepared by C. Robert Bland following the 1991 debris flow event. The Bland reports also describe two structures, as follows:

- a ±500 m long berm and associated erosion protection works on the left bank of the Cheekye River upstream of Highway 99, constructed by the BC Ministry of Transportation and Highways (MoTH) to mitigate overland flooding and reduce the likelihood of a subsequent avulsion; and
- material from the 1985 gravel removal "bulldozed mostly to a linear stockpile along the left bank", shown on one of Bland's drawings as an "existing berm" extending about 650 m from the BC Rail right-of-way to approximately 550 m upstream of Fernwood Road.

Bland also confirms that the structure upstream of Highway 99 was turned over to the District for maintenance following construction.

The information from Bland's reports correlates well with observations from KWL's 2006/2007 dike inspection report. The well-developed and extensive vegetation noted on both structures for the 2006/2007 report is also compatible with Bland's timelines given limited recent maintenance activities.

In summary, the 1.17 km length of the "Cheekye Berm" listed in the provincial records likely represents a misleading combination of the 1985 linear stockpile and the 1991 Cheekye training berm. The lower berm was constructed as a linear stockpile rather than a flood protection berm, and the upper berm may not meet provincial standards for a "standard dike".

Other flood protection structures that should be considered in the context of Cheekye River sediment management include a training berm constructed by the Squamish Nation on I.R. No. 11 opposite the Cheekye confluence. The top of the Squamish Nation training berm matches the low chord of Fergie's Bridge to avoid surcharging the bridge opening (the berm is designed to overtop during a large flood). There is also a private dike on the left bank of the Cheakamus River downstream of Squamish Valley Road at Fergie's Bridge.

The Squamish Nation is working with AANDC to pursue improved flood protection works for the Cheakamus I.R. No. 11 community.

4.3 Incremental Flood Hazard Mitigation Strategies for Cheekye River

A variety of options exist to mitigate the incremental flood hazard posed by on-going Cheekye River aggradation. Options vary in terms of associated cost and disruption. In general terms, flood hazard mitigation strategies may be categorized as follows:

- **Accept:** recognize the hazard and adopt a "reactive" response strategy
- **Protect:** implement sediment management and/or structural flood protection works (e.g., diking)
- **Accommodate:** apply floodproofing and other policy measures
- **Retreat:** buy out vulnerable properties and promote natural functioning of the river
- **Avoid:** limit future development to no-hazard or low-hazard areas

A combination of options (e.g., retreat and protect with a setback dike) may also be used to protect against flood hazard. Specific approaches potentially applicable to the Cheekye River are summarized below.

1. **Accept: "Reactive" Response Strategy**

   If no action is taken to mitigate the flood hazard associated with on-going Cheekye River aggradation, the flood hazard will increase over time due to annual deposition. Periodic larger events may result in sudden increases to the flood hazard (e.g. as a result of debris flow events). Because the District is responsible for local emergency response measures, this option would ultimately result in more frequent need for emergency flood response.

   This option may raise questions of liability in regard to a real or perceived duty to protect previously-approved development on the Cheekye fan. In particular:

   - Continued aggradation at the mouth of the Cheekye River increases the potential for overbank flooding on Cheakamus I.R. No. 11.
   - Continued aggradation further upstream along the Cheekye River (e.g., above Highway 99, at the secondary fan apex, or in the vicinity of Fernwood Road) increases the potential for a channel avulsion to the south.

2. **Protect: In-channel Sediment Management**

   In-channel sediment removals could be used to reduce the likelihood of overbank flooding and maintain the historic flood profile. It may be possible to offset the cost of the removals by selling the sediment, or by seeking provincial approval to use the sediment royalty-free for District or First Nation projects of public benefit (e.g., diking).

   There are a number of challenges associated with in-channel sediment removals, including:

- Regulatory permitting is challenging, and can be both costly and time-consuming.
- Regulators are increasingly reluctant to permit repeat sediment removals without justification (i.e., proof of the effect of the removals on the flood profile) and an options assessment that confirms there is no better alternative for flood hazard mitigation.
- The associated cost can be quite high, both due to permitting requirements and due to construction.

