BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

SQUAMISH-LILLOOET REGIONAL DISTRICT

SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

FINAL

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BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

April 6, 2018
Project No: 1358005

Ryan Wainwright
Emergency Program Manager
Squamish-Lillooet Regional District as agent for Emergency Management BC
Box 219
Pemberton, BC V0N 2L0

Dear Mr. Wainwright,

Re: Seton Portage Area Integrated Hydrogeomorphic Risk Assessment – FINAL

Please find enclosed a copy of our above referenced final report. This version of the document incorporates comments and suggestions from the steering committee on a draft of the report issued on January 10, 2018. This final version of the report also supersedes the January 10, 2018 draft. Should you have any questions or comments please do not hesitate to contact the undersigned.

We appreciate the opportunity to work on this most interesting project.

Yours sincerely,

BGC ENGINEERING INC.
per:

Matthias Jakob, Ph.D., P.Geo.
Principal Geoscientist

EXECUTIVE SUMMARY

BGC Engineering Inc. (BGC) was retained by the Squamish-Lillooet Regional District (SLRD) as agent for Emergency Management BC (EMBC) to assess hydrogeomorphic hazards and risks at Seton Portage, British Columbia. Hydrogeomorphic hazards are defined herein as hazards stemming from Bear/Pete's, Whitecap and Spider creeks and include floods, debris floods, debris flows and bank erosion. Other hydro-geomorphic hazards such as landslide-generated waves may exist, but were not included in this assessment. BGC's scope also included snow avalanches whose hazard was reviewed. Lastly, hazards were assessed that could indirectly affect steep creek processes such as deep seated landslides.

The key objectives were to assess hydrogeomorphic hazards, assess risk and propose conceptual mitigation measures for risks that are considered unacceptable by the key stakeholders.

Hazards

BGC assessed debris flow hazard at Bear and Pete's creeks (which share a common fan), and debris flood hazard at Whitecap and Spider creeks. Flood hazard was also assessed at a cursory level at Portage River (also known locally as Portage Creek). Debris floods on Whitecap Creek and debris flows on Bear Creek can impact, dam and deflect Portage River into Seton Portage. The tributary events were modeled, but not the outbreak floods on Portage River that could result from such damming events given the very substantial uncertainties related to such processes and the high likelihood of human interference (engineered breaching of a landslide dam). Return period scenarios considered in this study ranged from 10 to 3000 years. Debris flows and debris floods were numerically simulated for each scenario, which led to development of hazard maps that identify areas that may be impacted during future hydrogeomorphic flood events.

Table E-1 summarizes the estimated sediment volumes transported past the fan apex and peak discharges for each return period class and study creek.

Table E-1. Frequency-magnitude estimates for the three creeks studied.

	Bear Creek		Whitecap Creek		Spider Creek	
Return Period (T) (years)	Sed. Volume Estimate (m^3)	Peak Discharge (m^3/s)	Sed. Volume Estimate (m^3)	Peak Discharge (m^3/s)	Sed. Volume Estimate (m^3)	Peak Discharge (m^3/s)
10 to 30	11,000	30	30,000	60	13,000	25
30 to 100	70,000	220	38,000	130	17,000	55
100 to 300	150,000	480	46,000	275	20,000	140
300 to 1000	240,000	760	59,000	410	24,000	280
1000 to 3000	320,000	1000	66,000	600	28,000	up to 1000

Table E-1 shows that estimated sediment volumes transported past the fan apex at Bear Creek can be up to 5 times higher than those estimated for Whitecap Creek for higher return period classes and up to 11 times higher than at Spider Creek. The difference for peak discharges is less. In the case of Whitecap Creek and Spider Creek, peak discharges of return periods in excess of 300 years are likely governed by landslide dam outbreak floods (LDOFs). Lesser return periods are likely to be floods that exceed a critical threshold for significant sediment mobilization.

Bank erosion was estimated for Whitecap and Spider creeks. Bank erosion was not expected to be significant for Bear/Pete's creek as debris flows are less likely to erode their banks.

Snow avalanche hazards formed part of BGC's scope and were thus reviewed. BGC concluded that snow avalanches are very unlikely to reach developed areas under current conditions. Large scale deforestation by fires, logging or landslides may require a review of current avalanche hazards.

While not within BGC's scope, it is worthwhile highlighting that landslide-generated tsunamis from Anderson Lake or Seton Lake could impact Seton Portage. The risk associated with this process has not been quantified.

Risks

The risk assessment considered safety and economic risk, including estimating the probability that hazardous events will: impact dwellings; cause loss of life or economic damage; or impact roads, bridges or the railway. For the risk assessment, BGC assumed that evacuation of residents only occurs for bank erosion scenarios on Whitecap Creek, but that areas impacted directly by Whitecap Creek debris floods or Bear Creek debris flows would not be evacuated due to the expected lack of response time.

Two different safety risk metrics were considered: individual risk and group risk. Individual risk evaluates the chance that a specific individual (the person judged to be most at risk) will be affected by the hazard. Group risk, also known as societal risk, evaluates the potential number of fatalities that could be caused by a hazard scenario.

BGC's safety risk estimates are summarized in Table E-2, and economic risk estimates are summarized in Table E-3. Results were compared to quantitative risk tolerance criteria to help identify areas where mitigation measures are warranted. Risks associated with hazard scenarios with greater than 3000-year return periods have not been quantified. Those exist and are in addition to those reported in Table E-2 and E-3.

Ultimately, the decision of which creeks require mitigation will be made by the stakeholders and be informed by the risk ratings in this report, but also by the available funds and comparison of other funding priorities at Seton Portage.

Table E-2. Individual and group safety risk.

Creek	No. of Buildings that Exceed Tolerable Individual Safety Risk	Group Risk	Mitigation Priority
Bear and Pete's Creek	59	unacceptable	High
Whitecap Creek	1	tolerable	Low
Spider Creek	0	acceptable	None

Table E-3. Maximum and annualized economic damage of the creeks studied. All figures are rounded.

Creek	No. of Buildings Affected	Maximum Economic Damage	Annualized Economic Damage	Businesses Affected
Bear and Pete's Creek	134	$ 8,000,000	$ 140,000	6
Whitecap Creek	5	$640,000	$ 8,000	3
Spider Creek	1	$70,000	$ 70	0

Mitigation

Table E-2 and Table E-3 demonstrate that debris flow risks from Bear and Pete's creeks are much higher than risks from other creeks at Seton Portage. These findings suggest that mitigation efforts and funds should be focused on Bear and Pete's creeks. Mitigation measures for Spider Creek have not been proposed because risks at Spider Creek are interpreted to be acceptable when compared to risk tolerance standards developed and applied elsewhere.

Tables E-4 summarizes three mitigation options and estimated conceptual costs for Bear and Pete's creeks. The measures have been sized for the largest magnitude event considered in this study with the objective of reducing risks to levels typically considered 'acceptable'. During the pre-design phase mitigation can be optimized to achieve tolerable risk targets if adopted by the stakeholders. The mitigation concepts listed also reduce economic and outage risk for a broad spectrum of other elements at risk including roads, railway, utilities, and power transmission, although this risk reduction was not quantified. Non-structural mitigation measures, for example education of residents about hydrogeomorphic hazards and development of emergency response plans, should be implemented along with any structural measures that are selected.

Table E-4. Mitigation options and costs for Bear and Pete's creeks to control risk up to the 3000-year return period event.

Proposed Mitigation Option	Description	Cost
1 – Basin and Anderson Lake conveyance	Attenuate flows with a basin at the fan apex; convey attenuated flows and remaining debris to Anderson Lake through the gap between the Whitecap Development and Necait.	$8.0 million
2 – Basin and diversion to eastern fan	Attenuate flows with a basin at the apex; divert attenuated flow and remaining debris to the northeast; retain debris on the eastern fan.	$8.0 million
3 – Basin and distal berms	Attenuate flows with a basin at the apex; build local berms on the distal fan to protect elements at risk.	$7.3 million

The three proposed options appear to be technically feasible and have a similar cost. Stakeholder input will be needed to select the option for final design. BGC prefers Option 3 because the potential for risk transfer is lowest, and measures could be upgraded if a limited mitigation budget were available at a later date.

Table E-5 summarizes mitigation options and estimated conceptual costs for Whitecap Creek. The design intent is to reduce the likelihood and duration of Anderson Lake road closure. The 30 to 100-year event was initially selected as the design event, similar to the size of both the 2015 and 2016 events. BGC understands that the 100 Anderson Lake Road[1] residence, which is currently exposed to intolerable safety risk, is planned to be moved in the spring of 2018. Safety risk is tolerable at other buildings on Whitecap Creek fan. After relocation of the 100 Anderson Lake Road residence, risk reduction would thus focus to reduce economic losses only. No risk reduction measures were proposed to avoid Portage River from being diverted into Seton Portage as the cost of such measures would likely grossly exceed the expected losses from such floods and would be difficult to justify.

Table E-5. Mitigation options and costs for Whitecap Creek (assuming 100 Anderson Lake Road residence is relocated).

Proposed Mitigation Option	Description	Construction Cost
1 – Short berm	Berm along Anderson Lake Road to protect the road.	$290,000
2 – Long berm	Berm along the creek to prevent avulsions from the existing channel. This is similar to the NHC concept presented after the 2015 event.	$1,070,000
3 – Event response	Prepare an emergency management plan and restore the road and Portage River channel as quickly as possible following each flood and debris-flood event.	$0

[1] Civic address provided by Cliff Casper, Tsal'alh Housing and Infrastructure Manager.

Bank erosion mitigation (Options 1 and 2) at Whitecap Creek would likely cost substantially more than the value of any damage that they would prevent. As such, BGC prefers Option 3, assuming the main design objective is to prevent closure of Anderson Lake Road. Anticipating that budget to reduce the risk of the various geohazard examined is limited, BGC recommends that the majority of the available budget be spent on reducing risk from Bear and Pete's Creek.

Several steps are required before the chosen mitigation measure can be implemented. BGC recommends that at the next design stage, mitigation measures be refined to optimize risk reduction given the available budget. Residual risk, should it still be deemed intolerable, could be addressed through land-use zoning and local protection of buildings. Recommendations for future work are provided in Section 8, including a description of studies and work sequence to support structural mitigation implementation, and guidance for policies that could be adopted to manage current and future development in the Seton Portage area.

It is important to note that at this stage of study, no attempt was made to optimize mitigation measures to reduce risk to 'tolerable' rather than 'acceptable' limits. The distinction between 'tolerable' and 'acceptable' is subtle but noteworthy: A tolerable risk level is one that is generally tolerated by society, but ought to be reduced where practical and where funding allows. An 'acceptable' risk is one that requires no further risk reduction. Once a decision has been made as to the risk tolerance considered acceptable by the SLRD and other stakeholders, such optimization should be achieved at the pre-design stage.

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LIMITATIONS

BGC Engineering Inc. (BGC) prepared this document for the account of Squamish-Lillooet Regional District (SLRD) as agent for Emergency Management BC (EMBC). The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of document preparation. Any use which a third party makes of this document of any reliance on decisions to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made of actions based on this document.

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1.0 INTRODUCTION

1.1. General

Over the last several thousand years, Seton Portage has been affected by episodic debris floods and debris flows from Bear/Pete's creeks, Whitecap Creek and Spider Creek, some of which have been of sufficiently large magnitude to pose a risk to human safety. BGC understands that to date, no one has died due to those events. Most recently, debris flows occurred on Bear Creek and Pete's Creek in September 2015 and August 2016 that impacted houses on the Bear Creek fan at Seton Portage and the Whitecap Development property (Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) 2016b, BGC 2017) (Drawing 01). Extreme runoff also occurred on Whitecap Creek in 2015 and 2016 that impacted Anderson Lake Road and the CN Rail line. Recorded hydrogeomorphic events that have occurred in the last 110 years are summarized in Appendix A.

Following the 2016 events, Emergency Management British Columbia (EMBC) and the Department of Indigenous and Northern Affairs (INAC) provided joint funding to the Squamish Lillooet Regional District (SLRD) for a comprehensive hydrogeomorphic risk assessment at Seton Portage. BGC Engineering Inc. (BGC) was retained to conduct the risk assessment following a competitive proposal process. This work was conducted under BGC's standard terms and conditions and under the SLRD's Consulting Service Agreement dated September 8, 2017.

The integrated hydrogeomorphic risk assessment includes Pete's and Bear creeks, Whitecap Creek and Spider Creek (Drawing 01). Each creek has unique characteristics and harbors variable geomorphic processes. Pete's and Bear creeks are prone to debris flows due to their steep and small watersheds, while Whitecap and Spider creeks are prone to debris floods as the watersheds are larger and less steep. Recognition of the different hazard and risk characteristics of each creek is key to successful study execution and mitigation planning. Pete's, Bear, Whitecap, and Spider creeks also interact and affect Portage River (also referred to as Portage Creek), its banks and floodplain.

The overall objective of the integrated risk assessment is to estimate the frequency and magnitude of hydrogeomorphic hazards at Seton Portage and to identify mitigation options that can reduce risk to a tolerable risk level, if required. Risk, in the context of geohazard management, is a measure of the probability and severity of an adverse effect to health, property or the environment, and is estimated by the product of hazard probability (or likelihood) and consequences. This report focuses on identifying and assessing key risks to people and infrastructure of Seton Portage that can be used as a basis for cost-effective risk management decision-making. To achieve this goal, input has been sought from key stakeholders including the SLRD, Tsal'alh First Nation and the Ministry of Forestry, Lands and Natural Resource Operations (FLNRO).

A public meeting will be held with stakeholders and residents in April 2018.

1.2. Scope of Work

Geohazards considered in this risk assessment include debris flows, debris floods, landslide dam outbreak floods (LDOF) and floods with the potential to impact the low-lying areas separating Anderson Lake from Seton Lake, known as Seton Portage. Deep seated gravitational slope deformations (DSGSDs) that could potentially result in rock avalanches, and snow avalanches formed part of BGC's scope, and were thus reviewed as potential auxiliary hazards. Snow avalanches were found not to penetrate into currently developed areas. DSGSDs were included in the assessments where they have a credible chance of damming creeks discharging into the Seton Portage area within the frequencies considered in this report. They were not included in the quantitative risk assessment where there are no precedents for rock avalanche damming of creeks. Other geohazard types (e.g., earthquakes) were not considered.

Figure 1-1 describes seven steps of geohazard risk management. The proposed work is structured around Steps 1 through 5 and the initial part of Step 6. The major work phases include hazard assessment, risk assessment, and mitigation concept development.

Assessment Type		
Geohazard Assessment; Geohazard Risk Identification; Geohazard Risk Analysis; Geohazard Risk Assessment; Geohazard Risk Management	**Risk Communication and Consultation** – Informing stakeholders about the risk management process	**Monitoring and Review** – Ongoing review of risk scenarios and risk management process

1. Scope Definition
- a. Recognize the potential hazard
- b. Define the study area and level of effort
- c. Define roles of the client, regulator, stakeholders, and Qualified Registered Professional (QRP)
- d. Identify 'key' consequences to be considered for risk estimation

2. Geohazard Analysis
- a. Identify the geohazard process, characterize the geohazard in terms of factors such as mechanism, causal factors, and trigger factors; estimate frequency and magnitude; develop geohazard scenarios; and estimate extent and intensity of geohazard scenarios.

3. Elements at Risk Analysis
- a. Identify elements at risk
- b. Characterize elements at risk with parameters that can be used to estimate vulnerability to geohazard impact.

4. Geohazard Risk Estimation
- a. Develop geohazard risk scenarios
- b. Determine geohazard risk parameters
- c. Estimate geohazard risk

5. Geohazard Risk Evaluation
- a. Compare the estimated risk against tolerance criteria
- b. Prioritize risks for risk control and monitoring

6. Geohazard Mitigation
- a. Identify options to reduce risks to levels considered tolerable by the client or governing jurisdiction
- b. Select option(s) with the greatest risk reduction at least cost
- c. Estimate residual risk for preferred option(s)

7. Action
- a. Implement chosen risk control options
- b. Define and document ongoing monitoring and maintenance requirements

Figure 1-1. Risk management framework (adapted from CSA 1997, AGS 2007, ISO 31000:2009 and VanDine 2012).

For this assessment, BGC and SLRD have chosen a quantitative risk assessment (QRA) approach for debris flows and debris floods on Bear/Pete's, Whitecap and Spider creeks. This approach is compatible with the APEGBC Guidelines for Legislated Landslide Risk Assessments for Proposed Residential Developments in B.C. (2010). It is also consistent with Canadian and international guidelines for risk management (CAN/CSA Q850-97) and the Canadian Landslide Risk Evaluation Guidelines (Porter and Morgenstern 2013) in that it provides a transparent, repeatable method to assess risk, define thresholds for risk tolerance, evaluates potential debris-flow and debris-flood mitigation alternatives, and describes uncertainties. Other jurisdictions where risk assessment is a more established standard of practice, such as Hong Kong and Australia, use similar frameworks.

The following sections summarize BGC's scope for the three project phases, according to the objectives laid out in the Request for Proposals (RFP) from the SLRD.

1.2.1. Hazard Assessment

- Conduct an integrated hydrogeomorphic hazard assessment for the Seton Portage area. Geohazards to be considered include landslides, snow avalanches, and steep creek geohazards (debris floods and debris flows).
- Develop, demonstrate, and provide runout models for snow avalanches (if reaching developed areas) and landslides initiating from slopes within the Seton Portage area, and demonstrate projected consequential flooding effects. Note that this does not include rock avalanches impacting either Anderson or Seton Lakes and resulting in landslide-generated tsunamis.
- Determine the likely deposition pathways and the effects of events of a given size and/or return period on changing runout to new pathways.

1.2.2. Risk Assessment

- Identify the values potentially affected by landslides initiating from slopes within the Seton Portage area, including those values potentially affected by consequential flooding such as bridges, housing and rail lines.
- Develop, demonstrate and provide a comprehensive risk assessment for the study area, including the risk tolerance criteria and rationale adopted for the project.

1.2.3. Mitigation Concepts

- Develop and provide conceptual mitigation options with approximate cost estimates for both structural and non-structural approaches (i.e., relocation of existing development, area exclusion for new development) to protect existing residences and infrastructure

1.3. Terminology

The appropriate use of this assessment requires some understanding of hazard and risk terminology. Key terms used in this assessment are defined in Table 1-1 below and additional terms are defined in the Glossary at the end of the report.

Table 1-1. Terminology.

Term	Definition
Hydrogeomorphic event	Earth-surface process involving water and varying concentrations of sediment.
Debris Flow	Very rapid to extremely rapid surging flow of saturated, non-plastic debris in a steep channel (Hungr et al. 2014). Debris generally consists of a mixture of poorly sorted sediments, organic material and water.
Debris Flood	A very rapid flow of water that is heavily charged with debris in a steep channel. It can be pictured as a flood that also transports a large volume of sediment that rapidly fills in the channel during an event.
Landslide Dam Outbreak Flood (LDOF)	A flood that is triggered by the abrupt breach of a landslide dam on a creek or river.
Rock Avalanche	Extremely rapid, massive, flow-like motion of fragmented rock from a large rock slide or rock fall. This study focused on potential rock avalanches with volumes greater than 1,000,000 m^3.
Rock (and debris) Slides	Sliding of a mass of rock (and debris). Our inventory focused on large rock fall and rock/debris slide events with volumes ranging between approximately 50,000 m^3 and 1,000,000 m^3.
Deep-seated gravitational slope deformation (DSGSD)	Large-scale gravitational deformation of steep, high mountain slopes, manifested by scarps, benches, cracks, trenches and bulges, but lacking a fully defined rupture surface. Slow mountain slope deformations can either evolve into extremely rapid rock avalanches or they can deform slowly for millennia.
Rock Fall	Detachment, fall, rolling, and bouncing of rock fragments.
Hazard	Process with the potential to result in some type of undesirable outcome. Hazards are described in terms of scenarios, which are specific events of a particular frequency and magnitude.
Element at Risk	Anything considered of value in the area potentially affected by hazards.
Consequence	The outcomes for elements at risk, given impact by a geohazard. In this report, consequences considered include potential loss of life, and potential damage to buildings and infrastructure.
Risk	Likelihood of a geohazard scenario occurring and resulting in a particular severity of consequence. In this report, risk is defined in terms of safety or damage level.

2.0 STUDY OVERVIEW

2.1. Introduction

This chapter describes some of the "why" and the "what" of this study: in other words, why is the study necessary and important, and what is the study about. The chapter also aims to provide an introduction to geohazards and hydrogeomorphic hazards for readers who may have experience with the debris flows or debris floods at Seton Portage, and want to learn more about these hazards in their community.

2.2. Study Area Description

The following section provides a technical summary of the study area physiography, bedrock geology, glacial history and surficial geology, fan development, climate and hydrology.

2.2.1. Physiography

Seton Portage lies on the leeward side of the Pacific Ranges in the Coast Mountains, southwestern British Columbia (Holland 1976). It is situated on an alluvial fan and floodplain landform that separates Anderson and Seton Lakes (Drawing 01). Following deglaciation about 11,500 years ago, the Seton/Anderson trough would have been a single lake, but during the early post glacial period, fan formation at the mouth of Bear Creek split the long single lake into upstream and downstream lakes. The portage is about 2300 m long along the valley axis and approximately 1000 m wide from valley side to side. From an elevation of 250 to 260 metres above sea level (masl) at the valley bottom, slopes rise to 1900 to 2200 m elevation along mountain crests on the valley sides and up to 3000 m in Whitecap Creek; with ~1900 to 2750 m relief. Treeline is around 2000 m elevation, with permafrost at 2160 +/- 340 m elevations.

2.2.2. Bedrock Geology

Bedrock geology is discussed here as it influences the characteristics of debris flows and because it has bearing on the type and location of large landslides. Some bedrock weathers into sand-sized particles (like the coastal granites) while others, weather into silt and clay size particles that are smaller than sand. The fine-grained weathered materials form the so-called matrix of debris flows, which are the sediments that carry the bigger particles.

At Bear Creek, the source area geology consists of rocks that weather into clay size particles which are so small that they cannot be seen by the naked eye. A matrix composed of clay-sized particles significantly increases the mobility of debris flows, which means they can run further than if they consisted of a largely sandy matrix. The study area is underlain by the Bridge River Complex a geological unit consisting of marine sedimentary and volcanic rocks (Cui et al. 2017). These geological units can weather to clay size particles, as confirmed by BGC's grain size analysis of deposits encountered in test pits (Appendix F).

The bedrock geology along Seton and Anderson lakes was first mapped by Camsell (1918) who described cherty quartzite, argillite, crystalline limestone, volcanic rocks, and schist in the study area. The main fabric of these units is orientated approximately north-south along the shorelines

(Camsell 1918). Roddick and Hutchinson (1973) mapped the headwater of Whitecap, Bear, Pete, and Spider creeks and, apart from the Bridge River complex found granodioritic plutons and conglomerate rocks in the headwaters of Whitecap Creek. These rock types appear to be more erosion resistant than rocks of the Bridge River complex.

A faulted geological contact (Figure 2-17) was mapped by Monger and Journeay (1994). The geological contact is situated immediately next to large deep-seated gravitational slope deformations (DSGSDs).

Detailed geological mapping located east of Spider Creek, documented the presence of pillowed and massive greenstone, limestone and minor amounts of chert, argillite diabase, sandstone and pebbly mudstone (Gray and Williams 1997). The rock mass was noted to be highly fractured, hydrothermally altered and limited bedding measurements were found to be orientated north to northeast with a moderately steep (45-66°) dip to the east and southeast. These rock mass characteristics may have contributed to the large rock slide that dammed Spider Creek in the past and which is described further in Section 2.3.5.

2.2.3. Glacial History and Surficial Geology

Surficial geology refers to the sediment and debris that overlies bedrock. In most of Canada, the surficial geology is a product of the area's glacial history.

> For thousands of years, thick glaciers occupied the valley between D'Arcy and Lillooet. When the glaciers retreated, a single continuous lake occupied the valley; the lake level was about 100 m higher than the current level. Sediment and rocks covered the unvegetated hillsides. Tributary creeks began to build their fans into the lake and eventually separated Anderson Lake from Seton Lake.

At Seton Portage, the surficial geology is a product of the last glaciation and post-glacial erosional processes. During numerous glacial phases, ice accumulated in the mountains nearby and valley glaciers flowed down the Anderson/Seton trough to merge with the Fraser River glacier at Lillooet. The last glaciation occurred between 29 to 11.5 ka (thousand years) before present (BP). During the glacial advance phase (29 to 19 ka BP), proglacial outwash fans at the ice front, and eventually ice directly, blocked tributary drainages and lead to the formation of glacial lakes (Huntley and Broster 1994). During the glacial maxima (14 ka), the advance glacial lakes were overridden and sediments eroded or buried by till. Glacial lakes may also have temporarily re-established during deglaciation – 13.5 to 11.5 ka BP.

As a result of this glacial scour, upper slopes in the study watersheds are dominated by bedrock outcrop. Further downslope mid to lower valley sides support a veneer/blanket of muddy to sandy till, and in places there may be pockets of gravelly glaciofluvial/colluvial or find-grained glaciolacustrine materials. Locally, these glacial sediments can form extensive ice-contact benchlands called kame terraces. At Seton Portage a 400-m wide kame terrace formed on the north side of the valley between 330 to 340 masl elevation (Drawing 08). An exposure in these sediments is located on the right bank of Whitecap Creek about 350 m upstream from the mouth is recorded by an exposure with glaciofluvial deltaic sediment (foreset/topset sequence) overridden by a landslide deposit presumably originating in Bear Creek (Figure 2-1).

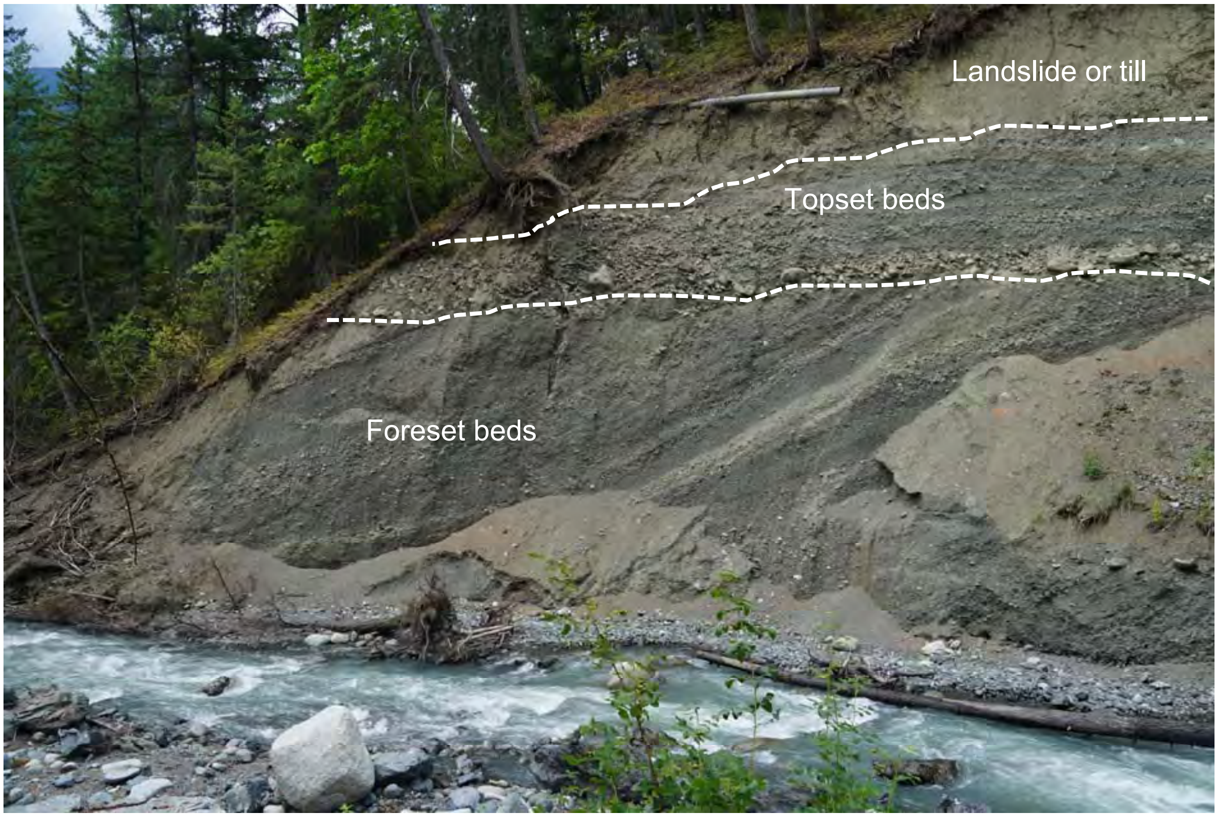


Figure 2-1. Glaciofluvial deltaic sediment (foreset/topset sequence) on the right bank of Whitecap Creek approximately 350 m upstream from the confluence with Portage River. Photo: BGC September 12, 2017.

2.2.4. Fan Development

During and immediately following deglaciation, hillslopes were very unstable with landsliding of glacially undercut slopes and shedding of unstable overburden. This time of heightened hillslope activity is termed the paraglacial period, and extended roughly from 11,000 to 7,000 years BP, (Church and Ryder 1972).

The iconic features of the paraglacial period in southwestern BC are the large alluvial fans formed along mainstem valley sides in the Fraser/Thomson region (Ryder 1971). These fans formed when sediment yield was high, but due to rapid decline in sediment yield after 7,000 year BP many of the tributary streams became deeply entrenched into the fan surface, isolating the now higher fan surfaces from modern stream processes. However, not all tributaries have entrenched fans, particularly those with relatively frequent debris flow and debris flood activity.

As an example, debris floods from Spider and Whitecap creeks and debris flows from Bear Creek episodically shed sediment onto their respective fans. However, while Bear Creek fan continued to grow through repeat debris flows that deposit more and more sediment on the fan, Spider and

Whitecap creeks incised by fluvial erosion into their glacial deposits and directly transferred their sediment on the floodplain or directly into Portage River. Each of the study creek fans is described in more detail below (Drawing 02).

After deglaciation, mass movement (debris slides, debris flow, rockfall, rock avalanche, snow avalanche) and stream erosion reworked bedrock and soil mantled slopes, forming rubble cones and aprons on mid to lower slopes. Larger streams eroded into kame and paraglacial sediments and formed valley bottom floodplains.

Three major tributaries to Portage River dominate the Valley at Seton Portage, but all behave quite differently. Whitecap and Spider creeks are deeply entrenched in fluvial sediments that were laid down right after the last Ice Age. Bear and Pete's Creek, being subject to debris flows, are not incised and continue to build up their combined fan surface by repeated landslides.