Of note, the magnitude of removal required to significantly reduce the flood hazard could be much greater in spatial scale and/or magnitude than the 2012 work, and would need to be repeated at some regular interval. Sediment management alone cannot fully mitigate flood and debris flow risks on the Cheekye River.

This strategy would only be feasible if implemented under a sediment management plan, discussed below.

3. **Protect: Sediment Management – Sediment Trap**

Sediment management on Cheekye River could be conducted by constructing a sediment trap at an appropriate location. Providing a discrete, controlled location for sediment removals reduces the in-stream footprint of disturbance. Similar advantages related to off-setting costs would apply as Option 2, above.

Potential challenges associated with a sediment trap may include:

- The capital cost to design and construct the trap may be relatively substantial, depending on the design criteria and permitting requirements.
- To be cost-effective in operation, the sediment trap must be located and designed to preferentially trap the fraction of sediment sizes that would drive the greatest increase in downstream flood hazard. The design of such works is complex, and significant uncertainties in both design and operation mean that the intended results can be difficult to achieve.
- Regulators may have concerns regarding potential downstream fish habitat impacts due to the interruption of sediment transport to the high-value Cheekye / Cheakamus / Squamish system.
- There would be an on-going operation and maintenance cost associated with the trap, both to maintain the structure and also to remove the deposited sediment.

Of note, a sediment trap alone cannot fully mitigate flood and debris flow risks on the Cheekye River; however, a sediment trap could potentially be integrated into an area-wide strategy for debris flow protection on the Cheekye fan. A site on the upper fan, upstream of Highway 99 and the Brohm River confluence, has been previously identified as promising.

4. **Protect: Structural Flood Protection Works**

Recent years have seen recurring discussions about an area-wide debris flow hazard mitigation strategy. Given the extreme magnitude of the Cheekye River debris flow hazard, the scale of such works would be very large, possibly including debris barrier(s), training berm(s), and sediment trap(s) as well as comprehensive planning for sediment management and secondary flood protection. To date, while some concepts have been proposed, no particular plan has been accepted by all stakeholders.

In the absence of an area-wide flood hazard mitigation strategy, it may be feasible to implement localized flood protection through construction of a setback dike or training berm on the lower

Cheekye River fan. A setback berm would minimize the need for in-stream disturbance, and would be less vulnerable to erosion during high flows. A setback berm also would allow for more channel aggradation without compromising the design level of protection.

A setback dike or training berm would result in much more significant impacts to local landowners than a riverside dike. Nonetheless, recent District projects have shown that this approach is likely to find greater favour with regulators and environmental stakeholders.

Some challenges associated with structural flood protection works may include:

- A setback dike or training berm alone is unlikely to be able to protect against the full range of flood and debris flow hazards on the Cheekye fan. As with either of the sediment management strategies discussed above, appropriate secondary flood protection measures would be essential.
- Any structure would need to be designed and constructed to avoid a significant transfer of risk to either the Cheakamus I.R. No. 11 community or properties on the Cheekye River right bank.
- There are likely to be significant political challenges associated with land acquisition and selection of an appropriate alignment.
- The cost to acquire the land and construct the dike may be substantial, and adequate space may not be available to accommodate a setback berm.
- There are operation and maintenance costs and obligations associated with a setback berm, including the need to monitor aggradation and confirm that the level of flood protection remains adequate over time.
- If aggradation compromises the level of flood protection, additional work would be required in the form of in-stream sediment removals or dike raising.

5. Accommodate: Floodproofing

A level of flood hazard mitigation could be provided through floodproofing measures (e.g., elevating buildings and incorporating designated floodways to direct overland flow). The key advantage of floodproofing is that it minimizes the need for in-stream disturbance.

Floodproofing is typically implemented as a secondary measure behind a primary system of structural flood protection works; however, floodproofing can sometimes be implemented as a stand-alone measure in sparsely-populated, lower-hazard areas.

The following challenges are noted with the application of floodproofing to mitigate Cheekye River flood hazards:

- Typically, floodproofing is only applicable on a go-forward basis, i.e., to new development, so existing developments would remain vulnerable until re-development occurs.
- Overbank flooding and associated deposition would still pose a significant disruption to developed areas in the floodplain, even if the habitable structures themselves are not flooded. Flooding, closure, and damage to Highway 99 are examples of disruptions that could be anticipated.
- Similar to structural flood protection works, on-going aggradation may eventually compromise the level of flood protection offered by floodproofing measures, resulting in the requirement for additional work (in-stream sediment removals, increase in FCLs). However, the time scale is expected to be significantly longer since the flood channel would not be geographically confined.

Similar but more substantial measures would likely be required to mitigate debris flow hazards as well as flood hazards.

6. **Retreat / Avoid: Floodplain Buy-out**

   The flood hazard due to channel aggradation also could be mitigated by eliminating development within the floodplain. This option sacrifices development potential in favour of avoiding the costs of mitigation, response, and/or recovery.

   In the case of existing development, this would require buy-out of existing properties. Recent District projects have shown that buy-out of existing properties can be applied on a limited basis where benefits are sufficient to offset the associated costs. Future development would not be permitted in areas subject to significant flood hazard. In-stream works would be avoided through this approach.

   Challenges associated with this option include:

   - The cost to purchase existing properties, which could be substantial.
   - The loss of potentially developable area, which could be quite a large area depending on how the floodplain is defined.

The spectrum of potential strategies (e.g., Appendix C of APEGBC's 2012 Guidelines[5]) also includes river diversions, which could be classified as Protect, Accommodate or Retreat depending on the situation. Such engineering-intensive options are well beyond the scope of this sediment management discussion.

5. Implementation

5.1 Short-term Issues

2013 Sediment Deposition at Cheakamus River confluence

Hydraulic modeling for the 2012 removal project found that a 3,000 m^3 deposit of non-mobile material (e.g., large-size sediment from a Cheekye River debris flow) within the Cheakamus River cross-section could raise the design flood profile by about 0.3 m.

The 2013 event deposited roughly three times more sediment below the CN Rail bridge as was modeled in 2012. Even allowing for mobilization of some 2013 sediment by high Cheakamus River flows, potential impacts on the Cheakamus River design flood profile could still be proportionally greater than the 2012 results.

Providing funding is available, it would be prudent to remove the 2013 material to the 2012 excavation limits as a short-term flood hazard mitigation measure while the District develops a long-term, area-wide strategy to address flood and debris flow protection. An appropriate focus for this short-term sediment management work would be to mitigate on-going and future obstructions of the Cheakamus River channel by large-sized, less-mobile material, as well as to demonstrate due diligence to landowners and local stakeholders with regard to flood hazard management.

In pursuing this work, proponents and regulators should recognize the significance of the background sediment transport regime on the Cheekye River. In particular, the high natural sediment loads, lack of

[5] APEGBC, 2012. Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC. 144pp.

recent sediment management above the CN Rail bridge and the significant deposition observed following the 2009 event - and of course the occurrence of the 2013 event shortly after the 2012 removal - illustrate the high potential for a short-term removal to be followed by delivery of new sediment to the confluence.

Integrated Flood Hazard Management Study

The District has recently initiated an Integrated Flood Hazard Management Study (IFHMP), which includes consideration of both the Cheekye and Cheakamus Rivers. The intent of the IFHMP is to provide a framework to assess flood hazards over the entire District, and to provide a means to prioritize flood mitigation works. A key decision that the District will need to make as part of the IFHMP is to select the relevant time scale and hazard return period to which they wish to protect. This information is key to developing a long-term strategy for Cheekye River sediment management. However, the IFHMP is expected to address a broad range of hazards over multiple rivers, and is not expected to be able to drill down to address the detailed issues considered herein.