Bear and Pete's Creeks

Pete's Creek watershed is a tributary watershed to Bear Creek, but currently does not join the channel of Bear Creek. Paleochannels above the fan apex, however, suggest that the two channels have intertwined and discharged water and debris into each other's channels.

The combined Bear and Pete's Creek fan grew rapidly during the paraglacial period. Detailed examination of exposed debris flows in the railway cut and dating of organic materials demonstrated that at some point in the early to mid-Holocene, Bear Creek fan likely extended across Portage River to form a fan barrier, with up to 20 m difference between Seton Lake and Anderson Lake. The lack of an entrenched channel on Bear Creek fan suggests there is insufficient stream power to remove fan sediment at rates higher than it is accumulating.

Bear Creek fan extends from 422 masl elevation at its apex to ~260 m elevation where it meets Anderson Lake. Based on interpretation of the LiDAR hillshade model that covers the entire watershed and was flow in September of 2017, different fan sectors can be inferred based on surface texture and patterning. The majority of the fan surface has a channeled and lobed expression with channel alignment radiating from the apex. However, a triangle shaped sector of the fan, with the base about 400 m wide along the "railway cut" and extending to a point about two-thirds up the fan, has fewer pronounced paleochannels and a smoother undulating expression (Figure 2-2).

Bear Creek fan is remarkably truncated (oversteepened) along its entire lower fan perimeter (Figure 2-2, Drawing 02). The gradient abruptly steepens from approximately 10% (6°) to 50% (27°). This truncation is unusual as active fans normally become less steep towards the fan edge. BGC interprets that large debris floods from Whitecap Creek may have redirected Portage River flows against the northern edge of the Bear Creek fan. Portage River would have eroded the Bear Creek fan, causing the truncated shape. An alternative (but speculative) mechanism for the truncation of Bear Creek fan could be tsunamis generated by rock avalanches impacting Anderson Lake.

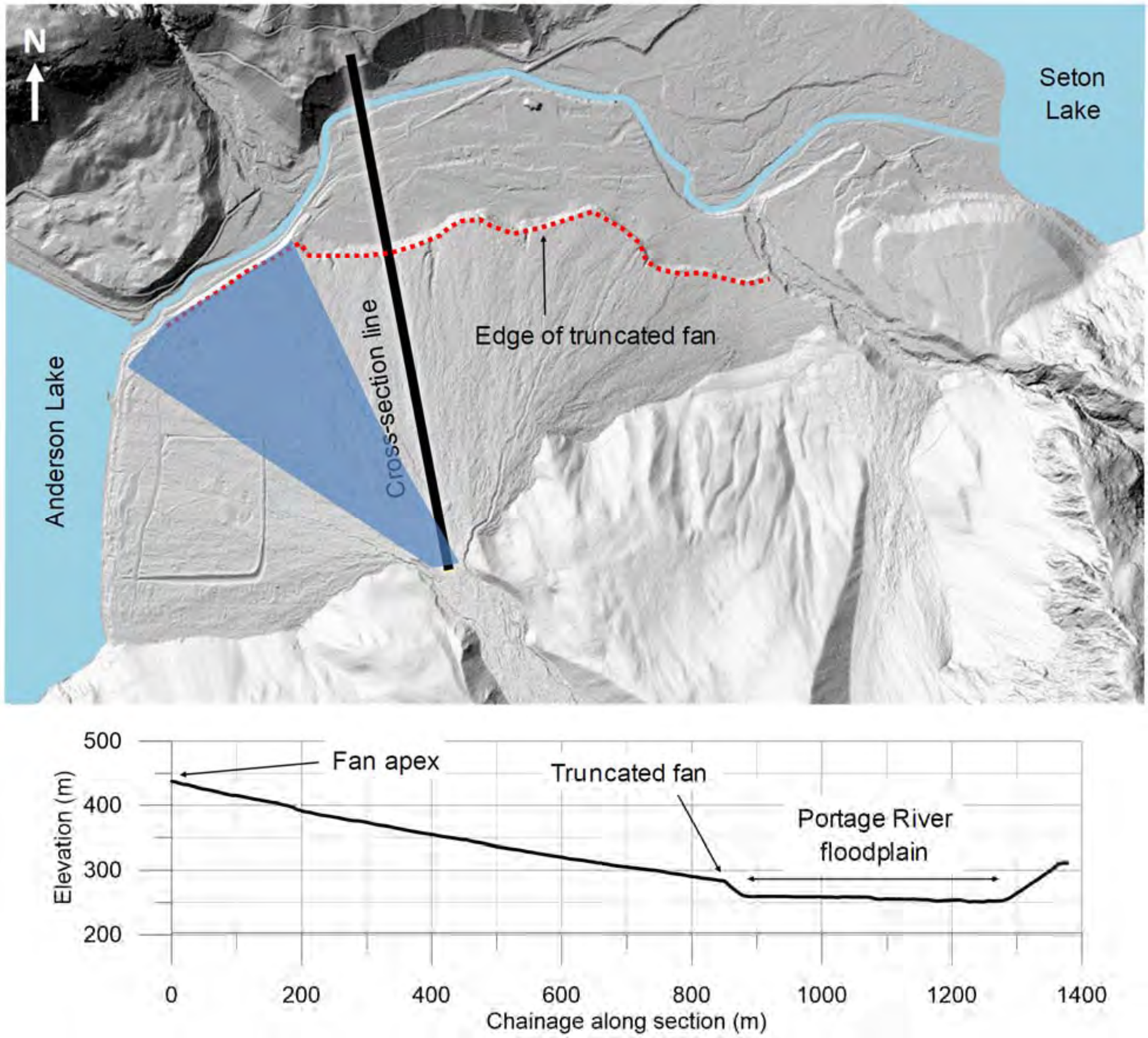


Figure 2-2. LiDAR hillshade image and cross-section of the Bear Creek fan showing the fan truncation and the triangular-shaped poorly channeled section upslope of the railway cut.

The truncated fan edge has created a knickpoint (abrupt slope change) on the Bear Creek fan. Several gullies have developed where Bear Creek has flowed over the truncated edge at different locations. Nine of these escarpment knick-points dissect the fan edge, and they range in size from poorly developed channels that are 5 m wide to 30 m long, to well-developed dry gullies 30 m wide to 150 m long. At the mouths of the erosion knickpoints alluvial fans radiate up to 75 m from their apices with relief up to 15 m. In contrast, the triangle shaped railroad cut (Drawing 09) sector has a less pronounced channeled surface, and lacks knickpoints on the escarpment crest. This means that relatively little recent debris flow activity of flooding has occurred in this sector which would otherwise have created preferential flow paths. While future debris flows may avoid this area due to its currently higher position, it is not free of hazard.

The western portion of the fan extends from Portage River inlet to the hillside about 750 m south. Here the fan grades into Anderson Lake, and is not undercut by stream processes. The south-western fan toe has been steepened by lakeshore erosion producing a noticeable scarp with 40° (84%) slopes and up to 12 m tall which is also mapped on Drawing 09.

Whitecap Creek

Where Whitecap Creek discharges onto the valley floor, the creek is deeply entrenched in a landslide deposit or till (interpretation unclear) overlying deltaic deposits. The resulting fan is only 310 m wide at Portage River and portions of the fan are inactive, as terraces flank the active channel on both sides (Drawing 09). Hydraulic modeling (Section 3.3) demonstrated that at high peak flows some of these terraces could be inundated and/or eroded (Drawing 11). The lower, more active portion of the fan was inundated during the 2015 and 2016 debris floods, both by the events and subsequent in-channel works to restore channel capacity. The channel bank materials are generally loose and will likely be entrained in future floods and debris floods. Whitecap Creek fan would extend further, but is constrained by Portage River eroding its edge as well as Bear Creek fan on the opposite side of the river. During and after debris floods, Portage River erodes the sediments that have been transported to the fan edge and they become bedload or suspended load in the river. Very large debris floods (Section 3.3.4) have in the past transported sufficient material into the Portage River channel that the river was likely diverted to the south and through the currently developed areas. The legacy of such events are escarpments and terraces flanking the Portage River floodplain to the south. Portage River diversion does not appear to have occurred since modern settlements in the late 1800s.

At some point, BGC postulates that a major debris flood or LDOF occurred on Whitecap Creek that pushed Portage River into its opposing (south) bank leading to the truncated fan edge of Bear Creek. An alternative explanation could have been a landslide generated tsunami on Anderson Lake, but in absence of data confirming a tsunami, this hypothesis is speculative.

Spider Creek

Spider Creek fan is an example of a paraglacial (early Holocene) landform, with at least four main levels above the modern floodplain (see Drawing 09). These levels can likely be attributed to glacial recession and a lowering of Seton Lake, presumably in the early Holocene. As the base level (Seton Lake and Portage River) lowered, a declining sediment supply led to incision into the paleo fan delta surface. Subsequent floods or outbreak floods created paired terraces along the stream bed that are still visible today. The base level of Spider Creek fan is 20 m lower than that of Whitecap Creek fan. This implies that properties adjacent to the creek are at much lesser danger of being affected by floods or erosion compared to Whitecap Creek.

2.2.5. Climate

The study area is on the lee side of the Coast Mountains, with a transitional maritime to continental climate regime (Table 2-1). At the valley bottom, seasonal temperatures are cool, and mean annual precipitation is about 430 mm with the precipitation peak in winter with 20% falling as snow. In the upper watersheds, precipitation is 2-3 times as high with 75% falling as snow, resulting in a late season snowpack of 2.5 m depth on average (UBC Forestry 2017). Transition to permafrost terrain may exist above about 1980 masl elevation, the alpine area above treeline. To further constrain permafrost existence, some 80 rock glacier snouts were mapped in the area between Anderson and Seton Lakes to the west and the Duffy Lake Road to the east. Rock glaciers are indicators of alpine permafrost and their lowest elevation is often equated to the lower limit of alpine permafrost. This analysis suggests a median rock glacier snout elevation of 2160 m with a standard deviation of 340 m. Hence, the lower limit of alpine permafrost may lie at approximately 1820 m asl on north-facing slopes. Lower permafrost occurrences may exist in areas with cold-air drainage such as some north-facing cirques or talus slopes.

Table 2-1. Climate statistics for the Seton Portage area.

Elevation (masl)	266	784	1975	2294
Mean annual temp. (ºC)	8.5	5.8	0	-1.6
Mean annual precip. (mm)	431	611	1025	1136
Mean winter precip. (mm)	311	451	776	863
Proportion as snow (mm)	78	184	698	863

Note: Accessed online at: http://climatewna.com/climatena_map/ClimateBC_Map.aspx

Rainfall quantiles for durations of 24 hours and three days were developed for the Tsal'alh[2] climate station, which is located approximately 5 km northwest of Seton Portage at an elevation of 244 masl and is maintained by BC Hydro. The analysis was conducted using the daily rainfall recorded during the 42 year period from 1963 to 2004. As the maximum 24-hour rainfall does not necessarily coincide with the 24-hour period during which daily precipitation totals are recorded (i.e., a single calendar day), each daily rainfall was multiplied by an empirical correction factor of 1.13 when estimating the 24-hour quantiles (World Meteorological Organization 2009). Table 2-2 shows the rainfall amounts associated with a range of return periods.

[2] Also referred to as Shalath climate station.

Table 2-2. Rainfall return periods in the Seton Portage area. Larger return period rainfalls are associated with higher uncertainty.

Return Period (Years)	3	10	30	100	300	1000
24-hour Rainfall (mm)[1]	40	60	79	102	126	156
3-day Rainfall (mm)	52	75	94	114	133	154

Note:

1. As a 24-hour rainfall does not necessarily occur during a single calendar day, the daily rainfall record has been increased by a factor of 1.13 to estimate the maximum 24-hour rainfall, according to guidelines developed by the World Meteorological Organization (WMO 2009). As no such adjustment factor has been applied for the 3-day rainfall totals, the 24-hour rainfall total may sometimes exceed the 3-day rainfall. Based on the historical 24-hour and 3-day rainfall events from 1963 to 2004, the estimated rainfall totals for high return period events are similar for the 24-hour and 3-day storm durations.

2.2.6. Hydrology

The hydrology of creeks is important as it describes how much water is being discharged in variable return period events. The maximum volume of water per unit time (the peak discharge) is critical to model the areas that would be inundated by water. Together with the stream gradient and the distribution of different size boulders in the channel, it also determines how much erosion could occur on stream banks which is a secondary hazard to flooding.

Hydrology by itself is not equally important to all creeks. For Bear Creek, debris flows are initiated by landslides or by entrainment of debris along the flow path. By the time a debris flow reaches the developed areas, it no longer resembles a flood, as the peak discharge can be more than ten times greater than the clearwater flood. Thus, knowing the clearwater peak discharge at Bear Creek is of lesser importance that at Whitecap and Spider creeks. At those creeks, clearwater peak discharge will determine which areas are flooded.

General

Streams in the study area show typical freshet type seasonal hydrograph, with a prolonged spring/summer melt runoff season from May through August, peaking in June and July. Peak flows occur in May and June, occasionally in July and August, and rarely in the fall rain season (October).

Hydroclimatic Conditions of 2015 and 2016 Debris Flows and Debris Floods

Multiple hydrogeomorphic events have occurred in both the Whitecap Creek watershed and the Bear Creek and Pete's Creek watershed in recent years. These events include:

- September 20, 2015 debris flow on Bear and Pete's Creek
- September 20, 2015 debris flood on Whitecap Creek
- July 30, 2016 debris flow on Bear and Pete's Creek
- November 8-9, 2016 debris flood on Whitecap Creek.

The hydroclimatic conditions during these four events were reconstructed from the Tsal'alh climate station. BC Hydro provided BGC with quality checked daily total rainfall and temperature records, as well as raw hourly and sub hourly records for this site. The rainfall intensity records for the 2015 and 2016 events are summarized in Table 2-3.

Table 2-3. Rainfall intensity records at Tsal'alh station for the 2015 and 2016 events at Seton Portage.

Duration (hrs)	September 20, 2015		July 30, 2016		November 8-9, 2016	
	Time (PDT)	Rainfall (mm)	Time (PDT)	Rainfall (mm)	Time (PDT)	Rainfall (mm)
1	09:44-10:44	9	14:57-15:57	15	06:40-07:40	3
2	08:44-10:44	15	14:57-16:57	17	05:40-07:40	5
6	07:44-13:44	35	14:12-20:12	23	01:40-07:40	10
12	01:44-13:44	56	11:57-23:57	27	19:40 (Nov 8) – 07:40 (Nov 9)	14
24	15:44 (Sep 19) – 15:44 (Sep 20)	64	05:12 (Jul 30) – 05:12 (Jul 31)	27	16:25 (Nov 8) – 16:25 (Nov 9)	15

The 2015 event – which included a debris flow on Bear and Pete's Creek and a debris flood on Whitecap Creek – occurred during an intense rainfall event on September 20, 2015. This rainfall event caused numerous debris flows in the Anderson Lake, Birken, and D'Arcy corridor. The 24-hour rainfall total at Tsal'alh was 64 mm, which has a return period of about 10 years (Table 2-2). In the seven days preceding the event, 13 mm of antecedent rain was measured, a rather moderate amount. The maximum daily temperature recorded on September 20 was 12.5°C. During the seven days preceding the event, the average maximum daily temperature was 19°C, with a 4° decline in temperature in the two days preceding the event. Temperatures were high enough to ascertain precipitation falling as rain over the entire watersheds.

The 2016 debris flow on Bear and Pete's Creek occurred on July 30, 2016. The 24-hour rainfall total at Shalalth was 27 mm, with a maximum hourly intensity of 15 mm in the mid-afternoon. Only 1 mm of antecedent rainfall was noted in the seven days preceding the event. The maximum daily temperature during the seven days preceding this event averaged 28°C, and the maximum daily temperature on this day was 28.4°C. The 2016 debris flood event on Whitecap Creek occurred several months later, on November 8-9, 2016. The 24-hour rainfall total at Tsal'alh was only 15 mm during this timeframe, with a maximum hourly intensity of 3 mm in the early morning of November 9. Prior to the event, 31 mm of rain was recorded over a period of seven days.

The rainfall data from the three storm events are plotted on rainfall intensity-duration-frequency (IDF) records at the Pemberton climate station (55 km southwest; Figure 2-3) and Lillooet climate station (28 km east; Figure 2-4). These two stations vary slightly, with the Lillooet climate station having lower IDF values than the Pemberton station due to the rain shadow effect of the Coast Mountains. IDF curves have not been developed for the BC Hydro Tsal'alh climate station.

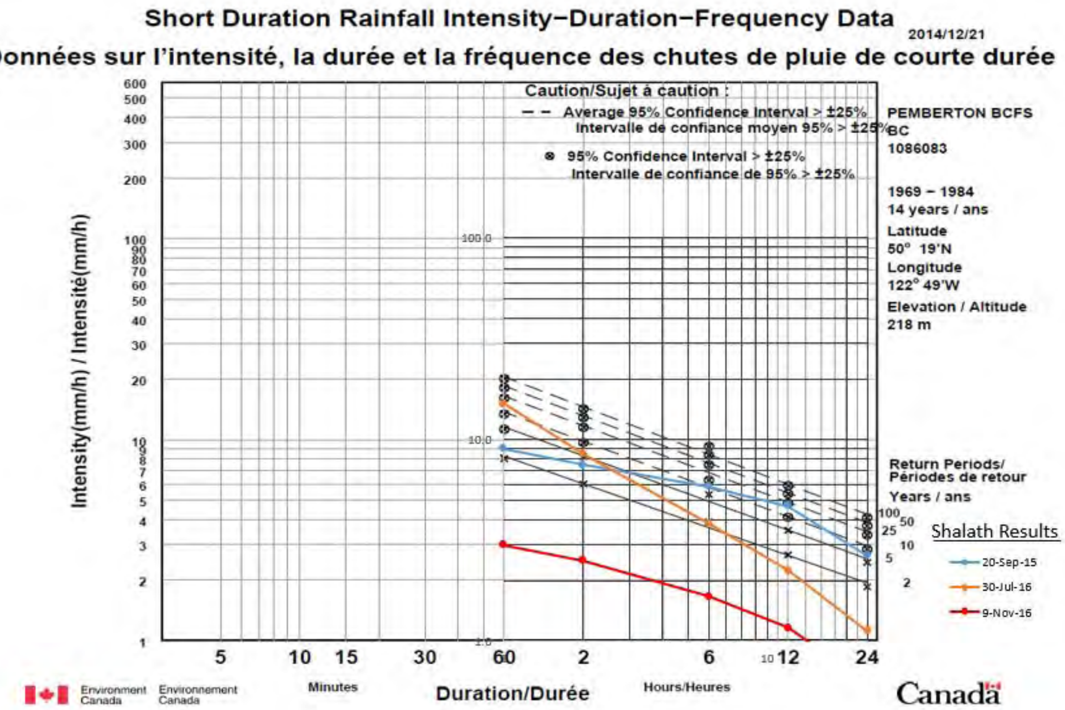


Figure 2-3. **IDF magnitudes for the September 20, 2015 (blue), July 30, 2016 (orange), and November 8-9, 2016 (red) events, compared to the estimated IDF values at the Pemberton Climate Station.**

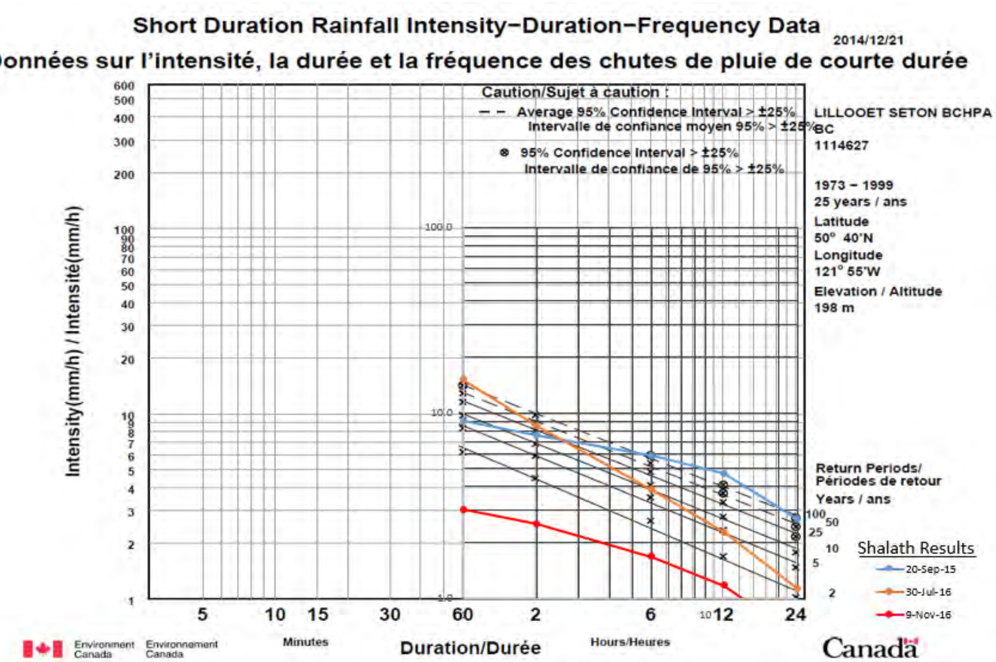


Figure 2-4. **IDF magnitudes for the September 20, 2015 (blue), July 30, 2016 (orange), and November 8-9, 2016 (red) events, compared to the estimated IDF values at the Lillooet Climate Station.**

The September 2015 rainfall event exceeded the 25-year return period for the 12-hour rainfall event at Pemberton (Figure 2-3), and exceeded the 100-year return period for the 6, 12, and 24-hour rainfall event in Lillooet (Figure 2-4). This event was characterized by long duration and high rainfall volumes, and produced both a debris flow on Bear and Pete’s Creek, and a debris flood on Whitecap Creek. In contrast, the July 2016 rainfall event, which was associated with a debris flow on Bear and Pete’s Creek, had higher 1 and 2-hour rainfall totals than the 2015 storm. This event surpassed the 10-year return period for the one-hour intensity at Pemberton (Figure 2-3), and the 100-year return period in Lillooet (Figure 2-4). The 2016 event was thus characterized by short duration – high intensity rain with low rainfall volumes.

The 2016 debris flood event on Whitecap Creek occurred during a relatively small, low intensity storm in November, rather than during the high intensity storm which occurred in July 2016. The November rainfall event was associated with a return period of less than two years for all storm durations (1-hour to 24-hour) at both the Pemberton and Lillooet climate stations (Figure 2-3 and Figure 2-4). The event had neither high rainfall totals, nor high rainfall intensities. In the case of the November 2016 storm, the debris flood was preceded by some antecedent rainfall in the week preceding the event. Moreover, a lot of sediment was likely still available from the 2015 event which allowed easier entrainment and transport.

Debris flow and debris flood events on Bear and Whitecap creeks do not have to occur at the same time. A very small convective cell over the 3.3 km^2 Bear Creek watershed suffices to trigger a debris flow, even in absence of antecedent moisture conditions. In contrast, for the 69 km^2 Whitecap Creek watershed, a regional-scale storm is required to trigger a debris flood.

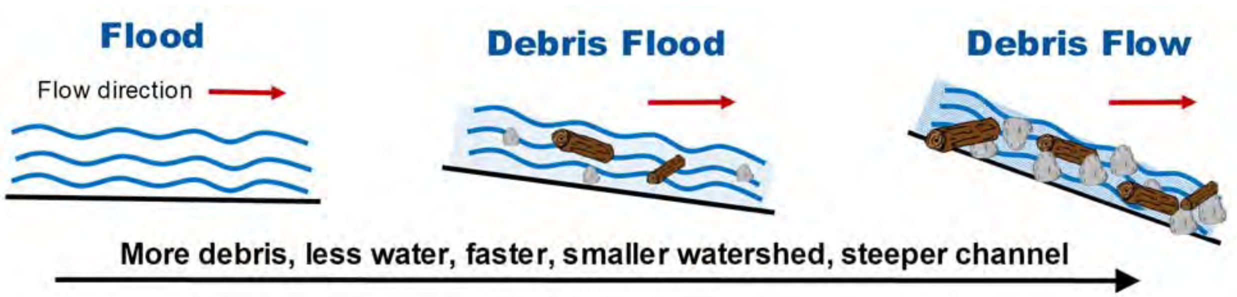
This brief analysis demonstrates that debris flows at Bear and Pete’s Creek, as well as debris floods on Whitecap Creek, can be triggered by different storm types and antecedent conditions. Recent events were triggered by a short duration, high intensity storm, a longer duration storm with a higher total storm volume, and a relatively minor storm with some antecedent rainfall. The 2015 event was recorded at the Pemberton climate station (see Figure 2-4), while the 2016 event was only recorded at Tsal’alh. Given the short and intense rainfall, the 2016 event was likely a localized thunderstorm over the Seton Portage area rather than being associated with a frontal storm as was the case in September of 2015. This finding is important, especially if a debris flow or debris flood warning system were to be contemplated at Seton Portage. At this point, there are insufficient data on debris flow or debris flood occurrence to produce a reliable early warning system.

2.3. Hydrogeomorphic Hazards at Seton Portage

2.3.1. What Are Hydrogeomorphic Hazards?

Hydrogeomorphic hazards are natural hazards that involve a mixture of water ("hydro") and debris or sediment ("geo"). These hazards typically occur on creeks and rivers in mountainous or hilly areas, usually after intense or long rainfall events. Because of this tendency to occur on steep creeks, hydrogeomorphic hazards are also referred to as "steep creek hazards".

The main types of hydrogeomorphic hazards are debris flows and debris floods. Debris flows involve more sediment and debris (up to 70%) than debris floods (up to 20%). They also move faster, have higher peak discharges and they generally occur in smaller watersheds with steeper channels. It's easiest to think about hydrogeomorphic hazards as occurring in a continuum, as shown below.



Peak discharge (Q) is the volume of water and/or debris that passes a channel cross-section during one second. For example, a peak discharge of 20 m^3/s means that 20 cubic metres or 20,000 litres of water pass through a cross-section in one second.

In terms of peak discharge, flood, debris flood and debris flow processes are rather different. A 100-year return period normal flood (a 1% chance of occurrence in any given year) on a given steep creek will typically have a lower discharge than a debris flood on the same creek. If the creek is subject to debris flows, the peak flow may be even higher. Figure 2-5 shows the cross-section of a steep creek, including:

- Peak flow for the 1-year return period (Q_1)
- Peak flow for the 200-year return period flood (Q_{200})
- Peak flow for the 200-year debris flood ($Q_{200\ debris\ flood}$)
- Peak flow for the 200-year debris flow ($Q_{200\ debris\ flow}$).

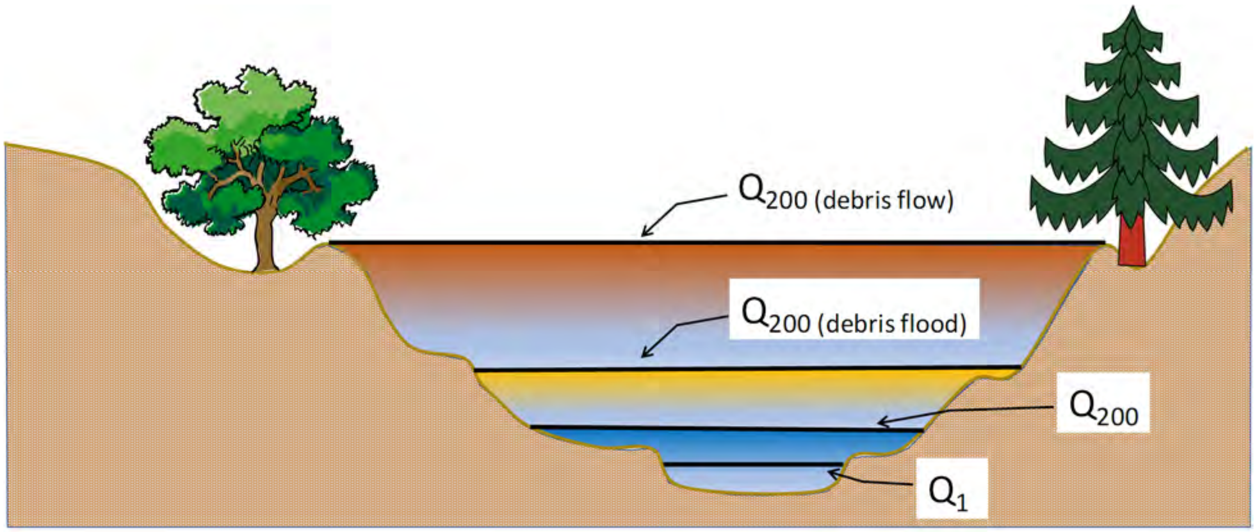


Figure 2-5. Steep creek flood profile showing peak flow levels for different events.

Peak discharge can also be increased by “landslide dam outbreak floods” or LDOFs. LDOFs occur when a landslide blocks the creek channel in the watershed. Depending on the type of landslide and the landslide material, water may begin to pond behind the debris, creating a landslide dam. Sometimes, these dams breach slowly, and release the ponded water in a gradual and controlled manner. Other times, the dam may breach quickly, suddenly releasing the ponded water. Depending on the size of the landslide dam, the release can create a very large surge of water and debris, which may intensify or even cause a debris flood or debris flow downstream.

This difference in peak discharge is one of the reasons that process-type identification is very important for steep creeks. If a bridge is designed for a 200-year flood, but subject to a debris flow with up to 50 times the peak flow, the bridge would likely be destroyed. An example of this occurred along the eastern shores of Howe Sound in 1981 when several bridges of Highway 99 (the Sea to Sky Highway) were destroyed by debris flows, leading to the fatalities of eight people in vehicles. Similarly, in October of 2003 a debris flood on Rutherford Creek destroyed the railway and Highway 99 bridges, leading to the death of five individuals. Appendix B provides additional technical details about debris flows and debris floods.

The small area of Seton Portage is affected by hydrogeomorphic hazards of all types. Bear and Pete’s creeks have debris flows, Whitecap and Spider Creek have debris floods and LDOFs, and Portage River is subject to flooding and bank erosion. These are described in the following sections.

2.3.2. Bear and Pete’s Creeks

Bear Creek originates from the steep watershed located immediately south of Seton Portage. Pete’s Creek originates from a smaller sub-watershed, west of and adjacent to Bear Creek. Currently, the two creeks flow parallel through a wide channel for about 1.3 km, about 70 m apart, before discharging onto a single large fan. The configuration of the two creeks and their watersheds is shown on Drawings 01 and 02, and their characteristics are described in Table 2-4. The creek profiles are shown on Drawing 03.