5.2 Long-term Issues

Area-Wide Hazard Mitigation Strategy

The IFHMP does not have sufficient scope to fully define and pursue stakeholder acceptance of an area-wide hazard management strategy for the Cheekye fan. Such a strategy will likely be pursued separately if and when development interests on the Cheekye fan can be considered.

Sediment Management Plan

In the long-term, there is a need for a sediment management plan to address the Cheekye River flood hazard, regardless of whether an area-wide hazard mitigation strategy is implemented. Local analogues for the Cheekye River sediment management challenges include Fitzsimmons Creek and Vedder River: both of these systems have high rates of aggradation, and both have developed a systematic plan to address the effects of channel aggradation on the flood profile. Unlike Cheekye River, both Fitzsimmons Creek and Vedder River have extensive development on the vulnerable floodplain protected by dike systems that meet all applicable provincial standards.

For both Fitzsimmons and Vedder, a technical committee has been formed to manage the river, including municipal government, environmental regulators, and other stakeholder representatives.

Based on these examples, the main components of a sediment management plan would include:

- **Monitoring**: repeat topographic survey to monitor bed levels and evaluate change over time.
- **Analysis**: hydraulic modeling to assess the change in the design flood profile.
- **Mitigation**: a means to address observed changes in the design flood profile.

A sediment management plan typically requires an "adaptive management" approach, where process and decisions are reviewed and modified periodically by the stakeholder group to maintain flexibility.

6. Summary and Recommendations

6.1 Summary

This technical memorandum documents the flood hazard posed by channel aggradation on the lower Cheekye River. Channel aggradation can result from floods, debris floods and debris flows on the Cheekye River. As the supply of sediment from the upper watershed is essentially unlimited, aggradation poses an on-going, long-term flood hazard that must be managed by the District. Unfortunately, there is little to no recent quantitative data upon which to base an assessment of the aggradation hazard. There is also currently no area-wide hazard mitigation strategy to comprehensively address the full range of flood and debris flow hazards on the Cheekye fan.

In the absence of a long-term strategy, sediment management can only be implemented on a reactive and subjective basis. In certain cases, including at the Cheekye River / Cheakamus River confluence, an argument can be made to support localized sediment management as an interim measure while a long-term strategy is developed.

6.2 Recommendations

Based on this assessment, KWL makes the following recommendations:

1. The District should develop a long-term strategy for Cheekye River sediment management that attains an appropriate balance between costs and benefits (i.e., risk reduction). Potential mitigation strategies should be considered over a relatively long time horizon (e.g. 50 to 100+ years), given the development / redevelopment cycle and the on-going nature of channel aggradation.
2. The long-term sediment management strategy should consider future integration with, or preferably, be developed as part of, an area-wide hazard mitigation strategy that addresses the full range of hazards on the Cheekye fan, including major debris flow hazards.
3. Part of the long-term strategy should address monitoring of channel conditions so that changes in bed level can be assessed over time, and be linked to changes in the flood profile and relative potential for avulsion.
4. While the long-term strategy is being developed, short-term measures can be considered to restore the confluence to post-2012 geometry. This could mitigate localized hazards and demonstrate due diligence to landowners and local constituents. Presenting a funding application as an "interim" measure, or combining both initiatives, may help secure regulatory buy-in.
5. The District should advise the provincial Inspector of Dikes of a potential inconsistency in their database with regard to structural flood protection works on the Cheekye River. A correction should be requested to more properly reflect the District's dike maintenance obligations, specifically excluding any and all reference to the emergency remnant works on the lower Cheekye River. These remnant works are already documented in the provincial database as a separate structure with no local maintenance authority.