Table 2-4. Watershed and fan characteristics of Bear and Pete's creeks.

Characteristic	Bear Creek	Pete's Creek
Watershed area (km^2)	2.3	1.0
Fan area (km^2)	1.3	Indistinguishable from Bear Creek fan
Maximum watershed elevation (masl)	2250	1780
Minimum watershed elevation (masl)	425	425
Average channel gradient (%)	57	51
Average fan gradient (%)	22	22

Bear and Pete's creeks have several characteristics that are typical of debris-flow watersheds. The watershed areas are small (< 5 km^2) and the channel gradients are steep (> 50%). Also, the fan is steep and large, especially compared to the watershed area.

Both Bear and Pete's creeks are "ephemeral", meaning that water does not flow continuously. When the creeks are flowing, Bear Creek currently flows northeast, and Pete's Creek flows west towards the Whitecap Development. According to anecdotal reports, Bear Creek used to flow continuously during the summer months into three ditches used for irrigation; the flows went underground after the 1964 debris flow (Randy James, Tsal'alh, November 21, 2017 email).

As of December 2017, Bear Creek and Pete's Creek are behaving as two separate systems, with effectively separate watersheds, creeks and fans[3]. However, this could change in the future. Pete's Creek can easily avulse into Bear Creek, and vice versa. For this reason, Bear and Pete's creeks are considered as a single debris-flow system in this report. BGC's hazard assessment, risk assessment and mitigation designs account for debris flows resulting from Bear Creek and Pete's Creek at the same time.

Debris flows from Bear and Pete's creeks are highly mobile and can run out beyond the over-steepened fan edge, as seen in the 2015 and 2016 events (Figure 2-6, Drawings 02 and 09). The mobility can be attributed to the high clay content of the debris (7 to 10%; see Appendix G). The upper fan of the Bear Creek fan complex is also deeply incised (Figure 2-7). This implies that debris flows or concentrated runoff originating from the upper watershed are funneled into a narrow channel where further debris can be entrained.

[3] Although there is one large fan, Pete's Creek currently deposits on the western fan sector, and Bear Creek currently deposits on the northeast fan sector.

Figure 2-6. Deposit from the 2015 Bear Creek event, below the edge of the truncated fan. The deposition angle was only 2 degrees. Photo: BGC, Sept 12, 2017.

Figure 2-7. Bear Creek channel near fan apex. The channel is incised about 10 m and has a channel gradient of 48%. Bear Mountain in the background. Photo: BGC September 12, 2017.

Bear Creek fan area is unusually large compared to its watershed as shown in Figure 2-8. This may be attributed to the long runout distance of fine-grained debris flows, but may also be related to a high frequency of debris flows associated with low rock mass strength and subsequent higher rates of weathering in the upper watershed. Finally, it is possible that large rock slope failures in the past have translated into very large (> 300,000 m^3) debris flows. Some of those are discussed in Section 3.3.3.

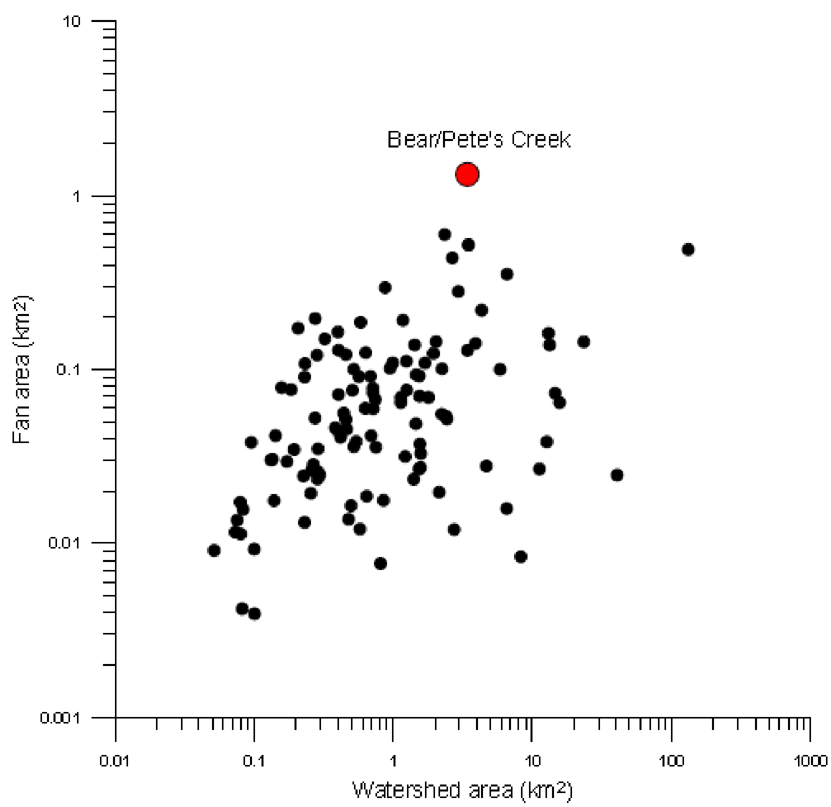


Figure 2-8. Watershed area versus fan area for 116 creeks in BC (data from Lau 2017). Bear and Pete's Creek data are plotted as a large red dot.

The upper fan of the Bear Creek fan complex is deeply incised and suggests that debris entrainment (scour) is likely in this reach. For this reason, BGC selected a runout model (DAN 3D) that allows for debris to be picked up by debris flows and then re-deposited downstream.

The Bear Creek fan complex and the adjacent areas on or near the Portage River floodplain also show most of the development potentially subject to debris flow impact (compared to Whitecap and Spider creeks). To account for this higher risk potential, BGC used several methods to estimate frequency-magnitude relationships that are discussed below.

2.3.3. Whitecap Creek

Whitecap Creek joins Portage River from the north some 670 m downstream of Anderson Lake. The creek has formed a fan with an area of approximately 90,000 m^2 and thus occupies only 7% of the area of the Bear Creek fan complex (1.3 million m^2), even though the watershed area of

Whitecap Creek (74 km^2) is 21 times larger than that of Bear Creek (3.3 km^2). This discrepancy is primarily due to the fact that Bear Creek produces more debris than Whitecap Creek. The reason is that Whitecap Creek, while draining a large watershed is at much lower angle and sediment reaching the main creek can be stored in the floodplain. At Bear Creek fluid mass movements (debris avalanches and debris flows) will travel at least to the fan and many will reach the fan edge. Another reason for the comparatively small fan of Whitecap Creek is that the higher discharge (which is proportional to watershed area) regularly moves debris into Portage River which then carries it downstream. Bear Creek, according to residents' narrative, rarely carries clear water floods that bring sediment to Portage River. Only large debris flows can do so.

Whitecap Creek watershed is characterized by steep tributaries some of which produce debris flows and snow avalanches. 2.7 km^2 are still glacierized (4%), though current climate change predictions would call for a total ice loss by the end of the century (Clark et al. 2015).

Whitecap Creek is a hanging valley with a steep bedrock canyon connecting the low gradient (10%) mid channel from the fan. This hanging valley landform is typical for many creeks in the area (Spider Creek, Lost Valley Creek) and is attributable to a late Pleistocene glacier prevailing for some time in the valley bottom, not allowing creeks to incise into the freshly carved steep bedrock flanking the former glacier. Directly upstream of the steep bedrock canyon, a large (50,000 m^2) till slope is being undercut by Whitecap Creek and is continuously providing sediment that is then readily available for transport downstream (Figure 2-9).

Figure 2-9. Extensive till slope at angles of 35 to 39˚approximately 700 m upstream from the fan apex of Whitecap Creek looking west. The slope is approximately 150 to 180 m long. Photo: BGC, November 9, 2017.

Whitecap Creek is subject to floods and debris floods that can erode channel banks, readily avulse out of the current channel, impact the 100 Anderson Lake Road residence on the lower fan, affect the Tsal'alh First Nations offices located on the eastern upper fan, and damage or destroy the access road bridge. Debris floods on Whitecap Creek could also sever or inundate Anderson Lake Road that provides connection to D'Arcy and Pemberton and interrupt the CN Rail line.

The events of 2015 (MFLNRO 2015) and 2016 (MFLNRO 2016a) were debris floods leading to sudden channel changes, avulsions and substantial sediment transport (Figure 2-10). Table 2-5 summarizes the watershed and fan characteristics of Whitecap Creek. The creek profile is shown on Drawing 04.

Table 2-5. Watershed and fan characteristics of Whitecap Creek.

Characteristic	Value
Watershed area[1] (km^2)	74
Fan area (km^2)	0.09
Maximum elevation (masl)	2918
Minimum elevation (masl)	282
Average gradient mainstem (%)	7.5
Average gradient on lower fan (%)	5

Figure 2-10. November 8 and 9, 2016 debris flood on Whitecap Creek. Portage River and Anderson Lake Road bridge in the foreground. Flow on Portage River is left to right. Photograph by John Pattle, FLNRO November 9, 2016.

2.3.4. Spider Creek

Spider Creek drains a 25 km^2 watershed east of Bear Creek. Like Whitecap Creek, Spider Creek is also prone to debris floods. In some cases, the debris floods may be triggered by LDOFs, as there is some evidence of previous, breached landslide dams in the upper watershed.

Tsal'alh member William Alexander recounted a 1961 or 1962 event where a landslide above the Spider Creek waterfall blocked the creek for a few hours. Mr. Alexander reported that when the landslide dam broke, a sudden surge of water descended Spider Creek (Figure 2-11).

Figure 2-11. Spider Creek about 150 m upstream of Spider Creek road. In 1963, an LDOF would have been several meters high, though did not destroy the older trees living alongside the creek. Photo: BGC September 12, 2017.

The lower channel of Spider Creek is deeply incised between abandoned terraces (Drawing 09) and even extreme floods are likely to stay contained between those terraces. The only infrastructure impacted during minor flows (10 to 30-year return period events) is the elliptical corrugated steel culvert at the Spider Creek crossing (Figure 2-12). The culvert is 3.3 m wide and 2.0 m high, with a maximum capacity of 14 to 17 m^3/s.

Figure 2-12. Downstream view of corrugated steel culvert underneath Spider Creek Road at Spider Creek. Photo: BGC September 13, 2017.

Table 2-6 summarizes the watershed and fan characteristics of Spider Creek. The creek profile is shown on Drawing 05.

Table 2-6. Watershed and fan characteristics of Spider Creek.

Characteristic	Value
Watershed area (km^2)	26.7
Fan area (km^2)	0.06
Maximum elevation (masl)	2855
Minimum elevation (masl)	330
Average gradient mainstem (%)	30
Average gradient on lower fan (%)	8

2.3.5. Portage River

Portage River connects Anderson Lake in the west with Seton Lake to the east (Figure 2-13). The river is 2.8 km long and about 15 to 45 m wide, with an average width of 30 m. The river is single-thread from Anderson Lake until about 2.1 km downstream, where it changes to braided due to the confluence with Spider Creek and the shallower gradient on the lower floodplain.

Figure 2-13. Portage River looking upstream facing west from the Seton Portage Road bridge. Photo: BGC September 13, 2017.

The longitudinal profile of Portage River is shown on Drawing 06. The profile mirrors the geomorphic development of the river. From Anderson Lake to the Anderson Lake Road bridge, the river has a gradient of 0.1%. This comparatively low gradient can be attributed to the episodic sediment discharge of Whitecap Creek debris floods, which creates a back-water effect upstream. Downstream of the confluence, Portage River steepens to 1.3% on average to the railway bridge. From the railway bridge to the braided section, the gradient drops to 0.7%; the gradient at Seton Lake is 0.4%.

Between the Anderson Lake Road bridge and the confluence with Seton Lake, the river is flanked by terraces (Figure 2-14). These terraces may be a legacy of the river downcutting when Seton Lake level dropped. Alternatively, these terraces may have evolved from high sediment input either by Bear Creek or Whitecap Creek and subsequently eroded by flooding by the following processes:

- Debris floods on Whitecap Creek with high (several 10,000 m^3) debris loads which fill Portage River and divert the river towards the south.
- Landslide-generated displacement waves from rock mass failures along Anderson Lake.

These two processes presumably act at different time scales with debris floods diverting Portage River occurring with an annual probability of perhaps 1% (100-year return period) and landslide-generated waves occurring with an annual probability of perhaps 0.1 to 0.01% (1000 to 10,000-year return period). More work would be needed to assert these estimates. However, loose boulder lobes observed in parts of the Seton Portage downstream of Spider Creek Road indicate that flood events through Seton Portage have occurred in the recent (~100 to 200 years) past.

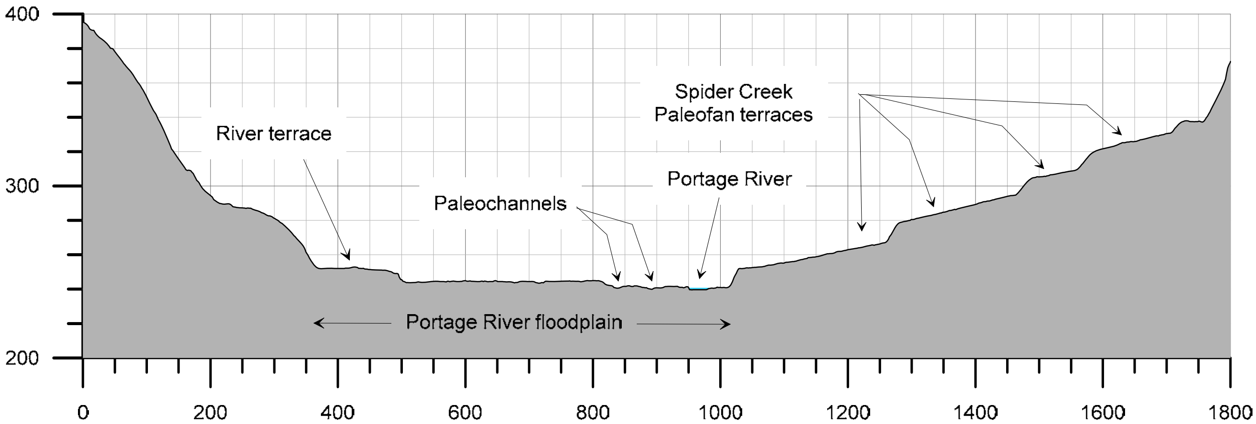


Figure 2-14. Valley cross-section across Portage River valley near the confluence with Spider Creek (shown schematically)

Many different hydrogeomorphic processes occur and interact in the Seton Portage area. Bear and Pete's Creek are subject to debris flows which resemble wet concrete. They travel fast (at full running speed) and can be destructive due to their impact force.

Whitecap and Spider creeks are subject to debris floods which transport less sediment for a given return period compared to debris flows on Bear and Pete's Creek, even though their respective watersheds are much larger. The main hazard from debris floods is bank erosion, and in the case of Whitecap Creek, damming of Portage River which can cause upstream and downstream flooding when the landslide dam breaks.

Portage River can flood if impounded by Whitecap Creek or via a displacement wave of a landslide impacting Anderson Lake. Snowmelt or rainfall-related flooding is infrequent because Anderson Lake buffers peak flows and because Portage River is mostly well incised into the floodplain.

2.4. What Other Hazards Affect This Area?

2.4.1. Snow Avalanches

Snow avalanches can run out very long distances and be very destructive. In the study area, snow avalanches are very unlikely to reach developed areas. However, clearcut logging or additional stand-replacing forest fires may change the snow avalanche risk.

A snow avalanche is a rapid flow of snow down a sloping surface. Avalanches are typically triggered in a starting zone from a failure in the snowpack (slab avalanche) when the forces on the snow exceed its strength by either gradually widening (loose snow avalanche) or abruptly widening (slab avalanche). After initiation, avalanches usually accelerate rapidly and grow in mass and volume as they entrain more snow. If the avalanche moves fast enough, some of the snow may mix with the air forming a powder snow avalanche, which is a type of gravity current.

This hydrogeomorphic assessment included a cursory review of snow avalanches where they could potentially reach currently populated areas. This work was completed by BGC's avalanche specialist Dr. Michael Conlan who reviewed satellite, LiDAR, and oblique photograph imagery. Analyzing terrain alone, there are three prominent areas subject to snow avalanches located on the south side of Seton Portage (Figure 2-15). The starting zones reach up to 2250 masl.

Figure 2-15. Potential snow avalanche zones (initiation, transport, and runout) on the south side of Seton Portage (Google Earth 2015 imagery, looking southeast).

Areas 1 and 2 appear to be mostly vegetated, with relatively small and steep (i.e., mostly 35-45°) starting zones. Wet or dry snow avalanches that initiate in those paths would be unlikely to run far enough to reach the community. This conclusion is corroborated by over 50 years of observations by locals, who have not observed snow avalanche debris close to the community. The area probably experiences more frequent avalanches in the starting zones/track rather than large slabs because of the steep nature of the terrain. However, should the vegetation be modified, such as from downed trees from a forest fire, the starting zone sizes could substantially increase, potentially allowing for larger snow avalanches to form. Should this happen, a detailed snow avalanche hazard assessment should be conducted. Similarly, should climate change result in higher snow accumulations in the future, a detailed snow avalanche assessment may become necessary in the future.

Area 3 is a large V-shaped area that flows towards a confined gully above the community. Dry avalanches that form on the side slopes would lose momentum from run-up on the adjacent valley wall, probably losing enough momentum to inhibit the flow from flowing through the confined gully. Large, wet avalanches would have less cross-valley run-up and could follow the gully towards the community. To reach the community, this would require a substantially large area to release, probably from a wet slab avalanche. Large wet slabs are generally uncommon, and furthermore, the starting zone angles appear to generally be 35-45°, which promote frequent and smaller releases. Because much of the starting zones on the slopes are vegetated, it is unlikely that a large enough wet slab could form to travel through the gully and into the community. Similar to Areas 1 and 2, should the starting zone areas increase, larger snow avalanches could form, which may reach the community.

To the north of the community towards Whitecap Creek, the terrain is heavily vegetated, which will inhibit snow avalanche formation on the short slopes directly north of the community. Steep, rocky slopes could produce relatively small loose dry avalanches over the winter, but not large enough to reach the community. There are some snow avalanche paths near the ridgetop, but they are well-back of the community, with snow avalanches likely stopping above or on the bench where the powerlines are. These paths are generally south-facing and likely accumulate less snow due to often being windward and exposed to solar radiation. The area to the north is therefore unlikely to produce snow avalanches that could reach the community. Should the vegetation change, such as from forest fire, a detailed assessment may be warranted.

Gradient and vegetation are not the only controls on snow avalanche formation, a sufficient snowpack depth is also required. For snow supply, records from a BC Ministry of Transportation (MoTI) AVALX station at Mission Mountain at an elevation of 1190 masl, were analyzed. This station had a snowpack of up to 100 cm in 1997 and 120 cm in 1982, which were two strong La Niña years (meaning higher above precipitation in southwestern BC). However, even with a full-depth release of ~100 cm, a slab from the current unvegetated, small starting zones on the north side would not likely reach the community.

2.4.2. Rock Slope Movements

This section will focus on large rock slope instabilities, rock falls, and rock slides that have the potential to directly impact the Whitecap, Bear, Pete's and Spider watersheds. The large rock slope instabilities are called deep-seated gravitational slope deformations (DSGSDs), and they involve more than 1,000,000 m^3 of material.

We detected six slope deformations in the upper watersheds of Whitecap and Spider creeks. While these rock masses are likely moving at low rates (millimeters to centimeters per year), they show no signs of immediate failure. BGC's analysis showed that the overall risk coming from such landslides is mostly low to moderate with three sites being moderate high relative risk. Rock slope failures of this size are not mitigatable at any reasonable cost. Should they occur and dam either Whitecap or Spider creeks, evacuations will become necessary.

Figure 2-16 and Figure 2-17 show the location and type of rock slope instabilities and failures inventoried in the eastern and western part of the study area respectively. An inventory of landslide in the Seton Watershed has previously been completed by Baldeon Vera (2014). That inventory was supplemented with observations from the imagery and LiDAR available for the present study area (Figure 2-16 and Figure 2-17). The combination of varied geology, structure, and steep topographic relief has contributed to the occurrence of a wide range of type and volume of rock slope failures and instabilities.

Three main DSGSDs were identified in the Spider Creek watershed (Figure 2-16) while an additional three DSGSDs were identified in the Whitecap Creek watershed (Figure 2-17). The hazard associated with the each of the DSGSD was characterized using the methodology proposed by Hermanns et al. (2012), which BGC has applied to several projects in British Columbia over the last three years. This approach is a hazard scenario-based system derived from the Norwegian experience in assessing large unstable slopes that can cause loss of life. The system focuses on structural criteria (existence of a back-scarp and sliding surface, as well as lateral failure boundaries) and analysis of the slope activity (landslide velocity, change in deformation rate, rock fall activity history or prehistoric events). Because it may be difficult to assign discrete categories to each of these parameters, the methodology assigns probabilities to account for the uncertainty. Based on the field and desktop characterizations of each parameter, a relative ranking was calculated for each of the six DSGSDs (Figure 2-18).

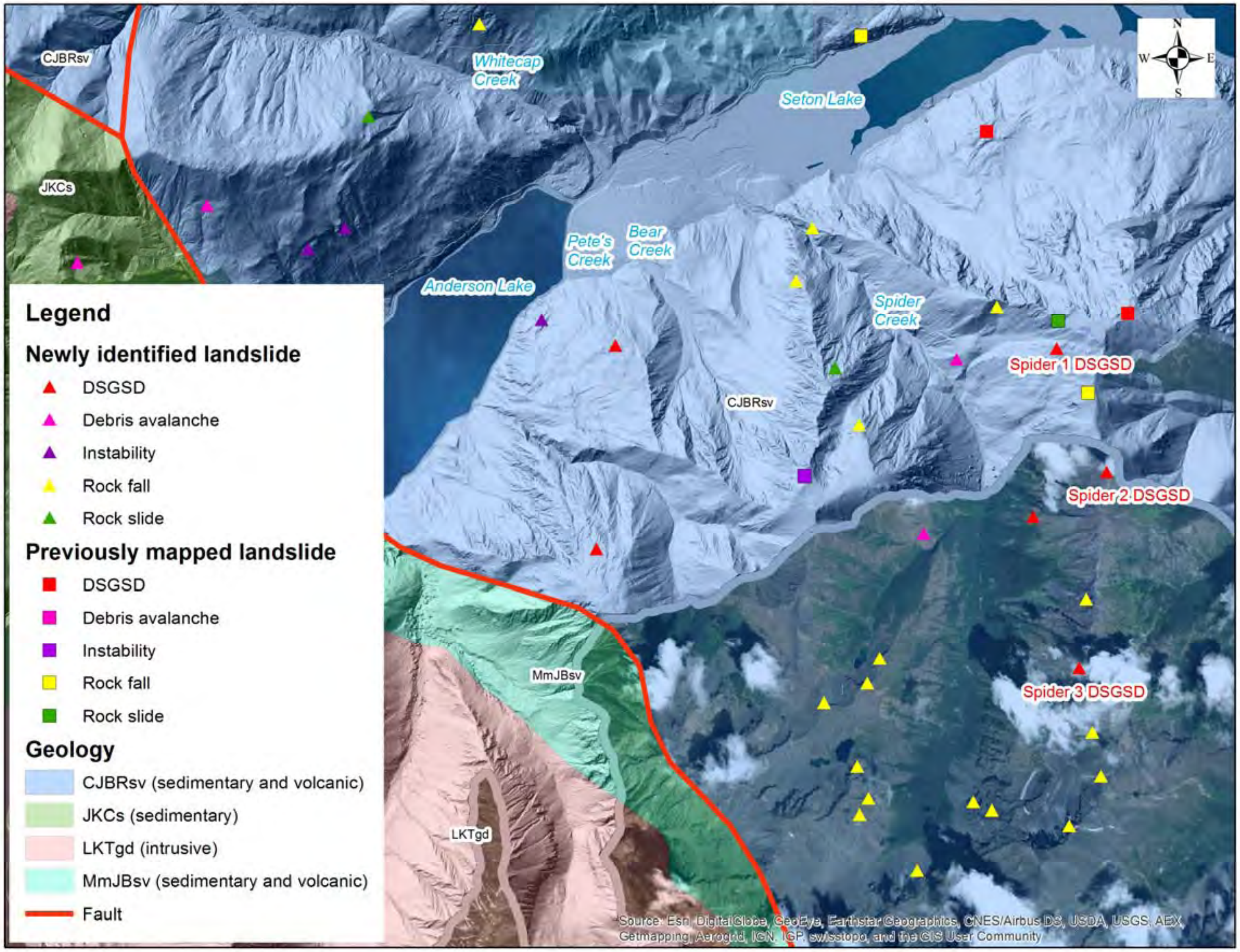


Figure 2-16. Geology and rock slope failure inventory (discussed in Section 2.4.2) in the eastern part of the study area.

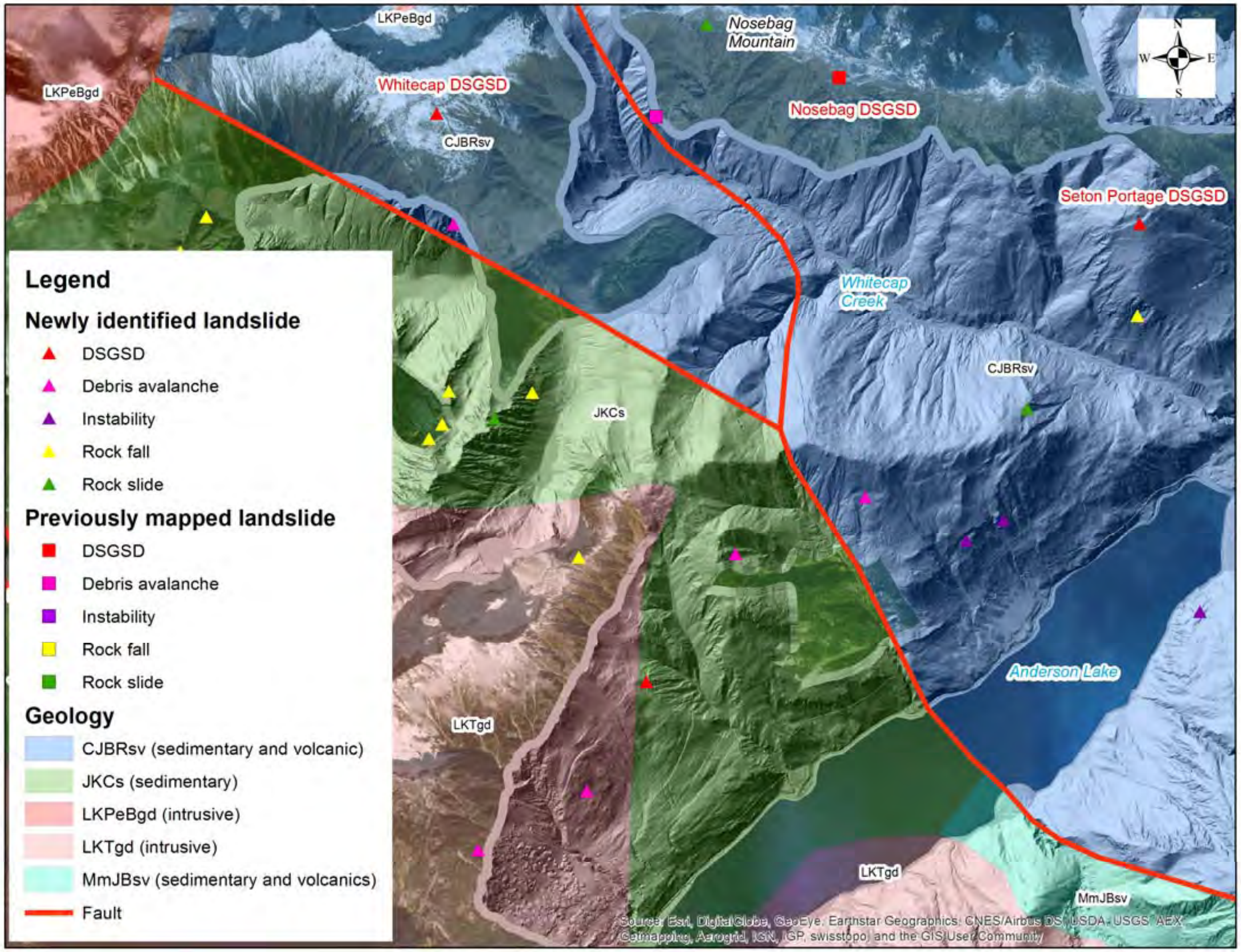


Figure 2-17. Geology and rock slope failure inventory in the western part of the study area for previously and newly mapped landslides (Baldeon Vera 2014)

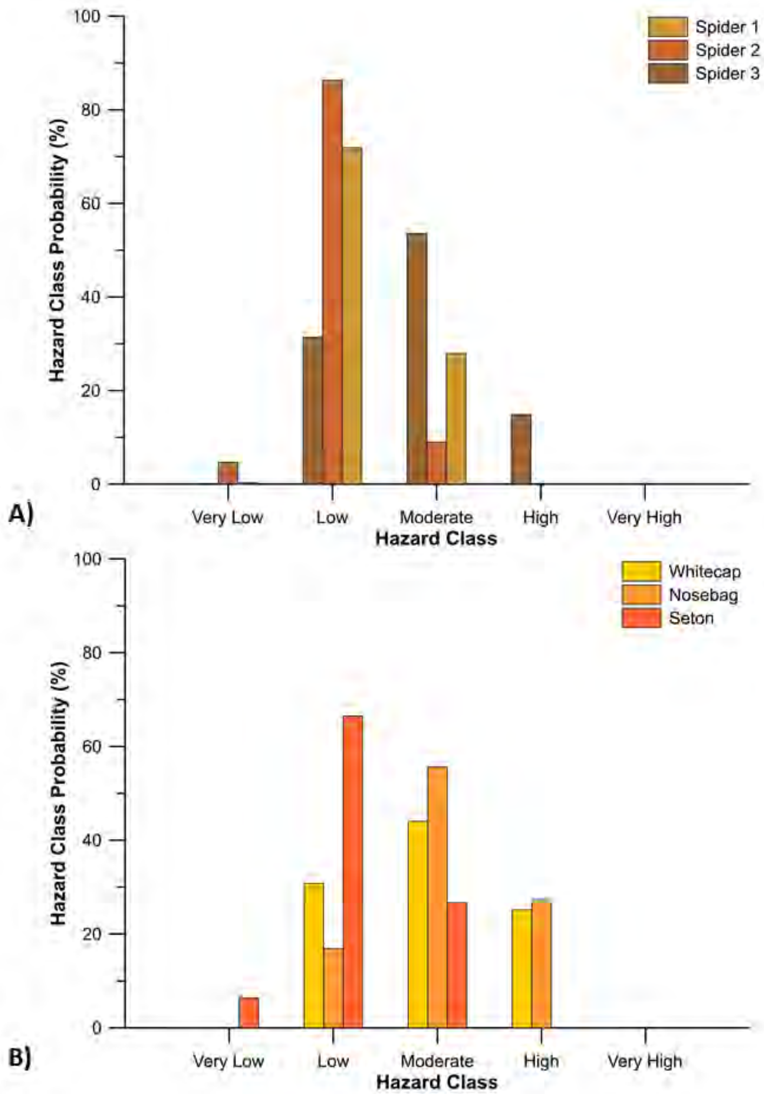


Figure 2-18. Summary of the hazard classification based on the Hermanns et al (2012) methodology for the A) eastern zone and B) western zone. The sum of the hazard class for a given DSGSD feature adds up to 100%. For the example Nosebag DSGSD has a 17% probability of being a low hazard feature, 56% of being a moderate hazard feature and 27% of being a high hazard feature.

The Nosebag, Whitecap, and Spider 3 DSGSDs have the highest hazard rating, with a hazard rating distribution that peaks in the Moderate category. The Seton, Spider 1, and Spider 2 slides have a hazard rating distribution with a peak in the Low category. These hazard assessments are preliminary desktop values of ground conditions, as interpreted from the 2017 helicopter fly-over, 2017 LiDAR, 2015 aerial photographs. A detailed field assessment and changes in the slope conditions over time could both affect the hazard rating distribution presented in Figure 2-18. BGC did not identify any DSGSDs that would suggest the need for immediate detailed study based on their appearance on LiDAR imagery and still photographs. However, if any of the identified landslides in the Whitecap watershed were to fail catastrophically, they would result in a large landslide dam that may require evacuations in the Seton Portage area.

In addition, the scars and deposits of rock falls, rock slides and debris avalanches have been identified. These smaller rock slope landslides have a low likelihood of blocking the flow of the creek along which they occur but they provide colluvial material that can be remobilized during a debris flood or debris flow. The distribution of these smaller rock slope instability can be influenced by DSGSDs (Capitani et al. 2013). An increase in the activity of these smaller rock slope landslides could be indicative of increase hazard associated with the larger DSGSD (Hermanns et al. 2012).

In summary, a number of deep seated landslides have been detected including a landslide complex in the Spider Creek watershed that have likely impounded Spider Creek in the past. No large DSGSD having dammed Whitecap Creek were identified. The current level of activity of DSGSDs cannot be determined with confidence. Should a large landslide develop and move rapidly downstream, it will likely lead to a landslide dam that could break out once water overtops or it fails through internal piping. This can result in LDOFs of substantial magnitude. This hazard has not been quantified by BGC in this report.

2.5. What Is at Risk?

The study area encompasses the community of Seton Portage. Development is concentrated on the valley bottom, which separates Anderson and Seton Lakes and is bisected by the Portage River. Land tenure is a mix of Crown Federal, Crown Provincial, Crown Municipal, First Nations (Federal), and Private (SLRD) (Drawing 14). According to the Tsal'alh, there are approximately 250 First Nations residents in Seton Portage. Population estimates for residents on Private land were not available, however based on the average occupancy rate of 1.9 (Statistics Canada 2016) and the presence of approximately 63 private dwelling, the population is estimate as approximately 120 other residents. BC Hydro staff and tourists regularly visit the area, particularly in the summer months.

The total estimated value of buildings development in the study area is $16.7 million (M). This includes $11.7 M in taxable buildings "improvements" (BC Assessment, 2017), approximately $3.7 M of development on First Nations Land (Pers. comm., Cliff Casper, Tsal'alh), and approximately $1.3 M assigned as average values to buildings where no data was available. Assessed building values do not necessarily correspond to replacement value, which may be higher. An extensive lifeline network provides food, water, energy, communication and transportation access to the community. CN Rail, BC MoTI and BC Hydro infrastructure lies within the community.

Table 2-7 lists the elements at risk considered in this assessment. Table 2-7 does not include all elements that could suffer direct or indirect consequences due to a geohazard event, but focuses on those that can be reasonably assessed, based on the information available.

Table 2-7. List of elements at risk considered in the risk assessment.

Element at Risk	Description
Building Structures	Commercial, institutional, residential, transportation.
Persons	Persons located within buildings.
Lifelines	Sewerage, stormwater management, gas distribution, electrical power and telephone line distribution, railway, roads[1], bridges[2].
Critical facilities	Hotel, Canada Post/Corner store/restaurant (all one building), Church, Pumphouse in Necait
Business activity	Businesses located on the fan that have the potential to be directly impacted by geohazards, either due to building damage or interruption of business activity due to loss of access.
Cultural/ecological significance	Seton Portage Historic Park, graveyard, other.

Notes:

1. Local roads include: Anderson Lake Road, Seton Portage Road (referred to as Seton Road west of the hotel), Cresta Road, Scott Road, Edwards Road, Williams Lane, Spider Creek Road, Mission Reserve Road, S Slosh Reserve Rd (also referred to as Bull Alley).
2. The location of bridges and rail crossings of Portage River are illustrated on Drawing 02. Bridge crossings include Anderson Lake Road (west) and Seton Portage Road (east), with a railway bridge located between the two road crossings.

The potentially impacted elements at risk differ between Spider, Whitecap and Bear creeks. The following sections describe the elements at risk for each creek.

2.5.1. Bear and Pete's Creek

Elements at risk on Bear/Pete's Creek fan and adjacent areas with the maximum debris flow runout in the Seton Portage area includes approximately 85 houses and outbuildings, a trailer park, several roads, businesses and a church (Drawings G01 to G05). Approximately six businesses employing 24 people with business revenues[4] totaling approximately $680,000 are located in the area (Hoovers 2017).

Development is concentrated in the following areas on the Bear/Pete's fan and north of the fan towards Portage River:

- Residences on private land to the west, including the Whitecap development property. Cresta Road and Seton Portage Road provide access to this area.
- Structures on Necait Indian Reserve (Drawing 14) land to the northwest, including residences, a church and a trailer park. A graveyard, pit houses and the Anderson Lake boat launch are also located nearby. The CN rail tracks are located northwest of the Necait Indian Reserve and Seton Portage Road Provides access to the area.
- Residences to the north and northeast on both Private and Mission Indian Reserve land. Critical facilities and businesses (Hotel, Canada Post/Corner store/restaurant) are also concentrated along the main section of Seton Portage Road.

[4] Annual business revenue data available for three of six businesses, therefore this is likely and underestimate of business revenue.

2.5.2. Whitecap Creek

Elements at risk at Whitecap Creek include the Tsal'alh Development Corporation (TDC) administrative building, three cabins used for BC Hydro accommodation, a campground, and a single small residence located on the lower active fan of Whitecap Creek (Drawings G06 to G10). In addition, a small private bridge crosses Whitecap Creek to provide access to the TDC admin building and cabins and Anderson Lake Road provides access in and out of Seton Portage. On the very distal portions of the fan, the BC MoTI Anderson Lake Road bridge crosses Portage River. On the opposite (south) side of the river the CN rail line parallels the river and could be impacted during particularly large events through inundation or erosion as Portage River is forced into the opposing banks.

2.5.3. Spider Creek

At Spider Creek only one residence appears to be in the potential runout area of debris floods (Drawing G11). The creek also crosses Spider Creek Road and its elliptical corrugated steel culvert.

2.6. Summary

This section described the geology, climate, geomorphology and elements at risk.

Glacial action shaped the valley over the course of several tens of thousands of years. Erosional processes followed that carved out valleys and also led to landslides of various types and sizes. The geology of the watersheds surrounding and feeding into the Seton Portage area is made up of weak rocks susceptible to rapid weathering. Stream flow processes, debris floods, LDOFs and debris flows transported ample sediment to the area now known as Seton Portage. As sediment accumulated on opposing sides of the valley, narrow channel began to form which eventually was closed and Anderson Lake was separated from Seton Lake. Because Seton Lake level is lower than Anderson Lake, a river began to form to connect the two lakes.

Debris floods from Spider and Whitecap Creek and debris flows from Bear Creek continued to build their respective fans. However, while Bear Creek fan continued to grow through repeated debris flows that deposited more and more sediment on the fan, Spider and Whitecap creeks incised by fluvial erosion into their glacial deposits and directly transferred their sediment on the floodplain of Portage River.

Apart from the hydrogeomorphic hazards, geohazards also exist in the form of snow avalanches and deep-seated landslides. Snow avalanches were found to likely not affect existing development. Deep seated landslides have led to damming and outbreak floods on Spider Creek and continued slow deformation of those slopes may lead to future large landslides.

3.0 METHODS

3.1. Introduction

This chapter summarizes the methods employed by BGC to determine the frequency and magnitude of debris floods and debris flows on Bear, Spider and Whitecap creeks, as well as the modeling methodology, risk assessment and mitigation design methods. Figure 3-1 summarizes the principal steps. Additional detail about the methods is provided in the following appendices:

- C - Hydrology
- D - Frequency-Magnitude Analysis
- H - Numerical Modeling
- J - Risk Assessment
- L - Climate Change.

Five return period classes were defined for the work reported herein. These classes are defined similarly to those provided by APEGBC (2012).

- 10 to 30 years
- 30 to 100 years
- 100 to 300 years
- 300 to 1000 years
- 1000 to 3000 years.

Higher return periods were typically not considered as those are associated with very high uncertainty and are thus difficult to quantify. Consequently, the risks associated with hazard scenarios with return periods greater than 3000 years have not been quantified.

3.2. Hazard Analysis

3.2.1. Introduction

Hazard analysis includes the steps summarized in Figure 3-1. The results of the hazard analysis inform the risk analysis and therefore mitigation.

All steps contained in the hazard analysis were aided by analysis of imagery generated through Light Detection and Ranging (LiDAR), a remote sensing technology used to examine the earth's surface and make high-resolution maps such as the geomorphic map shown in Drawing 05.

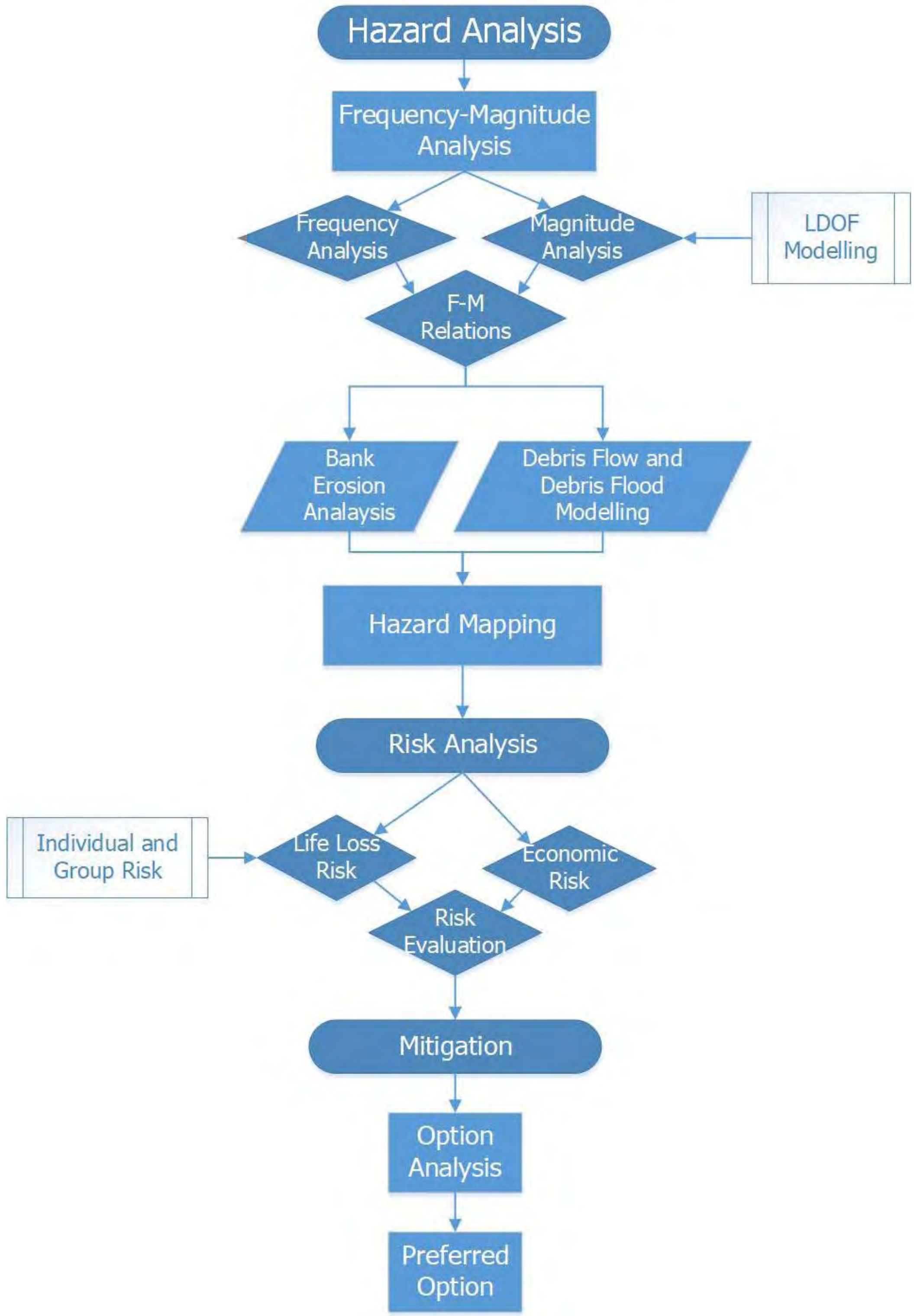


Figure 3-1. Flow chart of the work steps required to arrives at a suitable mitigation option to reduce geohazard risk.

3.2.2. Field Investigation

Fieldwork was completed in two separate visits on September 11 to 13, 2017 and October 30 to 31, 2017.

The September 11 to 13, 2017 fieldwork was completed by Dr. Matthias Jakob, P.Geo., Jack Park, Emily Moase, P.Eng. and Sarah Kimball, P.Geo. of BGC, and Pierre Friele, P.Geo. of Cordilleran Geosciences. This work focused on hazard characterization and included traverses and surface mapping of the fans, a helicopter overview flight of the four watersheds, and a ridge top traverse at the head of Bear Creek watershed. Field observations on the fan surface included: test pitting; landform mapping; sediment yield estimation; mapping of the location and geometry of abandoned channels and debris lobes; description of grain size and roundness; identification of landslide-damaged trees; and collection of tree-ring samples. Mr. Friele directed the backhoe test pitting, using a machine supplied by the Tsal'alh Development Corporation. 22 test pits and exposures, 3 to 15 m deep were excavated and described (Appendix F). 16 samples were collected for radiocarbon dating. All test pits were backfilled immediately after they were logged.

Field observations in the basins included identification and inspection of potentially unstable areas within the basin, and inspection of lineaments and tension crack features at the slope crest.

The October 30 to 31 fieldwork was completed by Alex Strouth, P.Eng. Dr. Matthias Jakob, P.Geo., Emily Moase, P.Eng. of BGC and Pierre Friele, P.Geo. of Cordilleran Geoscience. It included a site reconnaissance to assess potential mitigation options, with the visit supported by LiDAR imagery that had been obtained in September 2017. Five additional test pits were also excavated to fill in data gaps, and 11 samples were collected for radiocarbon dating.

3.2.3. Frequency-Magnitude Relationships

Frequency-magnitude (F-M) relations are defined as volumes or peak discharges related to specific return periods (or annual frequencies). This relation forms the core of any hazard assessment because it combines the findings from frequency and magnitude analyses in a logical format suitable for numerical modeling. It answers the question "how often and how big can landslides become?". The ultimate objective of an F-M analysis is to develop a graph that relates the return period of the hazard to its magnitude. Figure 3-2 shows this conceptually. The red line levels off at some point because of either sediment supply or water limitations. This means that debris flows and debris floods have a finite sediment volume and peak discharge.

Any F-M calculation that spans time scales of millennia necessarily includes some judgment and assumptions, both of which are subject to uncertainty. However, the analysis described in this section is based on the best data available and is considered appropriate for the scale and level of detail of this assessment. Uncertainty can further be addressed by relying on the upper estimates and by building in redundancies and freeboard in mitigation measures to reduce risk to tolerable levels.

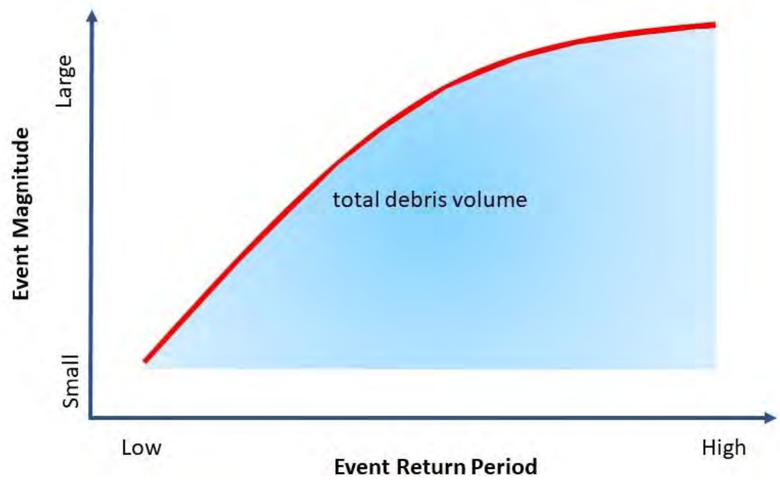


Figure 3-2. Conceptual frequency-magnitude curve. The area underneath the graph (shaded in blue provides the entire volume of the hydrogeomorphic event during the time period of interest)

There are no rules in Canada as to the maximum return period and corresponding debris flow or debris flood volumes to which mitigation measures should be designed. However, regulatory guidance and/or legislation worldwide mandate a range from several tens of years up to 10,000-year return periods. These relatively conservative return period ranges contrast present guidance in Austria which calls for examination of return periods of up to 150 years, while in Switzerland return period of up to 300 years are considered, including the assessment of residual risk associated with return periods exceeding 300 years.

For very long return periods (thousands of years) some degree of guesswork/judgement is inevitable and the degree of error is proportional to the length of the return period. Short-term extrapolation is analytically challenging which means that the results for very long return periods are uncertain.

Once events have been documented and their age and volume estimated, return periods need to be assigned to individual events that allow extrapolation and interpolation into annual probabilities beyond those extracted from the physical record. Such record extension is necessary to develop quasi-continuous event scenarios that then form the basis of numerical runout modeling and finally the consequence analysis that forms part of the risk assessment.

Table 3-1 summarizes the hazard assessment methods that were employed to develop the frequency-magnitude relationship for each creek at Seton Portage. The choice of method depended primarily on the process type, as some methods are only suited for specific hydrogeomorphic processes. The methods are described below.

Table 3-1. Methods to determine frequency and magnitude of debris flows and debris floods for the different study creeks. Details on each method are provided in Appendix D.

Method	Bear and Pete's Creeks	Whitecap Creek	Spider Creek
LiDAR remote sensing	✓	✓	✓
Field investigation	✓	✓	✓
Event reconstruction	✓	✓	
Air photo interpretation	✓	✓	✓
Test trenching and radiocarbon dating	✓		
Dendrogeomorphology	✓	✓	✓
Regional frequency-magnitude curves	✓		
Fan volume calculations	✓		
Debris flow sediment bulking	✓		
Rainfall-sediment volume relationships		✓	✓
Flood frequency and rainfall-runoff analysis		✓	✓

Source material depletion (which likely does not apply to Bear Creek), vegetation changes through wild-fires or logging, wildfire suppression, changes in the frequency and/or magnitude of hydroclimatic events and the occurrence of cataclysmic events such as large rockslides in the watershed can all alter the stationary assumption at different temporal scales. Some of these natural variations were accounted for the frequency-magnitude analysis whose details are included in Appendix D

3.2.4. Event Frequency Analysis

This chapter uses the terms "frequency", "hazard probability" and "return period" interchangeably, depending on the context. Frequency is numerically equivalent to hazard probability, and is defined as the annual probability of occurrence of a hazard scenario. Return period is the inverse of frequency, and is defined as the average recurrence interval (in years) of a hazard scenario. For example, an annual frequency of 0.01 corresponds to a 100-year return period.

Air Photo Interpretation

Debris-flow frequencies were estimated using air photo interpretation of photos dating back to 1948. Depending on the resolution and quality of the photos and the thickness of the vegetation, it is sometimes possible to observe changes to the fan surface such as fresh debris lobes or channels. Other changes are also recorded, such as land use, road construction, logging and fire history. The results from the air photo analysis are summarized in Sections 4, 5 and 6 with details provided in Appendix D. A comparison of historical air photos is shown on Drawings 07 and 08.

Test Trenching and Radiocarbon Dating

Test trenching allows us to determine the thickness of past debris flows/debris floods as those are typically distinct from overlying and underlying deposits. Dating of organic material permits assigning an age to the deposit.

Radiocarbon dating involves measuring the amount of the radioisotope ^{14}C preserved in organic materials and using the rate of radioactive decay to calculate the age of a sample. This method requires the deposition and preservation of organic materials within the sedimentary stratigraphy of the fan. The age range of this method is from approximately 45,000 years to several decades. As such, the method is applicable to the time scale of post-glacial fan formation in BC.

Backhoe test pitting was conducted on the Bear and Pete's Creek fan complexes on September 11-13, 2017 and again on October 30 and 31, 2017. Test pit logs were developed that identify sedimentary unit layers, unit thickness, unit texture, grain angularity and buried soil horizons (Appendix H). Unit contacts and buried soils were examined for organic carbon for radiocarbon dating. Test pits and exposures were photographed. Radiocarbon samples were collected in plastic bags, air-dried, and then sent to Beta Analytic labs in Florida for age determination by Accelerator Mass Spectrometry (AMS). A total of 11 excavated test pits and 2 natural exposures were described. Twenty-seven (27) samples were collected of which 22 were submitted for ^{14}C dating.

Dendrogeomorphology

Dendrochronology is an absolute dating method where annually distinct tree rings are used to determine the age of a tree. Dendrogeomorphology, a sub-discipline of dendrochronology, focuses on geomorphological processes that influence tree growth. It is used to date geomorphic events such as debris flows and debris floods. When a debris flow or debris flood impacts a tree, it can cause damage that overgrows. By coring or sawing into the scarred wood tissue, one can count the tree rings back from the present to the date of the scar and thus determine in what year the tree was impacted.

Depending on the ages of trees along the mainstem channel of a creek, dendrogeomorphology can extend the frequency record of debris flows and debris floods past the air photograph record. Depending on the quality of data sampled, dendrogeomorphology can potentially be precise to the nearest year in dating growth disturbances growth disturbance can be deciphered (Stoffel and Bollschweiler 2008).

Dendrogeomorphological analysis does not allow a clear designation of process type; thus, the dated events may have been debris flows, debris floods or other natural hazards. However, sampled trees were selected specifically to avoid possible influence from other processes. Not all noted historical events are preserved in the tree ring record, since the sampled trees may have been missed by some events. Figure 3-3 shows an example of a debris-flow scarred tree. Note that BGC did not conduct any chain sawing as part of this assignment and instead relied on tree coring.

Thirty-four coniferous trees were sampled as part of the field program: 14 trees on the Whitecap Creek fan; 15 trees from the Bear and Pete's creeks fan; and five trees on the Spider Creek fan. Two species were sampled: Douglas fir (*pseudotsuga menziesii*) and Western Red Cedar (*thuja plicata*). The growth rings in these samples were analyzed to identify anomalies that may be associated with debris-flood or debris-flow events. Appendix D outlines the processes of dendrogeomorphological analysis in further detail.

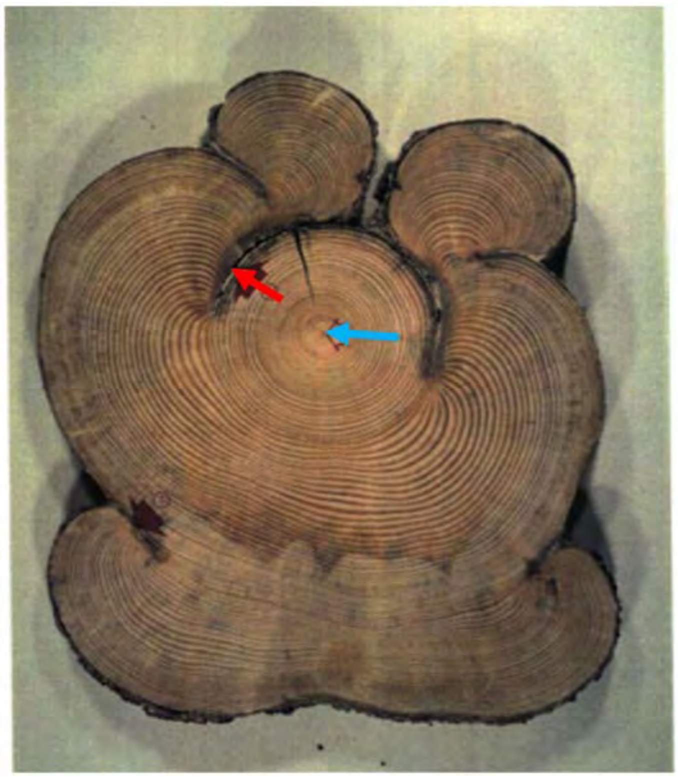


Figure 3-3. Impact scars on a spruce tree near Fergusson Creek in southwest BC showing an example of scars that can be dated precisely. The red arrow points at a scar, and the blue arrow points at the center of the tree (from Jakob 1996).

3.2.5. Event Magnitude Estimates

"Magnitude" herein is defined as the volume and/or peak discharge of debris floods, LDOFs and debris flows. The methods used to estimate the magnitudes differ for the study creeks as each process requires its own analytical methods.

Sediment Volume Estimation

For Bear Creek, BGC applied the following methods to determine event sediment volume:

- The volumes of debris flows for different return periods were estimated using a volume-fan area relationship recently developed by Jakob et al. (2015).

- The above relationship was tested by measuring the thicknesses of debris flows encountered in the test pits and determining their date from radiocarbon dating of organics found in soils separating the debris flows. The fan volume above those dated debris flow units was then determined.
- For further testing of the above relationship, deposits of previous debris flows were traced in the test pits and a thickness assumed, resulting in a debris volume estimate. This was particularly important to test if the maximum magnitudes assumed are in the right ball-park.
- Dendrogeomorphology aided in magnitude estimations of small and more frequent events by delineating approximate former flows captured by tree ring dating.

For Whitecap Creek the above analytical methods are inappropriate as the process of debris flooding is fundamentally different from debris flows. Even though debris flood volumes are not an input to runout analysis (Section 5.2.4), they are useful to estimate the volumes of sediment that may be discharged into Portage River or be temporarily stored on the Whitecap Creek fan. They could therefore allow an estimation of how much sediment may be required to block or divert Portage River.

The following steps were taken to estimate debris flood volumes. Further detail is provided in Appendix D.

- A "design storm" was defined as a three-day duration storm for which the total runoff volumes were determined by multiplying the depth of rainfall by the watershed area.
- The rainfall volumes were then multiplied by a factor of 1.2 to account for a 20% snowmelt contribution. The 20% contribution was chosen based on judgement and is believed to be conservative. Lower or higher contributions are possible, but will not substantially affect the volume estimate outcomes.
- An empirical rainfall-sediment transport equation developed in Switzerland and applied to the southwestern Rocky Mountains was applied to estimate the total volume of sediment mobilized during each return period event. This method is only applicable to watersheds, such as Whitecap Creek, with a quasi-unlimited amount of erodible sediment (so-called supply-unlimited watersheds).

Peak Discharge Estimates

For peak discharge estimates at Bear Creek, an empirical relationship was used that relates the peak discharge measured for debris flows in southwestern BC to the total measured sediment volumes of debris flows. This was developed by Jakob (1996) for coarse-grained debris flows typical in the granitic bedrock near the BC coast and for finer-grained muddy debris flows found in weak sedimentary rocks as well as volcanic rocks. Given the fine-grained nature of Bear Creek debris flows, the latter was chosen for analysis.

At Whitecap and Spider creeks, the following steps were undertaken to estimate peak discharge for the range of return periods (Appendix C and D):

- A regional flood frequency analysis.
- Rainfall-runoff modelling.

- The two values were compared and the higher of the two chosen for analysis.
- An estimate was made when to bulk flows with sediment by adding a factor to the above chosen runoff value and to account for potential LDOFs.

These estimates were then combined to model debris flows and debris floods on Bear, Whitecap and Spider creeks.

3.3. Debris-Flow and Debris-Flood Modelling

3.3.1. Introduction

Numerical modeling is used to determine the extent of hazardous events, and to estimate their intensity. BGC applied two different numerical models at Seton Portage: DAN 3D and FLO2D. DAN3D was used to model debris flows on Bear and Pete's creeks, and FLO2D was used to model debris floods on Whitecap and Spider creeks. Specifics of the models are presented in Appendix H.

To characterize the potential destructiveness of the modelled debris flows and debris floods, the flow intensity index (I_{DF}) was used for the models results (Drawings 10 to 12). The flow intensity was defined as an index according to Jakob et al. (2012) as follows:

$$I_{DF} = d \times v^2$$

where

d is flow depth in metres; and

v is flow velocity in meters per second.

While flow intensity could be expressed with units (m^2/s^3), it is treated as a unitless index for empirically-based correlation with vulnerability in the hazard mapping and risk assessment component of this work (Sections 3.6 and Appendix H, respectively).

3.3.2. Event Reconstruction

At Bear Creek and Whitecap Creek, we have the advantage of recent events (2015 and 2016) that are suitable for event reconstruction. This is necessary to calibrate numerical models whose confidence would otherwise be low. It also helps to contextualize the recent events with respect to the overall frequency-magnitude curves for each creek.

Events on Bear Creek were reconstructed by delineating previous events on LiDAR and by tracing the 2016 event by foot with a GPS to obtain the exact runout extent. Because it was not always entirely clear in the field which was the 2015 and which was the 2016 event, BGC chose the larger area if in doubt. Peak discharge at Bear Creek for the 2015/2016 event was reconstituted by measuring the cross-section area of the channel at numerous locations and estimating flow velocities using a number of different approaches, as summarized in Appendix D.

At Whitecap Creek, BGC delineated the area of erosion and deposition of the November 2016 debris flood event from available still photographs and assumed a deposition depth also from photographs. Peak discharge for the event was reconstructed from high water marks.