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Attachments: Figure 2-1; Figure 6-1 from KWL 2006/2007 Dike Inspection Report; our file 0463.163-300

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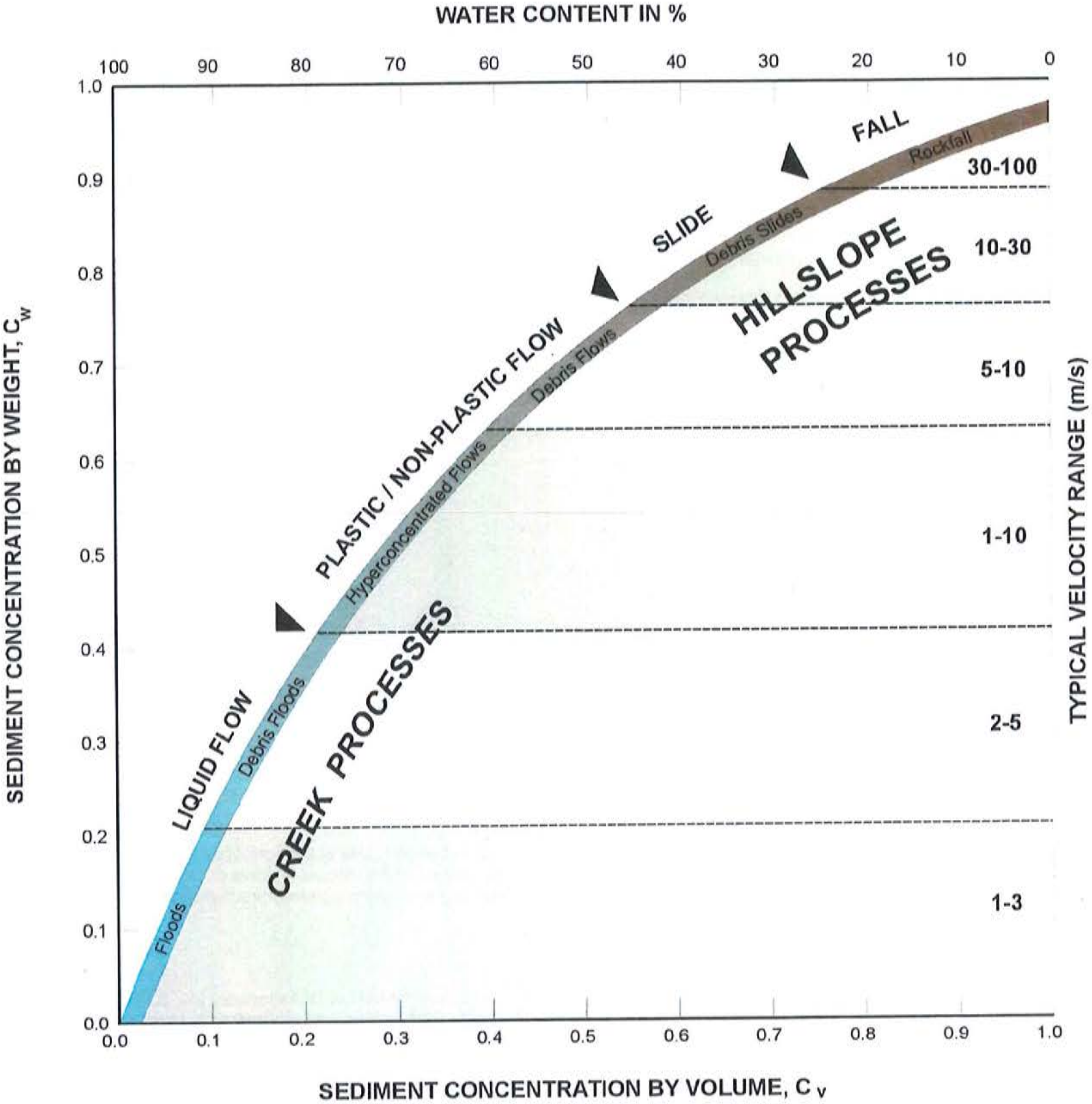
Revision History