3.3.3. Debris Flow Modelling with DAN3D

Debris flows were modeled using the three-dimensional numerical model *DAN3D* (McDougall and Hungr 2004). *DAN3D* was developed specifically for the analysis of rapid landslide motion across complex 3D terrain. This model was chosen because it (a) allows sediment entrainment along the flow path, and (b) provides flow velocities, runout areas, flow depths and deposition depths all of which are required to address debris-flow risk.

The model geometry was generated from the 2017 LiDAR data. Debris entrainment was allowed to occur within the transport zone above the fan apex. The model rheology and flow resistance parameters were calibrated by matching the observed event volume, runout distance, and impacted area resulting from the 2016 Bear Creek event. The observed deposit compared to the modelled impacted area on the Bear Creek fan is shown in Figure 3-4. Structural damage observations were also used to check the velocity at the edge of the Bear Creek fan.

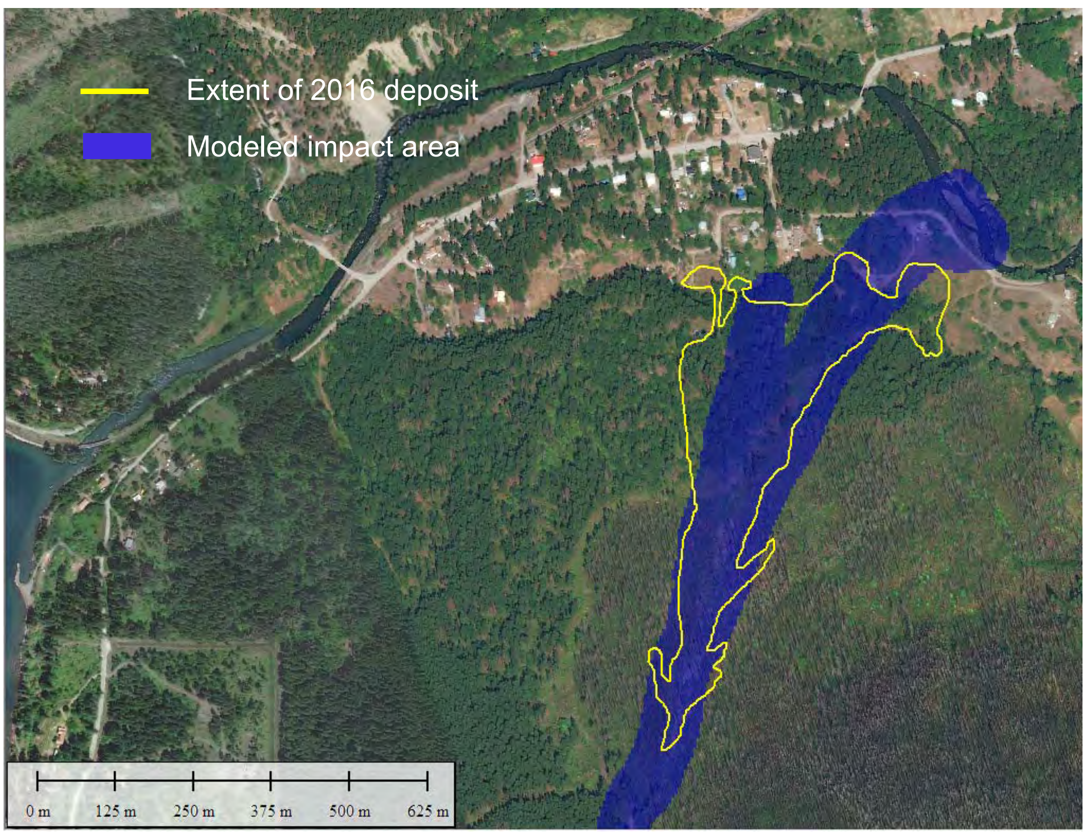


Figure 3-4. Observed 2016 deposit and modelled impact area.

The calibrated model was then used to estimate the impacted area and I_{DF} for the range of volumes obtained from the best-estimate frequency magnitude curve, described in Section 3.2.5.

Five debris-flow volume scenarios were modelled corresponding to 10 to 30-year, 30 to 100-year, 100 to 300-year, 300 to 1,000-year and 1,000 to 3,000-year return period events (Drawing 10). In all five cases, constant entrainment rates were specified between the source area and the fan apex to achieve the desired final 'best estimate' volumes. The initial and final debris-flow volumes that were modelled are summarized in Table 3-2.

All debris flows were modelled as single events as opposed to events involving multiple source failures and/or surges that result in the same total event volume. This approach likely results in conservative estimates of flow depth and velocity, and in turn vulnerability. Further details on the modelling methodology are available in Appendix H.

3.3.4. Debris Flood Modelling with FLO-2D

Modelling of debris floods on Whitecap and Spider creeks was completed using FLO-2D, a two-dimensional, volume conservation hydrodynamic model. It is suitable for debris flood modelling because it can model unconfined flows across fan surfaces. The model geometry was developed from the 2017 LiDAR using a 3-m grid. Additional information about modelling methods are available in Appendix G.

The Whitecap Creek models were calibrated using the 2015 and 2016 events for which photographic evidence was available. Those two events likely had return periods of 30 to 100-years in term of the sediment volumes involved in the debris flood. For peak flow, only the 2016 event could be reconstructed, again with a peak flow corresponding to approximately a 30 to 100-year return period (see Section 5.2.4). Drawing 11 shows that the flow distribution is close to the observed debris flood in November of 2016. Rather than simply modeling the peak flows over the existing topography, BGC created a surface mimicking sedimentation associated with the debris flood. This surface was created in Muck 3D with a depositional slope between 3% and 6%. BGC then modeled the estimated peak flows running over top of the deposit, hence assuming that sediment deposition had occurred on the fan prior to the peak flow occurrence. Further details are provided in Appendix G.3. Drawing 11 also shows flow distribution results for all debris-flood return periods considered.

On Spider Creek, no calibration event was available and thus BGC's efforts focused on forward modeling. Since the estimation of an LDOF peak discharge is associated with substantial uncertainty, BGC chose to model a range from 500 to 1000 m^3/s peak flows. Only the 1000 m^3/s discharge was able to leave the confines of Spider Creek which is further discussed in Chapter 6.0.

The Whitecap and Spider creeks models did not include sediment, as previous studies by BGC have shown that low sediment concentrations (<20%) do not significantly affect the model outcome. Sediment loads for both Whitecap and Spider creeks are expected to be in this low range. All debris floods were modeled as a singly hydrograph surge as opposed to multiple surges that may be associated with landslide dam breaches or multi-fronted storms.

3.4. Bank Erosion Assessment

Debris floods, while being able to inundate fans and floodplains, do most of their damage through eroding the creek's banks. Bank erosion can lead to the collapse of buildings that may then be carried away by the flood.

3.4.1. Introduction

In addition to hydrodynamic modelling, bank erosion modelling was also completed for Whitecap and Spider creeks as bank erosion is an important hazard associated with debris flooding. Debris floods have a tendency to erode their banks, particularly when those are already oversteepened as is the case for Whitecap Creek. Bank erosion on debris-flood prone creeks can lead to more damage than flooding or boulder impact (Jakob et al. 2015) and is thus of substantial importance to determining hazard potential and estimating associated risk.

3.4.2. Approach

When a debris flood occurs in a creek with erodible banks, the creek adjusts its banks to pass the higher discharge during the event. This adjustment can be through erosion of the creek bed (scour) or through bank erosion, which widens the channel. To evaluate the potential impacts on infrastructure on the Whitecap and Spider Creek fans, we assumed the worst-case-scenario: that all adjustment occurs through erosion of the channel banks. In other words, the creeks adjust to the increased flow by widening, rather than through bed scour or overbank flooding. Previous experimental research has shown that this scenario is realistic on fans, and that rapid widening may happen during a single flood event (e.g., Pitlick et al. 2013, Eaton et al. 2017).

In order to evaluate the maximum potential bank erosion during a range of flood events, we used an equation developed by Eaton et al. 2017:

$$E_{RP} = 0.85 \cdot W_f \cdot \left(\frac{Q_{RP}}{Q_f} - 1\right)$$

where

Q_f is the discharge that will first initiate erosion in m^3/s,

W_f is the wetted channel width when the flow is at the threshold discharge in metres,

Q_{RP} is the debris flood discharge, in m^3/s; and,

E_{RP} is the erosion associated with a given debris flood return period, in metres.

The method assumes that bank erosion initiates when the flow is deep enough to produce sufficient force to move the largest rocks on the channel bed. When these largest grains move, the toe of the channel banks destabilizes and the creek widens until the flow depth reaches the critical value (d_f), and the largest grains re-stabilize. In other words, once a critical depth is reached, the creek widens enough to approximately maintain this depth during the flood (Figure 3-5).

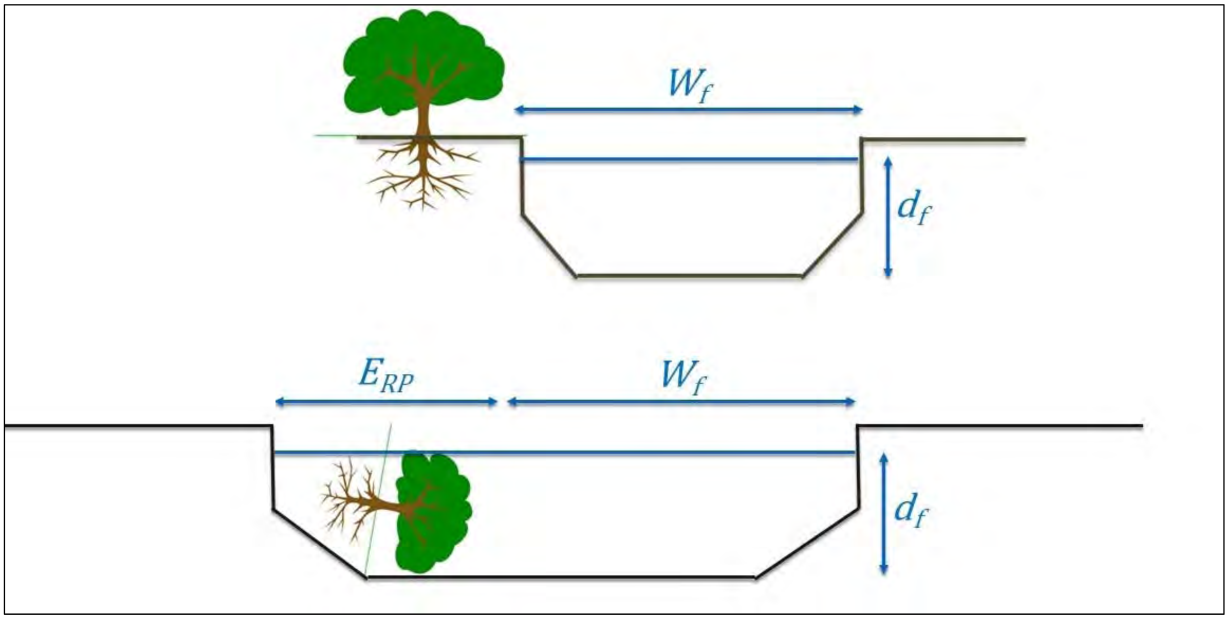


Figure 3-5. Summary of the bank erosion assessment methodology.

The steps involved in this method include:

- Divide the creek into stream reaches with consistent channel shape, grain size, and slope, using LiDAR data and photographs.
- Estimate the critical flow depth (d_f) needed to destabilize the largest grains on the creek bed (D_{95}), and to initiate erosion in each reach. This is calculated based on the size of the grain size (Church 2006).
- Use LiDAR cross sections from each reach to estimate the channel width (W_f) when the critical flow depth (d_f) is reached (Figure 3-5).
- Use a roughness equation to estimate the flow velocity (v_f) associated with the critical depth (d_f).
- Calculate the critical discharge (Q_f) needed for erosion to initiate. This is simply the product of the threshold flow depth (d_f), width (W_f), and velocity (v_f).
- Estimate the erosion (E_{RP}) associated with each debris flood return period based on the equation from Eaton et al. 2017, for each reach (Figure 3-5).

Results of the bank erosion analysis are presented in Sections 5 and 6.

3.5. Hazard Mapping

3.5.1. Introduction

Hazard mapping is useful to designate areas susceptible to specific or combined hazards. To create hazard maps useful for land use decisions a hazard map needs to be:

- Intuitive to government, and residents alike

- Be based on the intensities of expected hydrogeomorphic events to portray the potential destructiveness of debris flows or debris floods
- Account for auxiliary processes such as bank erosion
- Account for a variety of hazard scenarios (i.e., the full spectrum of return periods being considered and any potential avulsion scenario).

Given these objectives, composite hazard maps were created for Bear/Pete's, Whitecap and Spider creeks. The methods differed somewhat between Bear/Pete's creeks (debris flow creeks, bank erosion not considered) and Whitecap and Spider creeks (debris flood creeks, bank erosion considered) as explained in the following sub-sections.

3.5.2. Bear and Pete's Creeks

Two types of hazard maps were prepared for Bear Creek and Pete's Creek:

Interpreted hazard maps (Appendix G). These maps show the possible areas impacted by debris flow scenarios at some likelihood and intensity (Appendix G). The maps are developed from the results of debris flow modelling (Section 3.3), supplemented by fieldwork and judgement. Impact areas are generalized and smoothed compared to model results, and exceedance probability contour lines show the estimated conditional probability that debris flows of a given magnitude class will travel beyond the position of the line, somewhere along the length of the line. These maps form the basis for risk analysis but are not intended for policymaking and public communication.

Composite hazard maps (Drawing 13). These maps show the maximum area and intensity of impact by all debris flow scenarios and all creeks considered in the assessment. This includes areas of possible downstream flooding as well as backwater flooding upstream of the impact zone confluence with Portage River. These maps are intended for public communication, but are not used for risk analysis.

The debris flow hazard zones for Bear Creek are colour-coded as per Table 3-2.

Table 3-2. Definitions and colour coding for debris flows on Bear Creek.

Impact Intensity	Colour	Building Damage Potential	Description
< 1	Yellow	Minor	Slow flowing shallow and deep water with little or no debris. High likelihood of water damage. Potentially dangerous to people in buildings, on foot or in vehicles in areas with higher water depths.
1 to 10	Orange	Major	Potentially fast flowing but mostly shallow water with debris. Moderate likelihood of building structure damage and high likelihood of major sediment and/or water damage. Potentially dangerous to people on the first floor or in the basement of buildings, on foot or in vehicles.
10 to 100	Red	Severe	Fast flowing and deep water and debris. High likelihood of moderate to major building structure damage and severe sediment and water damage. Very dangerous to people in buildings, on foot or in vehicles.
>100	Dark Red	Destruction	Very fast flowing and deep water and debris. High likelihood of severe building structure damage and sever sediment and water damage. Extremely dangerous to people in buildings, on foot or in vehicles.

For reference, the impact intensity at 410 Spider Creek Road (Drawing G01 to 05) is classified as "Severe". This house was impacted by the September 22, 2015 debris flow and has since been abandoned.

3.5.3. Whitecap and Spider Creeks

Whitecap and Spider creek hazard maps are specific to debris-flood hazards and differ from the Bear creek hazard maps developed for debris-flow hazards. Creeks subject to flooding and debris flooding can result in substantial bank erosion.

Whitecap hazard maps (Drawings G06 to G10) were constructed following these steps:

- Numerical runout modeling of debris floods with FLO-2D for return periods from 10 to 3000 years.
- Translation of the debris flood model results into debris-flood intensities as defined in Section 3.3.
- Modeling of potential bank erosion extents along Whitecap Creek for return periods from 10 to 3000 years as described in Section 3.3. Potential bank erosion along Portage River due to an event on Whitecap Creek depends on depositional pattern as well as runoff of Portage River during and following the Whitecap Creek debris flood. These variations cannot be predicted with confidence and thus bank erosion along Portage River downstream of the Whitecap Creek confluence was not modeled.
- Translation of the bank erosion model results into areas potentially subject to bank erosion.

Spider Creek hazard map (Drawing G11) was constructed using the same approach as the Whitecap drawings, but only for a return period of greater than 1000 years. BGC's modeling shows that lower peak discharges are unlikely to reach nearby properties, therefore were not considered.

3.6. Risk Assessment Methods

3.6.1. Introduction

QRA involves estimating the likelihood that a hazard occurs, impacts elements at risk, and causes particular types and severities of consequences. Vulnerability estimation involves estimating the likelihood of consequences, given that a hazard occurs and impacts elements at risk. The key difference between vulnerability and risk estimation is that vulnerability estimates assume impact, whereas risk additionally provides estimates of the likelihood of impact.

The analysis methods are described in detail in Appendix H. The primary objective of the risk assessment is to support risk management decision making. Importantly, the assessment does not consider all possible risks that could be associated with a debris flow or debris flood. The risk assessment considers key risks that can be systematically estimated, compared to risk tolerance standards, and then used to optimize mitigation strategies. These mitigation strategies, once implemented, would also reduce relative levels risk for a broader spectrum of elements than those explicitly considered in this report.

This assessment also assesses risk of debris flows or debris floods separately for each creek. While it is possible that events may occur independently (e.g., the July 30, 2016 event on Bear and Pete's Creek and the November 8, 2016 event on Whitecap Creek), multiple events could occur on the same day (e.g., the September 20, 2015 events on Bear and Pete's and Whitecap creeks). Each of the watersheds studied are unique and produce different types of hydrogeomorphic events and have different times of runoff concentration. Separate assessment of risk for each creek (e.g. not combined risk) is a simplification that reflects the level of information available.

3.6.2. Safety Risk

Safety risk was estimated from two perspectives: risk to individuals and groups.

Individual safety risk considers the risk to a particular individual exposed to hazard, and is independent of the number of persons exposed to risk. BGC compared the individual risk estimate results to geohazard tolerance criteria adopted by the District of North Vancouver (DNV), BC and Canmore, AB which are the two jurisdictions in Canada that have formally adopted risk tolerance standards for residential development. Their criteria for individual geohazard risk tolerance are as follows (Figure 3-6):

- Maximum 1:10,000 ($1x10^{-4}$) risk of fatality per year for existing developments
- Maximum 1:100,000 ($1x10^{-5}$) risk of fatality per year for new developments.

For context, the DNV risk tolerance threshold of 10^{-4} (1/10,000) for existing development is comparable to the lowest background risk of death that Canadians face, on average, throughout their lives. This tolerance threshold is also similar to the average Canadian's annual risk of death due to motor vehicle accidents, 1/12,500, for the year 2008 (Statistics Canada 2009).

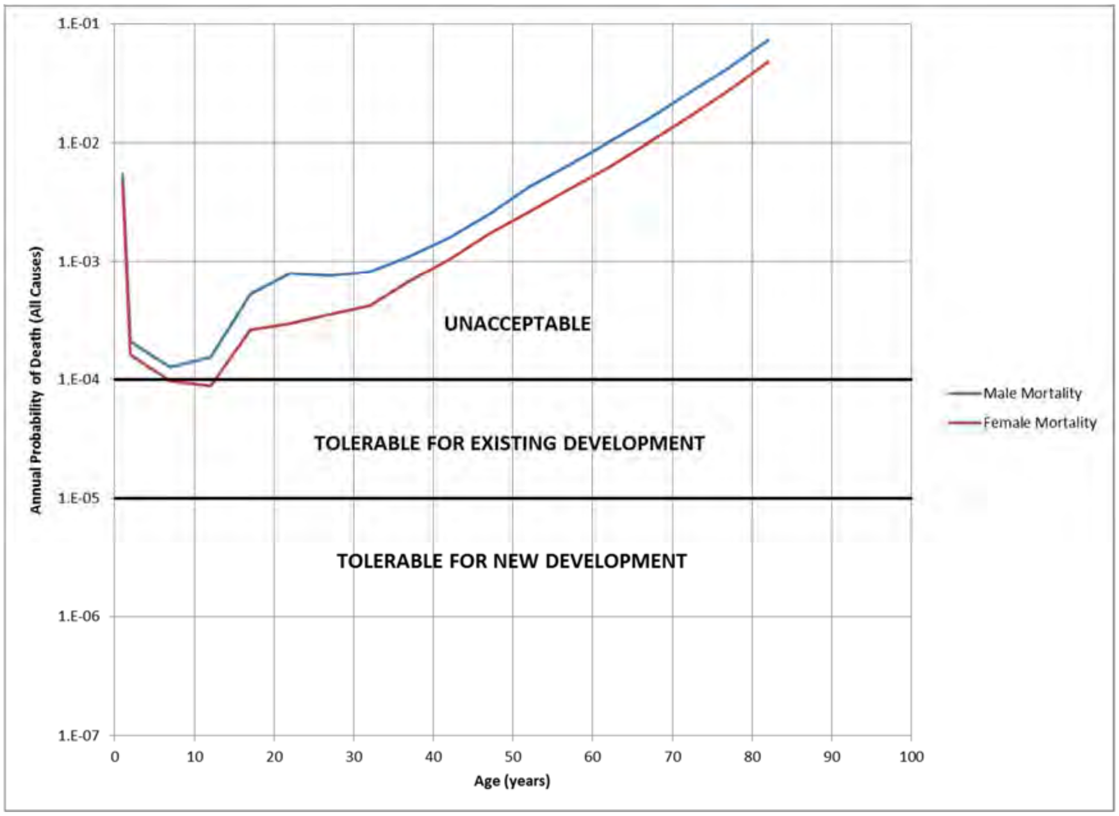


Figure 3-6. DNV individual risk tolerance criteria for landslides compared with Canadian mortality rates (all causes) in 2008.

Group safety considers the collective risk to all individuals exposed to hazard, and is proportional to the number of persons exposed to risk. For risk to groups, estimated risks were compared to group risk tolerance criteria formally adopted in Hong Kong (GEO 1998) and informally applied in Australia (AGS 2007), DNV (DNV 2009a and 2009b) and Canmore. Group risk tolerance criteria reflect society's general intolerance of incidents that cause higher numbers of fatalities. Group risk tolerance thresholds based on criteria adopted in Hong Kong (GEO 1998) are shown on an F-N Curve in Figure 3-7. Three zones can be defined as follows:

- Unacceptable – where risks are generally considered unacceptable by society and require mitigation.
- As Low as Reasonably Practicable (ALARP) or "Tolerable"– where risks are generally considered tolerable by society only if risk reduction is not feasible or if costs are grossly disproportionate to the improvement gained (this is referred to as the ALARP principle).
- Acceptable – where risks are broadly considered acceptable by society and do not require mitigation.

- Where N is calculated to be less than one (e.g., the probability of at least one fatality is not zero, but is not expected for any single scenario), group safety risk was considered to fall within the tolerable range.

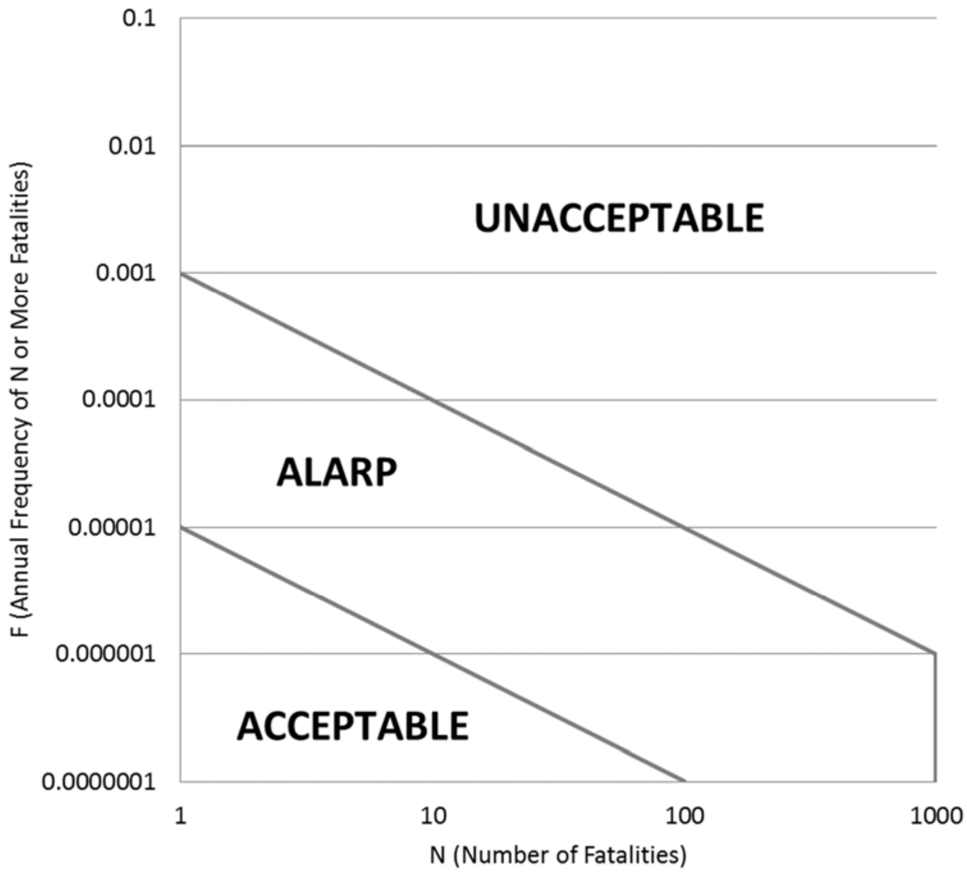


Figure 3-7. Group risk tolerance criteria as defined by GEO (1998).

3.6.3. Economic Risk

Economic risk considers direct building damage costs and interruption of business activity. Building damage costs were estimated based on the criteria presented in Appendix H. In summary, the proportion of building damage was estimated based on vulnerability criteria related to the hazard intensity index (I_{DF}).

BGC mapped the distribution of business activity by estimating the total annual revenue for each parcel identified as containing businesses based on data obtained from commercial data provider Hoovers (2017).

As a proxy for level of business impact, BGC summed the annual revenue estimated for parcels impacted by a debris-flood scenario. Additional factors such as indirect losses, damages to business equipment or inventory, interruption of transportation corridors, or effects of prolonged outage, were not estimated.

3.6.4. Lifelines and Critical Facilities

BGC mapped the distribution of lifelines (roads) and critical facilities located in the study area that would likely suffer loss of function following impact. The level of damage and functionality of roads once impacted is beyond the scope of this assessment. In the emergency response period, evacuation and road closures may also extend beyond the areas directly impacted.

3.7. Mitigation Design

If the risk assessment identifies an unacceptable risk, mitigation can be used to reduce the risk to a tolerable level. Mitigation involves reducing either the magnitude, intensity or probability of the hazard, or the severity of the consequences (Hungr et. al. 1987; VanDine 1996). This section describes the techniques that can be used for debris-flow and debris-flood mitigation, and the approach used for mitigation design at Seton Portage.

3.7.1. Mitigation Techniques

There are a wide variety of debris-flow and debris-flood mitigation techniques:

- Mitigation can be structural or non-structural
    - Structural measures involve construction of barriers, channels, or slope stabilization
    - Non-structural measures involve temporary or permanent removal of elements at risk from hazardous areas or changing people’s behavior to reduce vulnerability
- Structural measures can be located in the watershed, in the channel, on the fan, or in the community
- Structural measures in Canada are often located at the fan apex or on the fan.

Figure 3-8 shows selected examples of structural mitigation measures. These measures are often combined to create a “functional chain” of mitigation (Hübl and Fiebiger 2005). The most effective mitigation systems include a range of different techniques, to provide redundancy and optimize risk reduction.

Figure 3-8. Examples of debris-flow mitigation structures: (a) an earth-fill retention berm on Glyssibach, Brienz, Switzerland; (b) a stone diversion berm, Trachtbach, Brienz, Switzerland; (c) a conveyance channel with earthfill berms, Rennebach, Austria; (d) log crib check dams, Gesäuse, Austria; and (e) a flexible debris net for debris flood mitigation, Cougar Creek, Canmore, Alberta. Photograph (d) by M. Jakob, other photographs by E. Moase.

Selection of appropriate mitigation depends on several factors, including the process type, current and future land-use and budget. The following section explains the approach that BGC uses to select and develop debris-flow and debris-flood mitigation designs.

3.7.2. Mitigation Design Approach

BGC's debris-flow and debris-flood mitigation design approach for structural measures is summarized in Figure 3-9. This project focuses on the first two phases: Project Scoping and Conceptual Design.

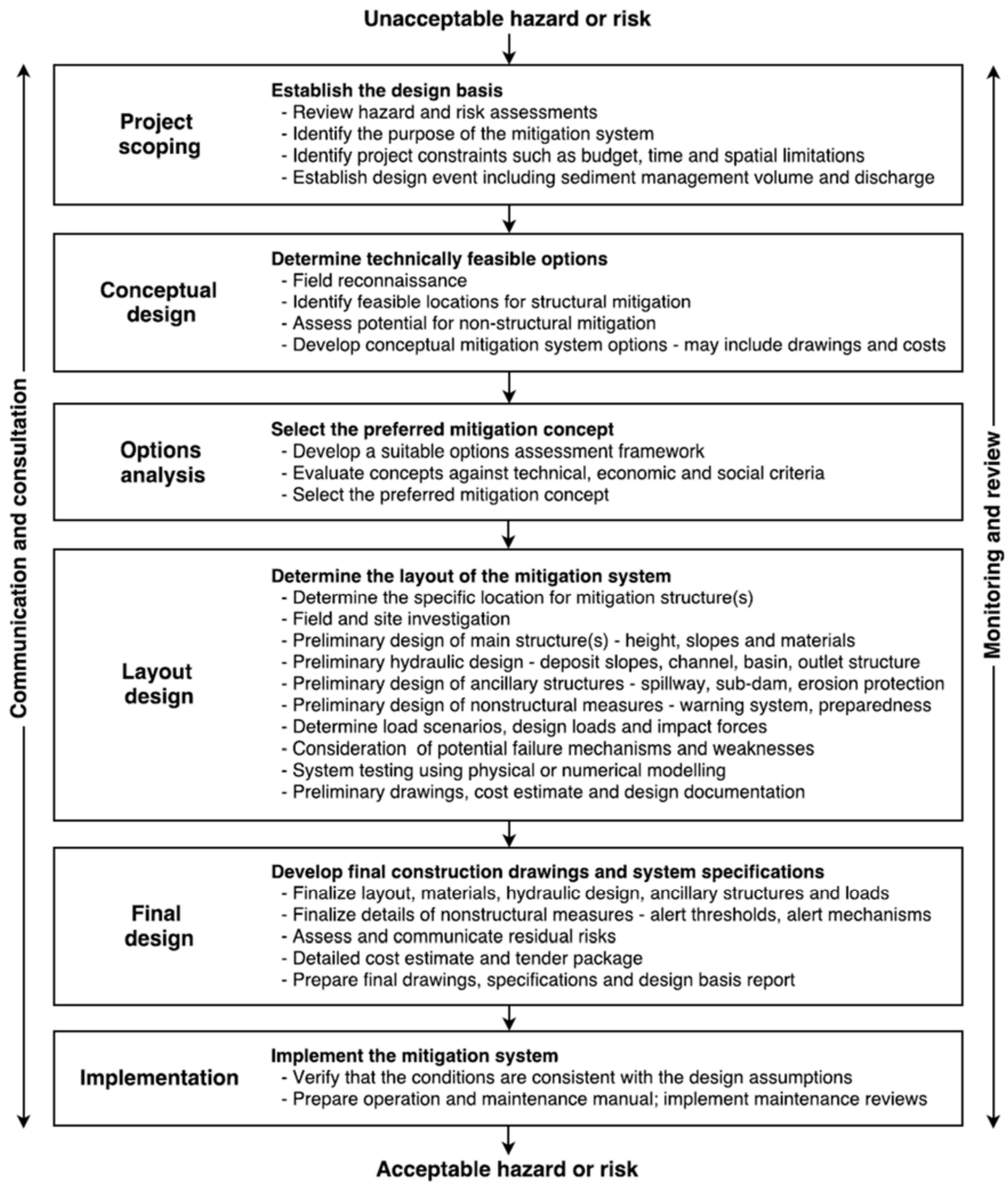


Figure 3-9. Recommended mitigation design approach (from Moase et al. 2017). This study included all of the first three phases and aspects of the Layout design phase.

Project Scoping

The objective of the Project Scoping phase is to develop the basis of the mitigation design, including the purpose of the mitigation, the design constraints, and the design event. Constraints to consider may include:

- The budget and any funding-related conditions
- The timeline for design and construction
- Land use or zoning restrictions
- Maintenance considerations, including capability for long-term maintenance, and options for debris disposal
- Social and cultural implications
- Environmental concerns, such as fish-bearing streams or wildlife corridors.

The design event is the debris-flow or debris-flood scenario that the mitigation system is designed to manage, usually expressed as a return period, sediment volume and peak discharge. Determination of the design event depends on the results of the hazard and risk assessments, and the risk tolerance criteria.

Conceptual Design

The objective of the conceptual design phase is to identify and develop feasible mitigation design options. Identification of feasible structural mitigation measures primarily depends on the accessibility of the watershed, channel and fan apex, and the level and type of development on the fan. It is also important to consider the types of processes that contribute to the hazard, such as side-slope landslides or channel erosion.

Once feasible mitigation options have been identified, the options are developed and sometimes combined into conceptual systems or “functional chains” that meet the design basis established during project scoping. A mitigation system can be a set of structural and non-structural measures that interact to provide redundancy and meet hazard or risk reduction targets. The mitigation systems consider factors including:

- Measures requiring minimal maintenance or intervention are likely to perform better and cost less in the long run, but sometimes can cost more to construct
- Measures that avoid disrupting the normal streamflow are generally preferable from an environmental and regulatory perspective
- If the sediment load is removed from a high discharge flow by a regulation or retention structure, the flow will tend to scour and entrain debris downstream of the structure, unless the channel is sufficiently protected (Piton and Recking 2015).

The conceptual design process typically identifies several feasible system options for comparison.

Regulatory Context

Construction of structural mitigation would be subject to local regulations, including:

- Berms and deflection embankments may require approval under the Dike Maintenance Act, and construction in accordance with the standards dictated by the act.
- The diversion of any streams would require authorization under the Water Sustainability Act. This would authorize both the diversion of the stream and facilitate long term maintenance approvals.

Design Life

The proposed mitigation measures have a design life of 50 years, assuming the structures are regularly maintained. Maintenance will need to include vegetation removal, sediment removal, post-event restoration and replacement of riprap, as necessary. Mitigation measures should be inspected on a regular basis and following large storm events.

3.7.3. Non-Structural Measures

Non-structural measures for debris flow and debris flood risk management typically include the following options:

- **Education** – Provide training for residents and workers who are commonly exposed to hazards. Training topics include: how to interpret hazard maps and identify areas exposed to hazards; causes and triggers of events; measures that individual property owners can take to protect themselves; emergency preparedness; and actions to take during an event. This can reduce the vulnerability of individuals to hazardous events.
- **Emergency Management Planning** – Develop plans to respond during or immediately after an event. This would typically involve plans for evacuation, checking in with neighbors, and staging of equipment and materials. This can reduce the consequences of a hazard event and improve resilience of the community.
- **Relocation** – Remove buildings from hazard zones. This can eliminate safety and economic risk from hazard sources, but the costs and tradeoffs can be prohibitive.
- **Temporary Evacuation** – This can include precautionary evacuation from hazard zones during periods of heavy rainfall, or alarm systems that signal an event has started. An alarm would provide only seconds or minutes of advance notice for the processes affecting Seton Portage. This method can reduce safety risk, but does not reduce property damage. This method can be difficult to implement effectively because of large uncertainties in predicting events, the possibility of frequent false alarms, and the requirement for occupants to evacuate quickly and without assistance.
- **Development Restrictions** – This involves creation of zones where future development is not allowed. This should be based on hazard maps that are updated as conditions and topography change. Particularly, construction of structural

mitigation measures can change the debris flow and debris flood impact location and extents.

Use of non-structural measures depends on the type and value of elements at risk, the regulatory and governmental context, and triggers and thresholds for warning system design. At Seton Portage, BGC interprets that none of these options would feasibly reduce risk to tolerable levels without construction of structural mitigation measure. However, all could be implemented in combination with structural mitigation measures to improve risk reduction. These options can be further developed after structural measures are selected.

3.8. Summary

This section summarized the different techniques that were applied for Bear, Whitecap and Spider creeks to: (a) decipher the frequency and magnitude of debris flows, debris floods and LDOFs and (b) numerically simulate the processes with two different computer models. Neither model, however, is capable of simulating bank erosion which is a critical hazard, particularly for debris floods at Whitecap Creek. The modeling of hydrogeomorphic processes allows determination of intensities associated with each process for the respective fan areas. This provides input to the risk assessment and informs mitigative designs whose techniques and approach is described in Section 3.7. Subsequent sections provide the results for each creek in question.

4.0 BEAR AND PETE'S CREEKS

4.1. Introduction

This section describes hazards, risks and mitigation for Bear Creek. Pete's Creek drains a tributary watershed of Bear Creek. However, both creeks' fans are fully coalescing and can therefore not be differentiated. For this reason, we refer in the text to the landform as the Bear Creek fan complex. Debris flows on the fan complex are highly mobile and even the most frequent events tend to travel to the distal fan.

4.2. Previous Events on Bear and Pete's Creeks

4.2.1. Documented Events

Based on eye-witness accounts, debris flow events on Bear and adjacent Pete's creeks occurred in 1907, spring 1964, sometime 1975, August 19 and 29, 1991, 2003, 2013, September 20, 2015 (Figure 4-1) and July 30, 2016. The July 2016 debris flow on Bear Creek had an approximate sediment volume of 67,000 m^3 (range 47,000 to 87,000 m^3). At this volume, it has an estimated return period of 50 years. Also of importance is a large forest fire that affected the eastern portions of the Bear Creek fan and watershed. Additional details on the events listed and a discussion on the effects of the forest fire on debris flow activity as well as relevant geotechnical assessments and mitigations works are included in Appendix A and D.

Figure 4-1. Looking southwest towards 410 Spider Creek Road impacted by the September 22, 2015 debris flow on the flats below the Bear Creek fan escarpment. Photo provided by Tsal'alh dated September 22, 2015. The house has since been abandoned.

4.2.2. Air Photograph Interpretation

Air photographs between 1948 and 2012 were examined to search for evidence of debris flows on Bear and Pete's creeks. A summary is provided in Appendix D.

Bear Creek and Pete's Creek watersheds show active rock fall and debris-flow processes in the air photo and satellite image record. The dense vegetation on the fan challenges determination of the exact number and extent of previous debris flows. However, several observations regarding the nature and frequency of debris flows on Bear and Pete's creeks can be made. Fresh rockfall and debris slide deposits were observed in the upper Bear Creek watershed in all air photos, highlighting active colluvial processes. Fresh debris flow deposits from the Bear Creek watershed extend below a waterfall at an elevation 1000 masl on all air photos. Additionally, at a minimum, one debris flow from Bear Creek reached the distal, truncated fan portions above Seton Portage, as seen in the 1948 air photo. As interpreted from the 1948 air photo, this debris reached the current location of houses along Cresta Road, south of the Whitecap Property.

4.2.3. Dendrogeomorphology

Eleven possible debris-flow dates were inferred from the dendrogeomorphology analysis on Bear and Pete's creeks. Drawing 02 shows the location of all sampled trees. The 11 dates, which extent back to 1885, imply an approximate return period of 11 years. Given that some events may have been missed, an approximate return period of 10 years is assumed for any debris flow reaching the lower fan. Of those, only the 1975, 1991, 2015 and 2016 events are known to have reached development according to historical accounts. The detailed results of the analysis are presented in Appendix D.

The dendrochronological analysis did not permit the delineation of previous flows on the fan, due to the large fan extents. Nonetheless, the analysis confirmed known events as well as provided new event dates that were previously unknown.

4.2.4. Radiocarbon Dating

The key conclusions for radiocarbon dates obtained from test pitting on the Bear Creek fan (Drawing 02) are:

- The lowest dated deposits are approximately 4300 years old and are located approximately 10 m below the fan surface. This implies that the fan thickness has grown by 10 m in approximately 4300 years, or 1 m every 430 years.
- The youngest deposits appear at depths of approximately 1.4 m and have an age of approximately 150 years. Younger flows can typically not be dated with radiocarbon methods and are more suitable for dendrogeomorphologic dating.
- Given that the oldest dates are "only" some 4300 years old, the visible fan of Bear Creek appears to have been formed over this time period. However, fan formation likely started much earlier (likely around 11,000 years ago), but the fan is now covered by Anderson Lake to the west, the floodplain of Portage River to the north and by the remnants of Spider Creek fan to the east.

- The return period of radiocarbon-dated debris flows depends on the site where the samples were obtained, ranging between 190 years at TP 16 and 1860 years at TP 5. Debris flows reaching the fan margin are likely of return periods greater than 30 years.

4.3. Debris-Flow Frequency Magnitude Relationship

The following key results were obtained from the different methods employed:

- Debris flows occur about every 10 years.
- Debris flows are postulated to occur as two types: Those initiated by in-channel entrainment of debris during high discharge events near the upper fan apex and those that are triggered by a point source (rock fall or debris slide/debris avalanche) in the upper watershed.
- Debris flows appear to have been larger immediately after the last Ice Age than they are in today's climate.
- Due to a high clay content, debris flows on Bear Creek travel further, spread thinner and have a lower peak discharge compared to "normal" debris flows in the Coast Mountains.
- The F-M relationship for Bear Creek is summarized in Table 4-1. The F-M graph is shown in Appendix D.

Table 4-1. Debris-flow magnitude for different return periods for Bear Creek.

Return Period (T) (years)	Annual Probability (1/T)	Max. Sediment Volume Estimate (m^3)	Debris Flow Peak Discharge (m^3/s)
10 to 30	0.1 to 0.03	11,000	30
30 to 100	0.03 to 0.01	70,000	220
100 to 300	0.01 to 0.003	150,000	480
300 to 1000	0.003 to 0.001	240,000	760
1000 to 3000	0.001 to 0.0003	320,000	1000

The values reported are uncertain, especially for events exceeding 300 years as there are no recently documented precedents for such volumes. However, BGC believes that these presented values are reasonable representations of expected debris flow volumes affecting the Bear Creek fan complex. The analyses presented here are based on the assumption that the relationship between frequency and magnitude of debris flows will remain unchanged. This assumption is increasingly being questioned and thus discussed in the following section.

4.4. Impacts of Climate Change

It is now scientifically accepted that humans will continue to alter Earth's thermal climate over the next 50 to 60 years (IPCC 2014). The relevance of climate change with regard to Bear Creek debris-flow hazards is that the predicted warming of the troposphere will very likely[5] increase the pattern of precipitation and temperature, both of which influence the frequency, possibly magnitude and runout behaviour of debris flows at Bear Creek. To provide a semi-quantitative basis to estimate future changes to debris flow activity on Bear Creek, BGC used available climate change ensembles that allow visualization and quantification of changes. This assessment is detailed in Appendix J and summarized here.

Debris flow frequency and magnitude at Bear Creek is sensitive to climate change for the following reasons:

- Bear Creek has a quasi-unlimited amount of sediment readily available for transport. This means that when, in the future, rainfall frequencies increase, this will result in an increase in the frequency of debris flows.
- The watershed is likely underlain by permafrost above 2100 masl elevation. This implies that rocks above that elevation could be held together by ice. When this ice melts, it could release such rocks either as rock fall, debris avalanches or rock slides, all of which could lead to debris flows in wet conditions. This again could increase the frequency of debris flows, but also the magnitude should increasing portions of the upper watershed become ice free.

In summary, it is likely that debris flows on Bear Creek will increase in both frequency and magnitude. Science has not advanced to a stage where those increases can be reliably quantified. However, such changes are likely to lead to an increased risk compared to the present risk. Given the uncertainty with the debris-flow magnitude estimates associated with long return period debris flows (that govern the design of mitigation works), it is unlikely that the projected changes in volume would require design alterations. It would, however, likely require more frequent maintenance in the form of basin cleanouts. Risk reduction measures are discussed in detail in Section 4.7.

4.5. Numerical Debris-Flow Modeling

Bear Creek debris flows were modeled using the three-dimensional runout model *DAN3D* (McDougall and Hungr 2004), following the procedures outlined in Section 3.3.4 and Appendix G.

At Bear Creek, debris flows with a return period greater than approximately 30 years are likely to reach the limits of present development. The 1991, 2015 and 2016 events all fall into this category. Debris flows are expected to have maximum flow depths of 1.2 m to 3.8 m and flow velocities of 6 m/s to 10 m/s at the edge of the present development, approximately 900 m downstream of the fan apex. Table 4-2 summarizes the range of impact intensities at the urban development interface for the different return period classes.

[5] See IPCC (2014) for a definition of "very likely" in the context of that report.

Table 4-2. Impact Intensities at urban development on Bear Creek fan. All figures are rounded to avoid the illusion of exactness.

Return Period (years)	Flow Velocities (m/s)	Flow Depth (m)	Impact Index (m^3/s^2)
10-30	NA	NA	NA
30-100	6	1	20
100-300	7	2	50
300-1000	9	3	70
1000-3000	10	4	190

Drawing 10 presents the results of debris-flow modelling for scenarios corresponding to return period classes from 10 to 3000 years and Table 4-3 summarizes key results including a brief description of areas impacted.

Table 4-3. Results from numerical modeling on Bear Creek.

Return Period (years)	Results
10-30	• Debris flows will likely stop before reaching the developed fan fringes on most of Bear Creek. • Debris flows of this return period could impact the "Whitecap dike" and overtop it. They could also reach the uppermost developments at Cresta Road.
30-100	• Debris flows will likely reach the fan fringe of Bear Creek and progress into developed areas south of Seton Portage Road. • At Pete's Creek, overtopping of the Whitecap dike could occur • Should a debris flow reach the Railway Cut downslope of Necait, it would interrupt rail service and constrict Portage River flow.
100-300	• Debris flows could reach Seton Portage Road. • Should a debris flow reach the Railway Cut downslope of Necait, it would interrupt rail service and likely impound Portage River. • Should a debris flow reach Cresta Road, it would lead to severe damage.
300-1000	• Debris flows would likely reach Seton Portage Road and flow beyond, potentially reaching Portage River. All road and rail access would be interrupted. • Should a debris flow reach the Railway Cut downslope of Necait, it would interrupt rail service and likely impound Portage River, possibly for days before the dam is overtopped. Necait could be destroyed.
1000-3000	• Debris flows could cross the entire valley and likely impound Portage River. All road and rail access would be interrupted. • Severe upstream and downstream flooding could be expected where Portage River is impounded. • Should a debris flow reach the Railway Cut downslope of Necait, it would interrupt rail service and likely impound Portage River, possibly for weeks before the dam is overtopped. Necait would be destroyed if in the flow path.

4.6. Risk Analysis

This section summarizes results of the Bear and Pete's Creek risk assessment based on the methods described in Appendix H. As described in Section 3.6, safety risk is estimated separately for individuals and groups (societal risk). The results presented are the combined annual risk from all debris-flow scenarios, given that some parcels may be impacted by more than one scenario.

4.6.1. Individual Risk

Table 4-4 lists the number of buildings where estimated individual risk exceeds 1:1,000 and 1:10,000 risk of fatality per year for occupied residential buildings for Bear and Pete's Creek. Table 4-4 includes results from Catiline Creek, also within the SLRD (BGC 2015), for comparison. Catiline Creek shares similar morphometric characteristics with Bear Creek, however, most structures are situated directly on the fan of Catiline Creek. At Bear Creek, most development is located below the modern fan fringes. Drawing 15 shows residential lots where BGC's best-estimate of individual risk (PDI) exceeds 1:10,000 risk of fatality per year assuming full-time occupancy. Lots not coloured did not exceed PDI = 1:10,000.

In summary, BGC's best-estimate of individual risk exceeded the DNV risk tolerance standard of 1:10,000 risk of fatality per year for 59 occupied buildings within the study area. Nineteen lots exceeded 1:1,000 annual risk of fatality, one order of magnitude above the DNV individual risk tolerance threshold. These results are similar to those from Catiline Creek (BGC 2015). A list of buildings exceeding risk tolerance thresholds is available upon request.

Table 4-4. Summary of individual risk results for occupied residential lots for Bear and Pete's Creek and Catiline Creek (BGC 2015).

Tolerance Threshold (Annual PDI)	Number of Buildings Exceeding Threshold for Bear and Pete's Creek (SLRD Jurisdiction[1])	Number of Buildings Exceeding Threshold for Bear and Pete's Creek (Indian Reserve Jurisdiction[2])	Number of Buildings Exceeding Threshold for Bear and Pete's Creek	Number of Lots Exceeding Threshold for Catiline Creek
1:1,000	11	8	19	18
1:10,000	44	15	59	76

Notes:

1. SLRD Jurisdiction includes Crown Municipal, Crown Provincial and Private parcel types.
2. Indian Reserve (IR) Jurisdiction includes the Crown Federal parcel type.

4.6.2. Group Risk

Figure 4-2 presents the results of group risk analysis on an F-N curve. Estimated overall group debris-flow risk plots well into the Unacceptable range when compared to the international risk tolerance standards described in Section 3.6.2.

Table 4-5 lists the range of expected fatalities for each main debris flow scenario for Bear and Pete's Creek. Results from Catiline Creek, which is located on Lillooet Lake, some 51 km south of Seton Portage (BGC 2015) are once again shown for comparison. The values in each column are shown as ranges. These ranges reflect the spectrum of different runout extents possible for a given volume class (e.g., for a given volume class, a longer runout event is less likely, but would impact more buildings and result in higher expected fatalities). It is important to note that the debris-flow return periods listed in Table 4-5 indicate the recurrence interval of the scenario, not the likelihood of fatalities (which is lower, as shown on Figure 4-2).

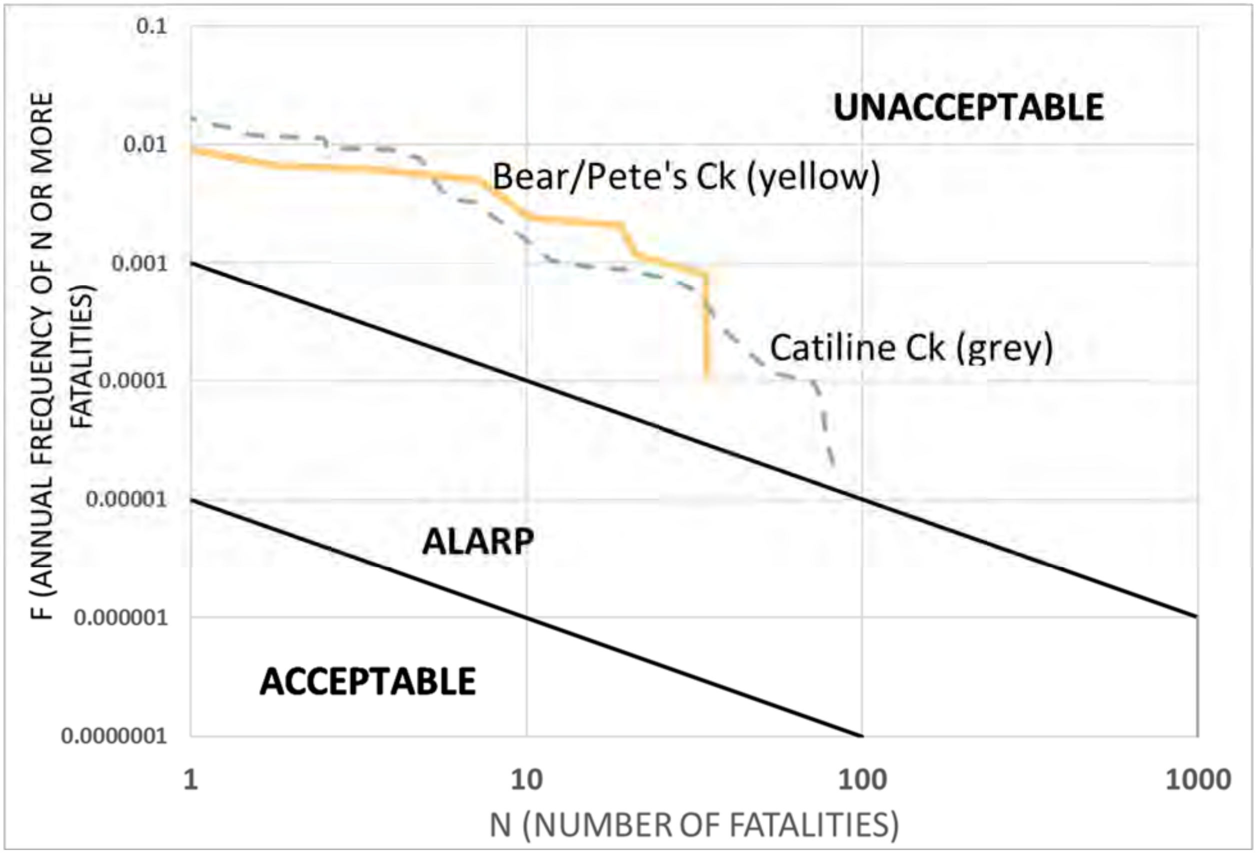


Figure 4-2. F-N curve showing the results of the Bear and Pete's Creek risk analysis for groups (yellow line). Results for Catiline Creek (grey dashed line) are shown for comparison.

Table 4-5. Estimated life loss for each scenario on Bear and Pete's Creek and Catiline Creek (BGC, 2015).

Scenario	Frequency (1:years)	Estimated Number of Fatalities (N) for Bear Creek	Estimated Number of Fatalities (N) for Catiline Creek (BGC 2015)
1	1:10 to 1:30	<1	0 to 2
2	1:30 to 1:100	<1 to 3	0 to 9[(1)]
3	1:100 to 1:300	2 to 9	
4	1:300 to 1:1000	8 to 17	2 to 38
5	1:1000 to 1:3000	to 30	to 80

Note:
1. BGC (2015) Assessed the 1:30 to 1:300 return period range for Catiline Creek.

4.6.3. Economic Risk

This section describes economic risk from building damage and interruption to business activity.

Building Damage

Table 4-6 summarizes building consequence estimates for each scenario, including the number of buildings affected and total building damage costs. For reference, total estimated building value for the Bear and Pete's fan and lower floodplain area is approximately $16 million. Average annualized building damage is approximately $140,000 based on the scenario damage costs listed in Table 4-6. Estimated building damage costs are based only on a portion of assessed building values and do not include damage to contents or inventory. In addition, costs of cleanup and recovery are not included.

Table 4-6. Summary of estimated building damage at Bear Creek.

Scenario	Frequency (1:years)	Number of Buildings Affected by Debris Flows	Building Damage Cost ($)
1	1:10 to 1:30	33	430,000
2	1:30 to 1:100	82	2,400,000
3	1:100 to 1:300	106	4,260,000
4	1:300 to 1:1000	134	6,160,000
5	1:1000 to 1:3000	134	7,940,000

Business Activity

Table 4-7 summarizes business activity impacts for business located within the study area. BGC mapped the distribution of business activity in the study area by estimating the total annual revenue for each parcel identified as containing businesses.

Based on the data available, it is not possible to determine the vulnerability of businesses to complete loss of function, and associated economic cost, due to debris flow impacts. For example, a retail store could suffer loss of inventory and business function, whereas a business generating revenue elsewhere could suffer office-related damages without necessarily losing their source of revenue.

As a proxy for level of business impact, BGC summed the annual revenue estimated for parcels impacted by a debris-flow scenario. Additional factors such as indirect losses, damages to business equipment or inventory, interruption of transportation corridors, or effects of prolonged outage were not estimated.

Table 4-7. Summary of business consequence estimates on Bear and Pete's Creek.

Scenario	Frequency (1:years)	Number of Businesses Affected	Number of Employees Affected	Annual Business Revenue ($)
1	1:10 to 1:30	-	-	-
2	1:30 to 1:100	1	1	130,000
3	1:100 to 1:300	61	22	680,000
4	1:300 to 1:1000	61	22	680,000
5	1:1000 to 1:3000	61	22	680,000

Note: Three of six businesses are located in the same building.

4.6.4. Lifelines

This section summarizes critical facilities and lifelines (roads, bridges) located within the debris-flow impact zones that may suffer loss of function following impact.

Table 4-8 lists the critical facilities identified in Section 2.5 impacted by debris-flow scenarios considered in this assessment.

Table 4-8 lists the intensity of debris flows reaching the critical facilities per the criteria listed in Table 3-2. More detailed assessment of the level of damage once impacted is beyond the scope of this assessment.

Table 4-8. Summary of I_{DF} values at critical facilities impacted by debris flow scenarios on Bear and Pete's creek.

Scenario	Frequency (1:years)	Hotel	Canada Post/Corner Store/Restaurant	Church	Pumphouse
1	1:10 to 1:30	-	-	0 to 1	0 to 1
2	1:30 to 1:100	-	-	1 to 10	1 to 10
3	1:100 to 1:300	0 to 1	0 to 1	10 to 100	10 to 100
4	1:300 to 1:1000	0 to 1	0 to 1	10 to 100	10 to 100
5	1:1000 to 1:3000	1 to 10	10 to 100	10 to 100	10 to 100

Table 4-9 lists lifelines (roads, railway and bridges) impacted by debris-flow scenarios. The level of damage and functionality of these lifelines once impacted is beyond the scope of this assessment. In the emergency response period, evacuation and road closures may also extend beyond the areas directly impacted.

Table 4-9. Summary of roads and bridges impacted by debris flow scenarios of Bear and Pete's Creek.

Lifeline		Scenario				
		1	2	3	4	5
Roads	Anderson Lake Road		✓	✓	✓	✓
	Broadhead Road				✓	✓
	Bull Alley				✓	✓
	Cresta Road	✓	✓	✓	✓	✓
	Edwards Road		✓	✓	✓	✓
	Scott Road		✓	✓	✓	✓
	Seton Portage Road	✓	✓	✓	✓	✓
	Spider Creek Road		✓	✓	✓	✓
	Williams Lane		✓	✓	✓	✓
Railway	CN Rail	✓	✓	✓	✓	✓
Bridges	Anderson Lake Road Bridge			✓	✓	✓
	Seton Portage Road Bridge			✓	✓	✓

4.7. Conceptual Mitigation Design

4.7.1. Design Event

The debris-flow risk assessment has shown that the current safety risk levels are unacceptable when compared to individual and group risk thresholds that have been adopted in other jurisdictions (see Sections 3.6.2 and 4.6). The conceptual designs presented in this report are sized to accommodate up to the largest event magnitude (1,000 to 3,000-year return period) debris flow considered in the risk assessment. This results in design options that are relatively expensive and may exceed the budget available for mitigation construction; however, this event was chosen for conceptual design because:

- It may be necessary to achieve a residual group risk that plots within the ALARP zone (see Figure 4-2).
- Sizing structures for the largest event during the conceptual design stage provides a sense of cost and scale to achieve maximum risk reduction.
- The length and extent of design elements is largely independent of the design event magnitude, and therefore the proposed conceptual options are applicable if a smaller design event is chosen at a future design stage.

During future mitigation design stages, debris-flow risk should be re-assessed with consideration of the selected mitigation measures to estimate the level of ‘residual risk’ following completion of mitigation measures. The residual risk assessment helps to optimize the mitigation design to within tolerable levels without being unnecessarily conservative or costly. For example, it may be possible to reduce the height of proposed berms or depths of basins and channels, if a smaller design event is selected.

4.7.2. Design Considerations

Table 4-10 summarizes the basis for the Bear and Pete’s Creek debris-flow mitigation designs presented in this report. The items listed describe the design objectives, constraints and assumptions that were used to compare design options.

Table 4-10. Bear and Pete’s creeks debris-flow mitigation design basis summary.

Consideration	Design Notes
Geohazard types	Presented mitigation options address debris-flow hazards only. Other geohazard risks related to snow avalanches, large rock slope deformations and gully erosion were interpreted to be tolerable and therefore have not been considered for mitigation design.
Design objective	The primary design objective is to minimize debris-flow life loss risk for residents within the potential runout path. The secondary objective is to minimize debris-flow economic losses. Where possible, the designs will also aim to maintain access along existing roads, but access is a lower priority objective compared to life loss and economic risks.
Elements at risk	Elements at risk include: • Residential development (mostly safety risk) • Roads (access and economic risk) • Railroad (mostly economic risk) Elements at risk are located around the distal edge of the fan (see Figure 4-3), leaving most of the fan surface available for mitigation structures.
Elements of cultural significance	Figure 4-3 identifies several locations of cultural significance that were considered in the Bear and Pete’s Creek mitigation designs. These include the graveyard on the west side of the fan, and the nearby pit house foundations. BGC encourages Tsal’alh members and stakeholders to determine the level of protection required, and to identify any other significant areas.
Risk transfer	Mitigation measures should not increase the life loss or economic risk at existing infrastructure or buildings.
Conceptual design level	Conceptual-level design options were developed. The intent of this design stage was to identify technically feasible options for further review and consideration.
Design event	The proposed mitigation options have been sized to accommodate the 1000 to 3000-year return period debris flow. This flow is estimated to include 320,000 m^3 of debris at a peak discharge of 1000 m^3/s.