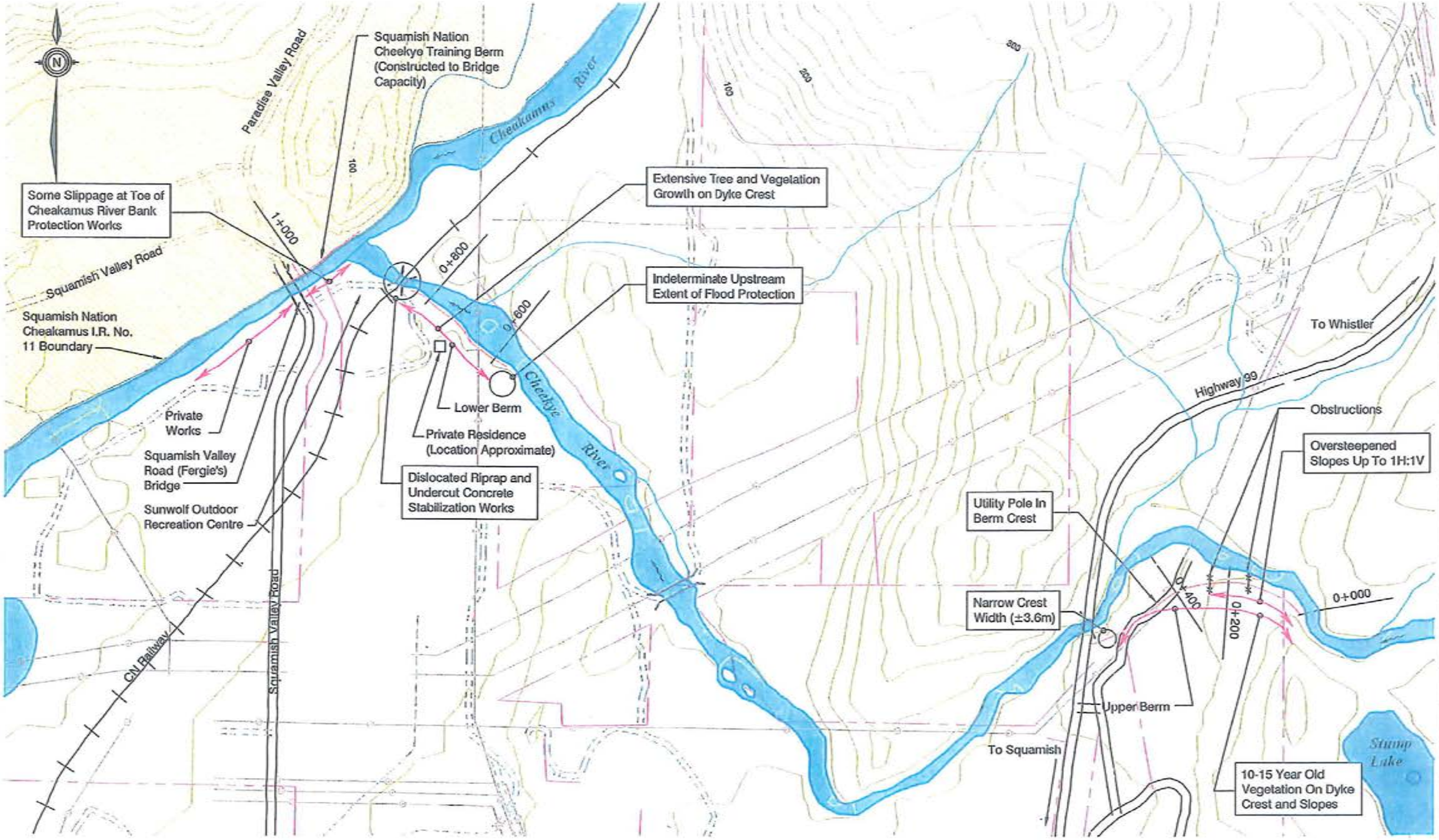
Revision #	Date	Status	Revision Description	Author
A	Feb. 28, 2014	Original	Draft report.	EE/DR
1	March 12, 2014	Final	Incorporate comments from District.	EE/DR

OQM | Organizational Quality Management Program



Classification of Mass Movement Processes

Figure 2-1



KERR WOOD LEIDAL associates limited CONSULTING ENGINEERS

Cheekye River Dykes

Figure 6-1

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