Consideration	Design Notes
Maintenance	All mitigation options presented require routine maintenance. The designs assume this maintenance will occur as needed. Maintenance and restoration of channels, berms and erosion protection will be required following debris flows, snow avalanches and annual peak flow events.
Topography	The layout of mitigation options is based primarily on interpretation of topography from a LiDAR-derived digital elevation model.
Geotechnical conditions	Geotechnical conditions have been assessed based on surface observations and test pits excavated for debris flow assessment. BGC has made the following assumptions for conceptual design purposes: • Groundwater will not be encountered in shallow excavations • The fan is composed of soil that is suitable for reuse as berm fill • Bedrock will not be encountered in excavations.
Fan geometry	The identification of mitigation options was influenced by the fan geometry, specifically the fan truncation above CN Rail, Seton Portage Road, Williams Lane and Spider Creek Road (Figure 4-3). Flows that reach this slope break have the potential to down-cut and entrain additional sediment, such as occurred during the 2015 event. The proposed mitigation designs avoid passing flows over the edge of the truncated fan.
Construction materials	Where possible, the designs make use of existing on-site materials and features, including the re-use of excavated fan material for berm construction. The objective was to achieve a cut/fill balance, with material excavated from basins and channels being replaced in berms.

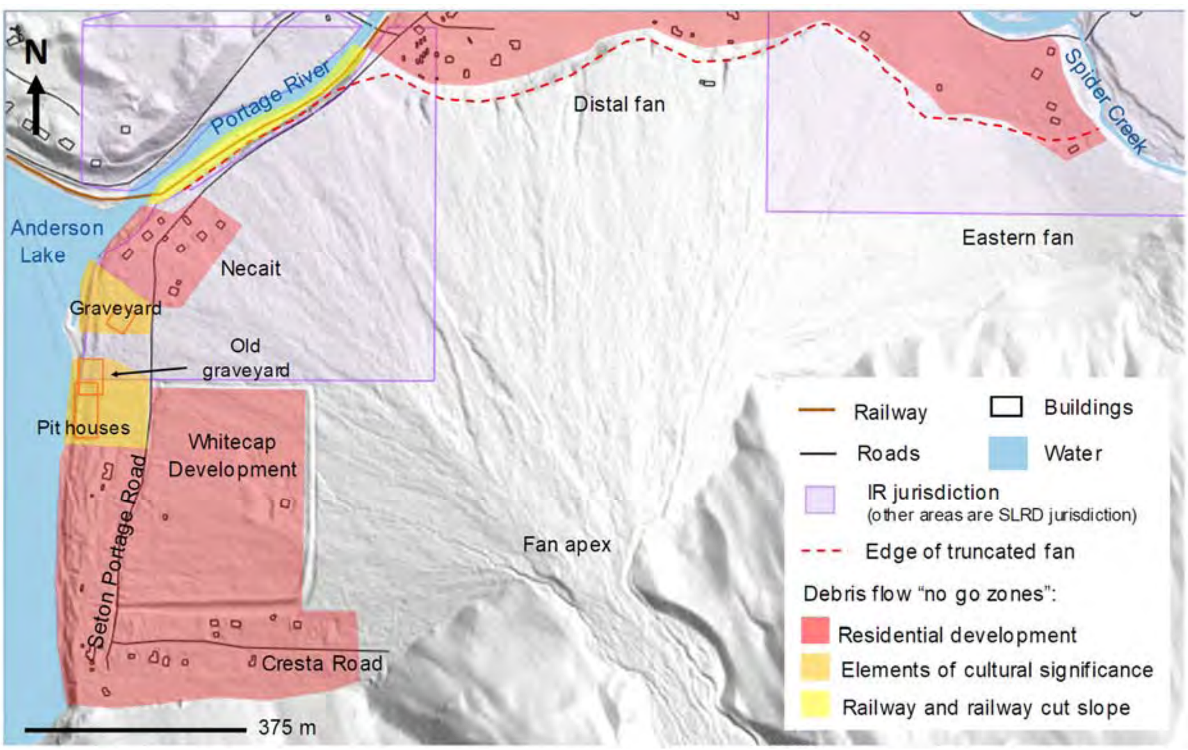


Figure 4-3. Overview map of the Bear and Pete's creeks fan showing elements at risk. The proposed mitigation options aim to prevent debris flows from entering the "no go zones" shaded in red, orange and purple.

Given the constraints above, the following system options are proposed to mitigate the debris-flow risk on Bear and Pete's creeks:

- **Option 1: Basin and Anderson Lake Conveyance –** Attenuate flows with a basin at the fan apex; convey attenuated flows and remaining debris to Anderson Lake, through the gap between the Whitecap Development and Necait
- **Option 2: Basin and Diversion to Eastern Fan –** Attenuate flows with a basin at the apex; divert attenuated flow and remaining debris to the northeast; retain debris on the eastern fan
- **Option 3: Basin and Distal Berms –** Attenuate flows with a basin at the apex; build local berms to protect elements at risk.

These options are discussed in the following sections. The mitigation alignments and geometries are conceptual, and are intended for option comparison purposes only. Additional detailed design will be required to optimize the preferred mitigation option. It may be possible to combine options or option components.

4.7.3. Debris Basin at the Fan Apex

A debris basin at the fan apex is included in all three options, because a basin provides the most risk reduction value for the least cost. Basins with storage volumes between 12,000 and 80,000 m^3 were considered by BGC. Regardless of size, the basin causes the flow to lose confinement, slow down and initiate deposition. Additionally, the basin excavation can be used as a borrow source for berm fill material.

The cost estimate assumes the following basin characteristics:

- The basin is excavated into the fan surface on all sides.
- An outlet structure for water flow is not included, because it is assumed typical creek flow can infiltrate into the fan surface as it does on the existing fan.
- The downstream edge of the basin is approximately horizontal allowing flow to spill over the basin without encouraging flow concentration.
- Basin side slopes, excavated into the fan, are 1.5H to 1V. Slopes are not erosion protected, except at the basin inlet. Erosion of the side slopes is assumed to be tolerable.
- Basin inlet erosion protection that is 100 m wide, 1.5 m deep and 10 m long per metre of basin width.

These characteristics need to be reviewed during future design stages. The design details listed here minimize construction costs, but could result in erosion, maintenance, or environmental impacts (e.g., water impoundment).

Perpetual maintenance will be required to remove sediment from the basin so that storage is available for future events. Sediment removed from the basin can be used to increase the size and extent of the proposed berms. To avoid filling the basin with smaller events and potentially reduce maintenance costs, a small channel could be constructed across the basin to maintain the confinement and encourage conveyance of small flows.

4.7.4. Option 1: Basin and Anderson Lake Conveyance

In this option, a berm system is proposed to retain and partially convey flows from Bear and Pete's creeks to Anderson Lake (Figure 4-4). The material from the basin excavation would be used to construct berms on either side of a wide corridor. At the upstream end, the two berms would tie in to high ground on either side of the fan apex. At the downstream end, the south berm would tie in with the north side of the existing diversion channel around the Whitecap Development. The north berm is proposed to end at Seton Portage Road, although the alignments of both berms would need to be refined and reviewed during detailed design. The north berm would be higher than the south berm, to prevent debris flows from avulsing out of the channel around the corner towards Necait.

An erosion protected swale is proposed across Seton Portage Road to direct flow across the road to Anderson Lake. A bridge over the debris flow path was not included due to cost considerations, however a bridge may improve emergency access to Whitecap Development and Cresta Road following an event, and could be considered during future design stages.

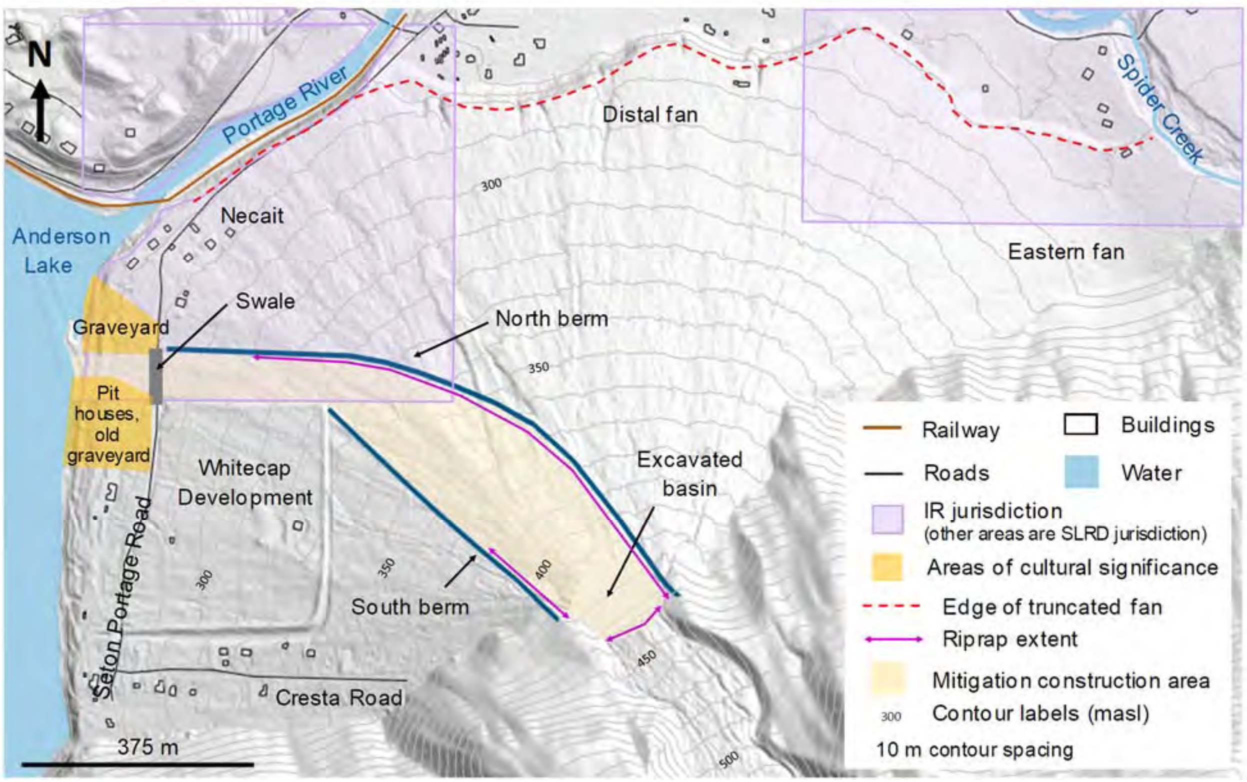


Figure 4-4. Bear and Pete's Creek mitigation Option 1 - conveyance to Anderson Lake.

The following geometry is proposed for the system:

- Berms: generally 3 m minimum height and locally up to 5 m high on upstream face, with a 4 m minimum crest width and 1.5H:1V side slopes. Total berm length is about 1600 m.

- Basin: capacity of about 45,000 m^3 for cut/fill balance with the berms, with erosion protection at the inlet.
- Riprap along the north berm (as delineated on Figure 4-4): 1.5 m thick and keyed in at the toe; total length of 10 m per metre of berm.
- Swale.

The cost estimate does not include an excavated channel; however, this could be considered during future design stages. A channel may improve conveyance of surface water and debris flows, but could increase construction costs and complicate the Seton Portage Road crossing.

The riprap extent shown is a minimum extent of erosion protection and requires review during future design stages. Erosion protection is focused on areas where berms are oriented oblique to the natural flow direction, which may tend to concentrate flow along the berm face.

The proposed outlet to Anderson Lake is located close to several sites of cultural significance for the Tsal'lah, including a graveyard and several pit house foundations; these sites are delineated on Figure 4-3. Assuming the current delineations are correct, the proposed Option 1 system should not impact either the graveyard or pit houses. However, the pit house extents should be confirmed by an archaeological team prior to proceeding with detailed design, if this option is advanced.

The primary advantage of this option is that flows are directed to Anderson Lake through the only undeveloped window on the distal fan. A defined flow path is provided for both debris flows and water flow, and the outlet location at Anderson Lake avoids the potential for debris flows to block Portage River.

The primary disadvantage is that berms are needed on both sides of the flow path to direct events to the narrow outlet location. This affects the construction cost and environmental footprint. Additionally, there is potential for risk transfer. All debris flows would be directed along the flow path toward Necait. The design relies on the north berm to contain flow and avoid risk transfer. Integrity of this berm is a critical consideration for detailed design and construction. The design significantly reduces the fan area available for debris deposition (compared to current conditions), and relies heavily on the proposed berms to contain the flows and avoid risk transfer. The berms are critical elements and there is no redundancy in the current design if the berms are overtopped or bypassed.

If this option is considered at a later date for additional design, consideration should be given to the necessity of a debris basin at the fan apex. A conveyance channel to Anderson Lake could be constructed in place of the debris basin. The main disadvantage of a basin is that it would need ongoing excavation to maintain its storage capacity, which might be an onerous responsibility for the maintenance authority.

4.7.5. Option 2: Basin and Diversion to Eastern Fan

In this option, a basin and berm system are proposed to redirect and capture flows on the eastern fan (Figure 4-5). The basin would capture the initial surges of the flow and attenuate the peak discharge. The berm would direct flows into a natural low area located between the Bear Creek and Spider Creek fans. The intent is capture all debris on the fan behind the main berm.

The following geometry is proposed for the system:

- Berms: generally 3 m minimum height and locally up to 5 m high on the upstream face, with a minimum 4 m crest width and 1.5H:1V side slopes. Total berm length is about 1600 m.
- Basin: capacity of about 50,000 m3 for cut/fill balance with the berms
- Riprap along the first 700 m of the berm, as shown on Figure 4-5.

The riprap extent shown is a minimum extent of erosion protection and requires review during future design stages. Erosion protection is focused on areas where berms are oriented oblique to the natural flow direction, which may tend to concentrate flow along the berm face. A series of channels or jetties or similar structures could be constructed near the downstream riprap extent to direct flow away from the berms and discourage flow concentration along the berm toe.

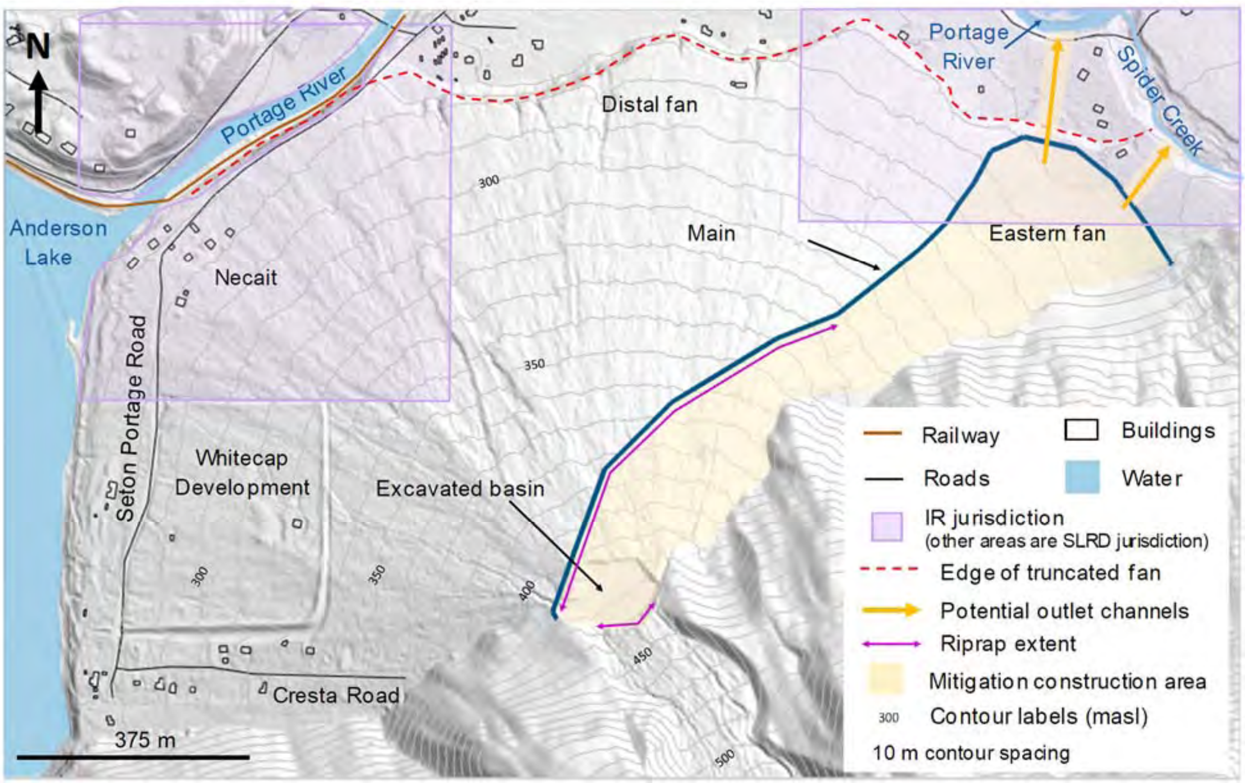


Figure 4-5. Bear and Pete's Creek mitigation Option 2 – basin and east diversion.

This option involves a more substantial diversion of Bear and Pete's creeks from their current primary drainage paths than Option 1, which raises three main issues. First, there is the issue of how to transfer water from the eastern fan to Portage River. Outlet structure(s) and channel(s) would be required to pass water through the northern berm limits into Spider Creek or Portage River. These channels would likely be located adjacent to existing houses, and may exacerbate or complicate the bank erosion issues affecting the road located at the Portage River cut bank.

These hydraulic structures would need to be designed to pass water from clearwater and debris flow events, and the hydraulic capacity of Spider Creek may need to be increased. Second, the upstream portion of the main berm would be more vulnerable to erosion compared to berms proposed for other options because of the abrupt change in flow direction near the fan apex. The third issue is potential risk transfer to residents near Spider Creek. BGC interprets this to be the fan area least susceptible to debris flows under current conditions.

4.7.6. Option 3: Basin and Distal Berms

The third option involves a basin and berm system, including (Figure 4-6):

1. **South berm** to divert flows away from the Whitecap Development and Cresta Road.
2. **Distal berms:**
    a. **Necait berm** to protect the properties at Necait.
    b. **Seton berm** to protect properties in the main town of Seton Portage.
    c. **Spider berm** to protect the properties near Spider Creek.

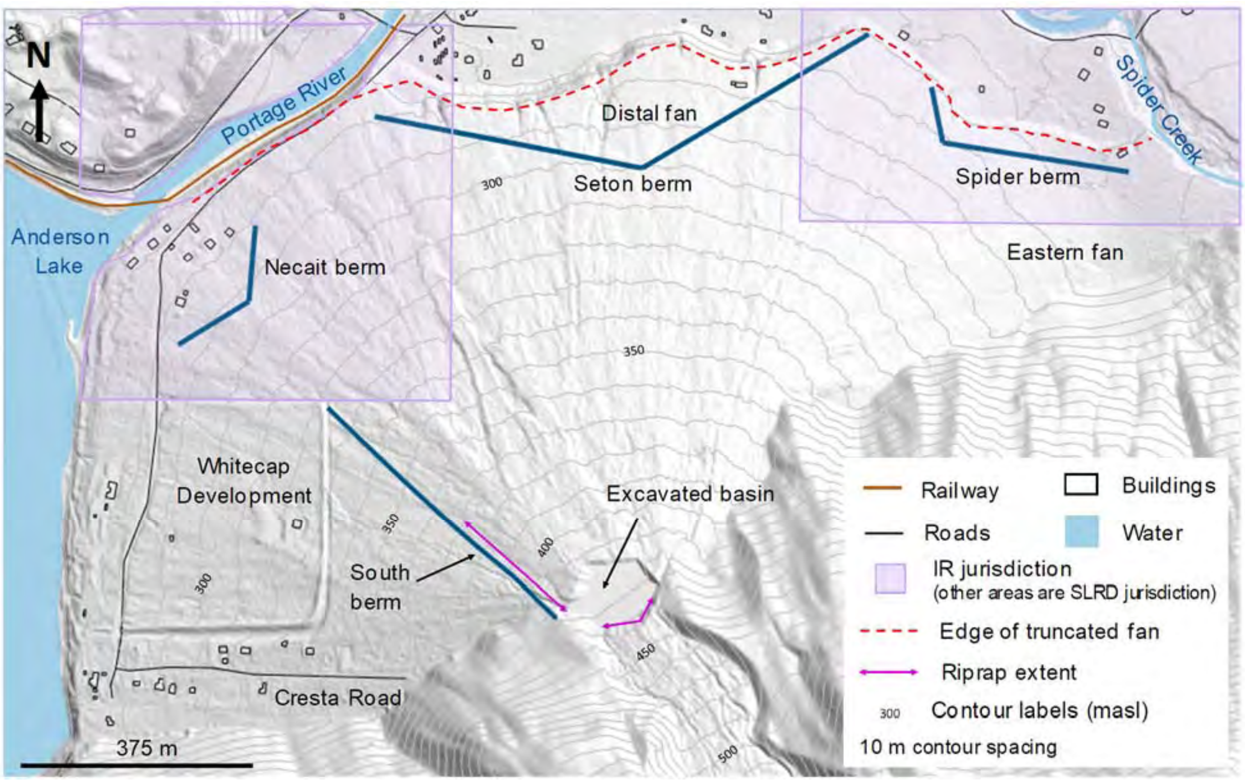


Figure 4-6. Bear and Pete's Creek mitigation Option 3 – basin and distal berms.

The following geometry is proposed for the system:

- Berms: generally 3 m minimum height and locally up to 5 m high on the upstream face, with a minimum 4 m crest width and 1.5H:1V side slopes
- Basin: capacity of about 80,000 m^3; which was selected based on DAN3D modelling of the design event flowing through different basin sizes.

The cost estimate assumes that the downstream edge of the basin is horizontal, without a defined outlet structure or channel. Debris flows would be allowed to overtop the basin in any direction, and the flow path out of the basin could vary between events.

Figure 4-7 shows a possible cross-section of the distal berms, assuming a 3 m high retention berm with 1.5H:1V side slopes. The berms are oriented along an a low-gradient (near-horizontal) alignment, and are intended to retain rather than divert flows. Erosion protection of the berm face is not included to save construction costs. Erosion of the berms is interpreted to be tolerable because the berms are located on the distal fan and flow is not concentrated along the berm alignment.

The 2016 debris flow that intersected and overtopped the Whitecap Development berm is interpreted to demonstrate the typical behavior of flows that intersect a berm. When a flow intersects the berm, it spreads laterally a short distance, but overtops the berms before filling in the full area behind the berm. No significant erosion of the berm toe or crest was observed. As an example, BGC estimates the Seton Berm (900 m length) can retain only about 16,000 m^3 of debris before overtopping when impacted by a 100 m wide debris flow that spreads laterally upon impacting the berm.

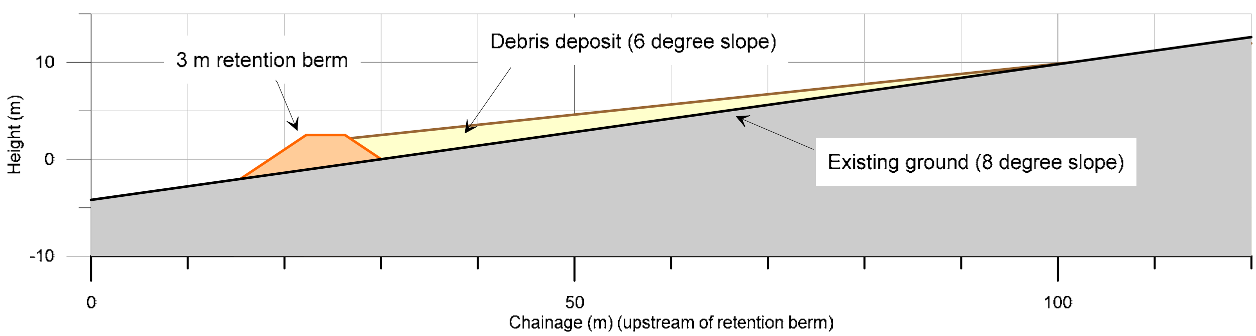


Figure 4-7. Cross-section of the Option 3 distal berm and excavation.

The primary advantage of this option is that flows are unconfined (which encourages deposition) and nearly the full fan surface is available for deposition. There is less potential for risk transfer compared to other options because larger flows are not diverted. Also, there is less potential for erosion of most berms because they are located on the distal fan and they are positioned to capture flow rather than divert along the berm toe. This will reduce the cost of necessary berm erosion protection compared to other options.

The primary disadvantage of Option 3 is the total length of the three distal berms. The proposed berm stretches from Necait all the way to Spider Creek, for a total distance of about 1.5 km. Including the 600-m long south berm, the total berm length is about 2.2 km. This extent is necessary because a debris flow could impact anywhere on the fan perimeter. Hence, extensive berm lengths are required to block an event that may only be 100 m wide.

If this option is selected, future design stages will need to consider the gaps between the berms where material could flow to Portage River. There are at least three options: 1. Leave the gap open, as shown, and accept higher hazard potential in these areas; 2. Leave the gap open, as shown, and impose development restrictions in areas with higher hazard potential; 3. Align the ends of the berms to direct flow to a designated channel that carries water and debris to Portage River.

4.7.7. Technical Issues for Future Consideration

The following technical issues should be considered during future options comparison and design stages:

- Non-Structural Measures
  - Options – Non-structural mitigation measures listed in Section 3.7.3 should be considered in parallel with structural measures.
- Construction Costs and Residual Risk
  - Design event – If the construction cost estimate exceeds the available budget, a smaller design event could be chosen. The length of the berms is largely independent of the design event; however, the berm height and basin volume could be reduced.
  - Residual risk assessment – A residual risk assessment should be included as part of all future cost optimization and design selection studies. One goal should be to minimize residual risk within the available budget. All of the options presented here address the same design event, which is the largest event considered in this study. Each has a similar residual risk that is related to larger, less-likely events.
  - Staged construction – It may be possible to construct berms, channels, and basins incrementally as funds become available. Similarly, berm extent could be increased using material that is excavated from the sediment basin during routine maintenance. Berms would need to be constructed in a sequence that avoids risk transfer. Option 3 is likely to be the most adaptable to a staged construction approach without risk transfer.
- Engineering Issues
  - Water management – the location of the normal stream flow outlet to Portage River is uncertain under current conditions, and the degree to which flow infiltrates to the sub-surface is unknown. The debris-flow mitigation works should avoid disturbing normal stream flow and infiltration, or should provide a channel to Anderson Lake or Portage River. Water will need to be conveyed before, during, and immediately after debris-flow events. Water management and outlet structure design for Option 2 are especially critical considerations.
  - Debris basin design – The debris basin design considered for the cost estimate seeks to minimize construction cost. Many design details require review, and tradeoffs between construction cost, maintenance costs, performance, and environmental impact should be considered. Important issues include:

management of typical water flow; inclusion or omission of an outlet structure and outlet channel; outlet channel to Anderson Lake; erosion protection.

  - Erosion protection – Erosion protection is expensive, and standard methods for riprap design are not applicable to debris-flow channels. The design should seek to balance cost and performance. It may be acceptable for some elements to be unlined, allowing erosion to occur. This could include channels excavated into the fan surface, basin walls, and retention berms on the distal fan. Alternatives to riprap (for example logs, soil-cement mixtures) should also be explored. In addition, BGC understands that the band is exploring options for obtaining discounted riprap, which could decrease the costs of the mitigation options presented here.
  - Berm heights – Berm heights presented in this report are conceptual. Berm heights should be selected based on the estimated design event flow depths, runup, deposition thickness, and freeboard.
  - Climate change – Designs should consider that climate change may increase the frequency and magnitude of debris flow events.
- Environmental Issues
  - Environmental assessment – An environmental review of the project area and the selected design will be needed for environmental applications and permitting. The most significant environmental impacts are expected to be related to extensive tree clearing and potential flow diversion. It is not clear if some portions of the fan have greater environmental value than others, but this could affect the berm layout selection.
  - Tree clearing – Construction of access roads, basins, channels, and berms will require tree clearing across large portions of the fan. All options clear trees near the fan apex. Each option affects the distal fan differently.
  - Flow diversion – The mitigation measures are likely to cause flow diversion before, during, or after a debris flow.
- Land and Stakeholder Issues
  - Land tenure – Land ownership or right-of-way will need to be established for the design footprint, access roads, and disposal sites.
  - Archaeological sites – The extent of the pit house foundations, graveyard, and other archaeological sites should be identified and considered during layout of mitigation elements.
  - Irrigation – The mitigation measures may change the volume of water that arrives at existing irrigation ditches.
  - Future development – Future development plans have not been considered in the conceptual design options. Development on the fan could be restricted as

a risk management measure or mitigation structures could be constructed to protect specific development areas. The level of protection needed to protect new development is typically greater than needed for existing development.

- Regulatory approval - Any work adjacent to the Whitecap development berm may require Dike Maintenance Act (DMA) approval. Any new dike and/or berm not on First Nations lands would require DMA approvals. Options that direct flows into the river or lake may be subject to review by Environment Canada or the Department of Fisheries and Oceans. Regulatory requirements and challenges would be considered as part of the more detailed options assessment process.
- Ownership - Likely would require an entity hold a license under the Water Sustainability Act (WSA) for the watercourse diversions.

- Operations and Maintenance
    - Operations and maintenance (O&M) – The authority responsible for O&M needs to be determined. A manual should be prepared describing the requirements for the final constructed works.
    - Financial considerations – The measures require regular maintenance, debris removal, and restoration following debris-flow events. There needs to be an appropriate long-term mechanism to cover these costs.
    - Access – All work need to have land tenure and equipment access for future maintenance and restoration.
    - Sediment disposal – The sediment basin will require perpetual maintenance to remove gradual sediment build-up and sediment deposited by debris flows. A suitable disposal location for sediment and large woody debris will need to be identified. It may be possible to add this sediment to berms, to increase berm thickness, height, or extent.

4.7.8. Cost Estimate

Table 4-11 provides a conceptual-level cost estimate for the Bear and Pete's Creek mitigation options. These are order of magnitude estimates, with expected variance from approximately -50% to +100%. The estimates are developed to support a comparison between options, and should not be used to set budgets for the mitigation works.

Each cost estimate is based on estimated quantities (e.g., volume of earthworks) and an assumed unit cost (Appendix I). More detailed cost estimates should be developed at the next stage of design, based on updated quantities determined for the selected design option, and improved unit cost estimates. Costs associated with operations and maintenance of the mitigation options have not been estimated, but may be a significant consideration.

Table 4-11. Conceptual-level cost estimate for Bear and Pete's Creek mitigation options.

Proposed Option	Cost ($CAD)
1 – Basin and Anderson Lake conveyance	$8.0 million
2 – Basin and diversion to eastern fan	$8.0 million
3 – Basin and distal berms	$7.3 million

These estimated costs may exceed the available budget for mitigation construction. Opportunities to reduce these costs may include:

- Selecting a smaller design event and tolerating higher residual risk, or managing residual risk with non-structural measures
- Optimizing the mitigation design geometry during the layout and detailed design stages, considering cut and fill balance, and the relative effectiveness of basin, channel and berm elements
- Minimizing the use of riprap; investigating options to reduce the unit rate of riprap, and considering other erosion protection options.

The main message of this cost estimate is that the three options have similar estimated costs, and that a preferred option cannot be selected based on cost alone. Instead, other operational and social factors should be accounted for when comparing options.

4.7.9. Option Comparison

Table 4-12 compares the three options. In cases where there is a clear preference, green shading indicates the preferred option or options for each criterion.

Table 4-12. Comparison of Bear and Pete's Creek debris-flow mitigation options.

Criteria	Option 1 Anderson Lake Conveyance	Option 2 Diversion	Option 3 Basin and Distal Berms
Cost	$8.0 million	$8.0 million	$7.3 million
Risk transfer	Potential risk transfer to properties at Necait, and cutoff road access to Cresta Road area following event.	Potential risk transfer to properties near Spider Creek	Potential for risk transfer is less than other options
Operation and maintenance	Berms and basin will require maintenance after most flows	Berm and basin will require maintenance after most flows	Berms and basin will require maintenance after most flows
Cultural impacts	Potential impacts to graveyard and pit houses	No known cultural impacts	No known cultural impacts

Criteria	Option 1 Anderson Lake Conveyance	Option 2 Diversion	Option 3 Basin and Distal Berms
Design flexibility	Outlet location and width at Anderson Lake is constrained by graveyard and pit houses. Berm and basin sizes can be modified.	Extent of berms and debris flow retention area is constrained by topography and existing development. Berm and basin sizes can be modified.	Most flexible. Berm heights and extents can be increased if additional funding or resources become available. Incremental construction is possible.
Design uncertainties	Potential for overtopping of the north berm and risk transfer to Necait.	Sharp channel bend required to divert flows to the eastern fan, which could erode or overtop. Potential for risk transfer to buildings near Spider Creek	Potential for distal fan retention berms to overtop.

Based on this comparison, BGC suggests that Option 3 is preferable. BGC encourages the completion of an inclusive, stakeholder-focused options comparison process to ensure that the mitigation design is in line with the preferences of the Seton Portage community. It may be possible to partially combine options, particularly Options 1 and 3.

4.8. Summary

Bear Creek and its tributary watershed Pete's Creek are subject to debris flows. Debris flows with return periods between 10 and 30 years can reach developed areas on and around the edges of the fan. Debris flows with higher return periods are very likely to travel to and beyond the sharply defined fan edge where they can lead to damage and potentially loss of life.

Seton Portage exists due to a dynamic interaction mostly between Whitecap and Bear Creek. This interaction is manifested in extremes. High magnitude debris floods on Whitecap Creek can divert Portage River into the presently developed areas along Seton Portage Road. Such floods are believed to have led to the over-steepening of the fan edge of Bear Creek in the past. Large debris flows on Bear Creek, however, can mimic this effect and in turn push Portage River back towards the north closer to its present position. A wealth of information was gathered that allowed our team to reconstruct debris flows back some 4500 years until the present.

The risk assessment indicates that up to 30 persons could lose their lives in a single debris flow (the 1000 to 3000-year event). The risk assessment for individuals suggests that 59 structures exceed risk tolerance criteria developed and applied elsewhere. For group risk which describes the total risk to all people affected for all debris-flow scenarios, we conclude that it well exceeds commonly accepted risk thresholds. These findings suggest that mitigation measures are in order to reduce risk to tolerable levels.

Three potential risk reduction measures were compared. Two of those divert water and debris either towards the west into Anderson Lake, or to the east towards the joining fans of Bear and

Spider creeks. One option aims to capture debris closer to the fan edge. Upon comparison of these options, Option 3 appears to be favoured.

5.0 WHITECAP CREEK

5.1. Introduction

This section provides the frequency-magnitude relationship of Whitecap Creek debris floods. Hazard intensity maps are developed based on numerical modeling and bank erosion potential. Safety and economic risks are assessed and possible mitigation measures are discussed.

5.2. Previous Events on Whitecap Creek

5.2.1. Documented Events

Whitecap Creek is prone to debris floods. Appendix A and D provide details of previously recorded events. In summary, events were noted in the 1920 to 40s, in 1973 or 1974, two in the 1980s as well as in 2015 and 2016. This suggests a debris-flood return period of approximately 14 years.

5.2.2. Air Photo Interpretation

Air photograph interpretation was completed for 10 aerial image sets dating between 1948 and 2012 (Drawings 07 and 08). A summary is provided in Appendix D. The 1974 air photos document an avulsion and confirm the 1973 to 1974 event documented above. Also, an avulsion visible on the 1987 air photos is consistent with the historical record.

5.2.3. Dendrogeomorphology

Eleven possible debris-flood dates were inferred from the dendrogeomorphology analysis on Whitecap Creek, with an approximate return period of 11 years over the period of record dating back to the 1890s. The trees sampled corroborated several of the events that were identified in the air photographs and historical records, including the events in the 1970s and 1980s. Events were also identified in 1936 and 1945, one of which may correspond to the lake-dropping incident on Seton Lake (described in Appendices A and D). The detailed results of the analysis are presented in Appendix D.

5.2.4. November 2016 Event Reconstruction

BGC reconstructed the approximate peak discharge and volume of the November 8, 2016 debris flood. Details of the event reconstruction are presented in Appendix D. The peak discharge ranged between 80 and 160 m^3/s with an average of 120 m^3/s. Using this discharge, the F-M relationship presented in Section 5.3 suggests a return period for the event of between 30 and 100 years.

The approximate depth of the deposit is estimated between 1.0 and 1.5 m: the resultant sediment volume was between 36,000 m^3 and 54,000 m^3, with an estimated average of 45,000 m^3. This volume suggests the high end of a 30 to 100-year event.

From reports and descriptions, the 2015 event also had a similar debris volume but with an unknown peak discharge. The occurrence of two 30 to 100-year events in subsequent years is a reminder that debris floods are independent processes on Whitecap Creek; the occurrence of a large event in one year does not preclude the occurrence of a similar or even larger event the next year.

5.3. Frequency-Magnitude Relationship

Details about the development of the F-M relationship are presented in Appendix D. The following key results were obtained from the different methods employed:

- Small debris floods occur on Whitecap Creek with a return period of about 10 years
- LDOFs are possible in the Whitecap Creek watershed, and are assumed to contribute to the magnitude of the higher return period events (>100 years)
- Debris volumes are considerably smaller than those of Bear Creek, which is due to very different sediment supply and transport processes
- Sufficient sediment is present in the Whitecap Creek watershed to initiate debris floods whenever a critical discharge threshold is exceeded.

Table 5-1 summarizes the frequency-magnitude relationship that was developed for Whitecap Creek.

Table 5-1. Whitecap Creek frequency-magnitude relationship for debris floods.

Return Period (T) (years)	Annual Probability (%)	Sediment Volume Best Estimate (m^3)	Clear Water Flood Peak Discharge (m^3/s)	Debris-Flood Peak Discharge (m^3/s)	Process
10 to 30	3 to 10	30,000	60	60	Debris Flood
30 to 100	1 to 3	38,000	130	130	Debris Flood
100 to 300	0.3 to 1	46,000	230	275	Small LDOF
300 to 1000	0.1 to 0.03	59,000	340	410	Small LDOF
1000 to 3000	0.03 to 0.01	66,000	395	600	Large LDOF

The F-M relationship established above is based on stationary conditions. Those imply that the relationship between the frequency and magnitude of debris floods is approximately constant. Human caused climate change, however, is challenging this assumption and is thus discussed below.

5.3.1. Impacts of Climate Change

With climate change, Whitecap Creek is projected to be subject to a substantial increase in the frequency of extreme rainfall events and a moderate increase in their magnitude (intensity) (see Appendix J). In addition, higher temperatures and a drying trend during summer will likely make the forests covering most of the Whitecap Creek watershed more susceptible to wildfires. Wildfires decrease the moisture update by trees and the duff layer at the forest floor and rainwater during storms and snowmelt can run off more rapidly. These conditions increase the volume of runoff, make runoff "flashier" (higher and narrower hydrograph peaks) and introduce additional sediment to the creek. In combination, these effects will likely increase both the frequency as well as the magnitude of debris floods on the Whitecap Creek fan. Those increases are still very difficult to quantify given the state of climate modeling and, most importantly, its translation into a debris-flood F-M relationship. This topic is the focus of ongoing research between BGC and the Pacific Climate Impacts Consortium (PCIC). The manifestation of climate change effects is also strongly dependent on which so-called "Relative Concentration Path" (RCP) scenario will come to fruition over the course of this century. RCPs describe scenarios of how much greenhouse gases will be released by humans as well as the feedback mechanism in the climate system that can enhance, or (less likely) reduce the greenhouse effect.

Given the projected increase in rainfall intensity, BGC believes that debris floods will likely become more frequent at Whitecap Creek over time, as sufficient sediment is present in the watershed to initiate debris floods whenever a critical discharge threshold is exceeded. Today's 10 to 30-year return period debris flood, by the end of the century, could become a 3 to 10-year return period event. The magnitude (peak discharge and sediment transported) would also likely increase, but given the episodic nature of sediment supply and or LDOFs, this potential increase is very difficult to estimate with any degree of confidence.

Should mitigation be decided on at some point in time, some climate-change resiliency should be considered during the design stage.

5.4. Hazard Analysis

5.4.1. Introduction

The hazard analysis described here involves three distinct steps: First, debris floods were modeled to determine their runout distance, area inundated, flow depth and potential impact to Portage River. Second, given that Whitecap Creek is highly susceptible to bank erosion, bank erosion was estimated for different return periods. Third, the combined hazards from debris-flood inundation and bank erosion were used to generate a single "composite hazard map" to inform the risk assessment and mitigation design.

5.4.2. Hydrodynamic Modelling

Numerical modelling of debris floods was the basis for the delineation of hazard intensity (maximum flow depth and velocity) zones which served as input to the QRA.

Peak flows for the five return period classes (i.e., Table 5-1) were routed downstream using the commercially available two-dimensional hydraulic model, FLO-2D (2007). Details of the model are provided in Appendix G. FLO-2D is suited for this type of application as it can model unconfined flows across fan surfaces. It has been applied numerous times worldwide and is on the U.S. Federal Emergency Management Agency's (FEMA's) list of approved hydraulic models. Its limitations include the model's inability to simulate sediment transport and deposition (including remobilization of sediment by subsequent surges) and bank erosion.

Model outputs include grid cells showing the velocity, depth, and extent of debris-flood scenarios. These outputs are imported into a GIS and overlaid on base maps. Results of the modelling are shown in Appendix G, Drawings G06 to G10. For areas with low flow velocity (< 1 m/s), only flow depths are shown. For areas of higher velocity (≥ 1 m/s), a flow "intensity" index (I_{DF}) is shown, calculated as modelled flow depth multiplied by the square of flow velocity (Jakob et al. 2012). This intensity parameter was chosen as it is useful to characterize the destructive potential of modelled flows. Key modeling results are summarized in Table 5-2; additional details are provided in Appendix G.

Table 5-2. Results from numerical debris flood modelling based on the 2017 LiDAR-generated DEM and interpretations by BGC.

Return Period (Years)	Whitecap Creek
10-30	• Flow stays mostly in the current channel but substantial amount of sediment is expected to reach Portage River. Low chance of Portage River damming. • Camp ground will be inundated with shallow (< 1 m water) • Bank to bank flooding near Whitecap Creek bridge. • Minor (< 6 m) bank erosion along Whitecap Creek channel. • Whitecap Creek bridge will likely survive.
30-100	• Flow stays mostly in the current channel but substantial amount of sediment is expected to reach Portage River. Moderate to high chance of Portage River damming. • Some bank erosion on the south bank of Portage River. • Bankfull flooding near Whitecap Creek bridge. • Whitecap Creek bridge may be outflanked or abutments eroded.
100-300	• Flow covers lower terraces and large volumes (10s of thousand of m^3) are expected to reach Portage River. High chance of Portage River damming. • Substantial bank erosion on the south bank of Portage River expected once dam breaches. • Whitecap Creek bridge likely to be outflanked or abutments eroded, leading to bridge collapse
300-1000	• Flow begins to cover upper terraces (TDC offices and BC Hydro cabins) • Substantial bank erosion on the south bank of Portage River expected once dam breaches • Whitecap Creek bridge very likely to be outflanked, abutments eroded, leading to bridge collapse, or covered by debris • Moderate chance of Portage River being diverted onto its floodplain
1000-3000	• Flow is likely to cover upper terraces (TDC offices and BC Hydro cabins) • Large volumes of sediment entrained and likely eroded from fan margins • Whitecap Creek bridge very likely to be destroyed • High chance of Portage River being diverted onto its floodplain

5.4.3. Bank Erosion Assessment

Bank erosion was estimated for debris flood events using the methods described in Section 3.4. The bank erosion analysis was conducted for the range of events presented in Table 5-1. The modeled discharge varied from 80 m^3/s during a 10-year flood event, to 590 m^3/s during a 1000-year debris flood resulting from a large LDOF event. The lower 600 m of Whitecap Creek was divided into eight reaches based on differences in channel width, slope, and sediment size. Bank erosion was estimated in each reach for each return period event, producing a range of erosion estimates for each return period (Table 5-3). The estimates for each reach were also used to generate the erosion contours shown in Drawings 06 to 10.

The bank erosion estimates were compared to those observed for the 2015 and 2016 debris floods. Unfortunately, there are no systematic measurements available, but photographs indicate bank erosion in the order of several metres, but clearly less than 20 m. According to Table 5-3 this would place the return period of bank erosion likely in the 10 to 30 years.

Table 5-3. Bank erosion estimates on the Whitecap Creek fan. Bank erosion figures are rounded.

Return Period (T) (years)	Annual Probability (%)	Debris Flood Peak Discharge (m^3/s)	Bank Erosion (m)[1]	Comments
10	10	60	0 – 8 (0)	Minor erosion is predicted.
30	3	130	0 – 20 (6)	Erosion confined to the existing floodplain.
100	1	275	20 – 40 (30)	Erosion mostly confined to the modern fan boundary.
300	0.03	410	40 – 70 (50)	Some erosion predicted to occur on terraces adjacent to the modern fan (high uncertainty).
1000	0.01	600	70 – 120 (110)	Widespread erosion; significant erosion predicted to occur on terraces adjacent to the modern fan (high uncertainty).

Note:
1. Median estimated value provided in brackets.

5.4.4. Composite Hazard Map

Drawing 13 illustrates the combined model scenarios for all return period classes, plotting the maximum estimated debris-flood intensity values from all model runs. Hazard zone boundaries are manually delineated and smoothed from the modelled intensity output.

5.4.5. Uncertainties

Uncertainties associated with debris flood modeling are summarized in Appendix G. This section focuses on specific uncertainties related to Portage River flooding.

As noted in Appendix D and G, modeling of debris floods on Whitecap Creek did not include separate modeling of potential outburst floods on Portage River, nor did it include the potential of Portage River to avulse completely and find a new stream bed through the Seton Portage area.

The former is unlikely to be of substantial consequence as an impoundment from a debris flood is wide and relatively shallow which implies gradual overtopping rather than an abrupt outburst. Given that Portage River is reasonably well incised downstream of the confluence with Whitecap Creek to the Seton Portage Road bridge, little overbank flooding is expected.

The latter would result in considerable damage to Seton Portage, perhaps comparable in terms of economic losses with a 1000 to 3000-year return period debris flow from Bear Creek. However, the return period of such event is very difficult to estimate and the process chain difficult to model reliably. Such an effort would introduce substantial uncertainty to the outcome of the risk assessment. Notwithstanding, it is critical for all stakeholders to understand that the possibility exists. For example, should a large (> ~ 100,000 m^3) landslide occur in the upper Whitecap Creek watershed and impound the creek, or should there be a large stand-replacing fire in the lower Whitecap Creek watershed, Seton Portage should be prepared for the possibility of such a major avulsion event occurring. Emergency preparedness could involve the preparation of heavy machinery that could be deployed at short notice and having a plan for monitoring.

Hazard maps represent a snapshot in time; conditions will change after each subsequent event, or with the construction of mitigation measures and other structures. Modeling and maps will therefore need to be updated either after significant sedimentation events, or significant construction on the fan or along the stream channels.

5.5. Risk Analysis

This section summarizes results of the Whitecap Creek risk assessment based on the methods described in Appendix H. Risk to the campground upstream of the TDC offices was not assessed due to lack of occupancy data. However, BGC's analysis suggests that the camp ground could be inundated by a 10 to 30-year event, and suffer severe bank erosion for a 100-year event that may affect most of the current camp ground's footprint (see Drawing G07). The risk analysis includes the impacts to Portage River due to a debris flood event on Whitecap Creek.

5.5.1. Individual Safety Risk

One parcel (the 100 Anderson Lake residence located on the lower active fan south of Anderson Lake Road) exceeded the individual risk tolerance threshold of 1:10,000 ($1x10^{-4}$) for existing developments (Drawing 15). BGC understands the Tsal'alh plan to move this residence in Spring of 2018.

5.5.2. Group Safety Risk

While the potential for loss of life cannot be entirely ruled out, fatalities were not estimated for any single debris-flood scenario. Debris flood risk was estimated as falling within the tolerable range according to the risk tolerance criteria presented in Section 3.6.2.

The risk to camp ground users upstream of the TDC offices on Whitecap Creek fan was not assessed as there are no data on usage. While camping during dry weather poses little risk, even a localized thunderstorm in the summer in the upper watershed could lead to a sudden flood which could jeopardize the safety of campground users either by inundation or bank erosion. As a mitigative measure, the campground could be permanently closed or signs be placed that discourage use of the campground during wet weather.

5.5.3. Economic Risk

This section describes economic risk from building damage and interruption to business activity.

Building Damage

Table 5-4 summarizes building consequence estimates for each scenario, including the number of buildings affected and total building damage costs. For reference, the total estimated building value for the Whitecap Creek study area is approximately $3.5 million. Average annualized building damage is approximately $8,300 based on the scenario damage costs listed in Table 5-4. Estimated building damage costs are based only on a portion of assessed building values and do not include damage to contents or inventory. In addition, costs of cleanup and recovery are not included.

Table 5-4. Summary of estimated building damage for Whitecap Creek.

Scenario	Frequency (1:years)	Number of Buildings Affected by Debris Floods	Number of Buildings Affected by Bank Erosion	Building Damage Cost ($)
1	1:10 to 1:30	5	-	20,000
2	1:30 to 1:100	12	1	60,000
3	1:100 to 1:300	27	5	510,000
4	1:300 to 1:1000	38	5	540,000
5	1:1000 to 1:3000	44	5	640,000

Business Activity

Table 5-5 summarizes business activity impacts for business located within the study area. BGC mapped the distribution of business activity in the study area by estimating the total annual revenue for each building identified as containing businesses.

Based on the data available, it is not possible to determine the vulnerability of businesses to complete loss of function, and associated economic cost, due to debris flood impacts. For example, a retail store could suffer loss of inventory and business function, whereas a business generating revenue elsewhere could suffer office-related damages without necessarily losing their source of revenue.

As a proxy for level of business impact, BGC summed the annual revenue estimated for parcels impacted by a debris-flood scenario. Additional factors such as indirect losses, damages to business equipment or inventory, interruption of transportation corridors, or effects of prolonged outage were not estimated.

Table 5-5. Summary of business consequence estimates on Whitecap Creek.

Scenario	Frequency (1:years)	Number of Businesses Affected	Number of Employees Affected	Annual Business Revenue ($)
1	1:10 to 1:30	-	-	-
2	1:30 to 1:100	3	18	320,000
3	1:100 to 1:300	3	18	320,000
4	1:300 to 1:1000	3	18	320,000
5	1:1000 to 1:3000	3	18	320,000

Note:
1. All three of six businesses are located within the same building.

5.5.4. Critical Facilities and Lifelines

This section summarizes critical facilities and lifelines (roads, bridges) located within the debris-flow impact zones that may suffer loss of function following impact.

Of the critical facilities identified in Section 2.5, only the Canada Post/Corner Store/Restaurant building is impacted by the 30 to 100-year and higher return period events at intensities (I_{DF})<1. More detailed assessment of the level of damage and functionality of the critical facility once impacted is beyond the scope of this assessment.

Table 5-6 lists lifelines (roads, railway and bridges) impacted by debris-flood scenarios. The level of damage and functionality of these lifelines once impacted is beyond the scope of this assessment. In the emergency response period, evacuation and road closures may also extend beyond the areas directly impacted.

Table 5-6. Summary of roads and bridges impacted by debris flood scenarios of Whitecap Creek.

Lifeline		Scenario				
		1	2	3	4	5
Roads	Anderson Lake Road	✓	✓	✓	✓	✓
	Broadhead Road	✓	✓	✓	✓	✓
	Bull Alley			✓	✓	✓
	Cresta Road					
	Edwards Road		✓	✓	✓	✓
	Scott Road					
	Seton Portage Road	✓	✓	✓	✓	✓
	Spider Creek Road			✓	✓	✓
	Whitecap Access Road	✓	✓	✓	✓	✓
	Williams Lane					
Railway	CN Rail		✓	✓	✓	✓
Bridges	Anderson Lake Road Bridge	✓	✓	✓	✓	✓
	Seton Portage Road Bridge	✓	✓	✓	✓	✓

5.6. Conceptual Mitigation Design

5.6.1. Design Considerations

The objective of debris flood mitigation options proposed by BGC is to reduce the likelihood and duration of closure of Anderson Lake Road. Further discussion is needed with stakeholders to confirm this objective. The provided mitigation options do not address the following issues:

- Safety risk – Safety risk is tolerable if the 100 Anderson Lake Road residence is relocated.
- Economic risk – The cost of alternative mitigation options exceeds the value of the buildings at risk.

Table 5-7 presents the basis for the proposed Whitecap Creek mitigation designs. The items listed describe the design objectives, constraints and assumptions that were used to compare design options.

Table 5-7. Whitecap Creek debris-flood mitigation design basis summary.

Consideration	Design Notes
Geohazard types	Presented mitigation options are focused on limiting flood and debris-flood risks.
Design objective	The primary design objective is to maintain access along Anderson Lake Road as much as possible. There is alternate access to Seton Portage along Mission Mountain Road from Lillooet.
Elements at risk	Elements at risk include: • TDC office and cabins • Access road to TDC office (including bridge) • Campground on the upper fan • Anderson Lake Road • Railroad (located on the other side of Portage River)
Risk transfer	Mitigation measures should not increase the life loss risk or economic risk of floods or debris floods for any existing elements at risk on the fan.
Conceptual design level	Conceptual-level design options were developed. The intent of this design stage was to identify technically feasible options for further review and consideration.
Design event	The 30 to 100-year event was selected as the design event, similar to the size of both the 2015 and 2016 events, and the design standard for typical forest service road bridges. The modelled flow depths near Anderson Lake Road are between 1 and 1.5 m. The estimated peak discharge is 130 m^3/s.
Maintenance	All mitigation options presented require routine maintenance. The designs assume this maintenance will occur as needed. Maintenance and restoration of channels, berms and erosion protection may be required following debris floods and annual peak flow events.
Topography	The layout of mitigation options is based primarily on interpretation of topography from a LiDAR-derived digital elevation model. The LiDAR was collected on September 22, 2017.
Geotechnical conditions	Geotechnical conditions have not been assessed. BGC has made the following assumptions for conceptual design purposes: • Groundwater will not be encountered in shallow excavations • The fan is composed of sand and gravel (trace silt and clay), which can be reused as berm fill • Bedrock will not be encountered in excavations
Construction materials	Where possible, the designs make use of existing on-site materials and features, including the re-use of excavated fan material for berm construction.

5.6.2. Proposed Mitigation Options

Given the constraints above, the following options are presented to mitigate the debris-flood risk on Whitecap Creek:

1. **Option 1: Short Berm** to divert flows from Anderson Lake Road.
2. **Option 2: Long Berm** along the creek to prevent avulsions (similar to the NHC concept presented after the 2015 event, see Appendix A).
3. **Option 3: Event Response** – Maintain the road and Portage River after each event.

Options 1 and 2 are shown in Figure 5-1. The mitigation alignments and geometries are conceptual, and should be used for option comparison purposes only. Additional details are included in the following sections.

In addition to these measures, BGC also recommends posting warning and educational signs in the campground or permanently closing the campground (Figure 5-1). If campers are allowed, they should be advised to leave the area during times of heavy rain.

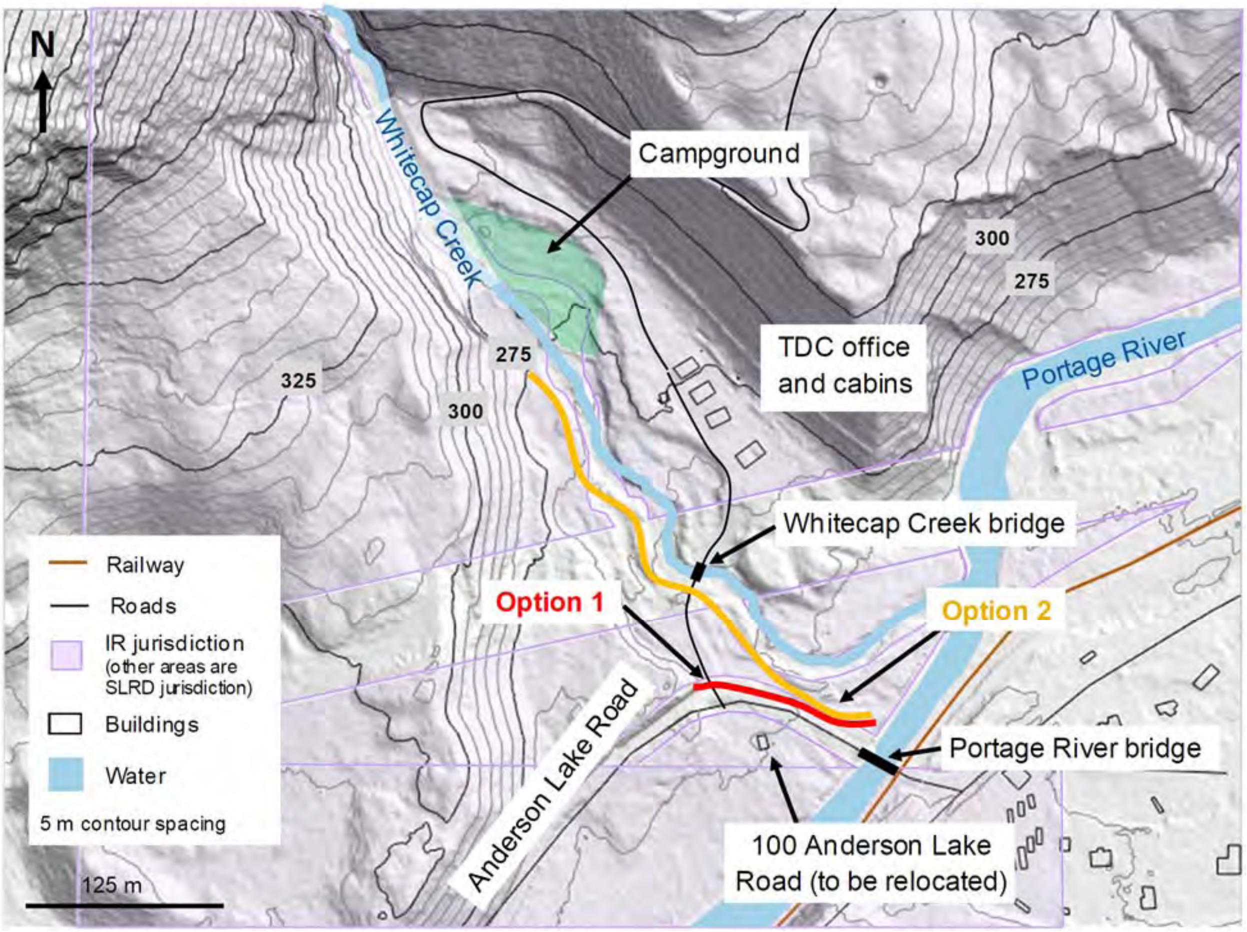


Figure 5-1. Whitecap Creek mitigation options including a short berm along the road (red) or a longer berm that prevents against avulsions (orange).

Option 1 – Short Berm

In this option, a low berm is proposed along Anderson Lake Road. The berm could likely be constructed from material sourced from the Whitecap Creek fan, or from the proposed retention basin on Bear and Pete's creeks. For cost estimation purposes, the berm was assumed to be 2 m high with 1.5H:1V side slopes and a minimum 4 m crest width. Geosynthetic reinforced soil (GRS) construction could also be considered to reduce the footprint of the berm. The proposed berm would have riprap on the river (east) side to protect against erosion.

The primary advantages of this option are the short berm length (about 100 m) and the limited confinement of Whitecap Creek, which encourages sediment deposition on the fan and may decrease potential for Portage River blockage and impacts to the railway. The primary disadvantage is the lack of protection for the TDC access road, including the access road bridge, which is currently vulnerable to bank erosion and out-flanking. In addition, this option does not actively protect against damming Portage River. If Portage River were to be impounded, Anderson Lake Road may flood and be blocked, even if the berm functions as designed.

Option 2 – Longer Berm

Option 2 includes a 350-m long berm along the existing channel to reduce avulsion potential, similar to the berm proposed by NHC. The berm would be lined with riprap to protect against erosion.

The primary advantage of Option 2 is the increased protection for portions of the TDC access road and possibly the bridge. However, the increased confinement of Whitecap Creek could also cause undermining of the Whitecap Creek bridge abutments, or overtopping of the bridge if the channel fills with sediment. In addition, the channelization may increase the potential for sediment to block Portage River (compared to Option 1) and could cause flooding on Anderson Lake Road from Portage River. The longer berm length also results in higher relative cost.

Option 3 – Event Response

Option 3 is to clear and maintain Anderson Lake Road following events, as was done following the 2015 and 2016 events. This option would involve developing an emergency management plan in which personnel and equipment could be on-site quickly following a flood event, as soon as flows had decreased and the area is safe. It may also involve maintaining an alternative access route to the TDC office and BC Hydro cabins towards the eastern portion of Seton Portage. BGC hiked part of such a road, but it is overgrown and would require some work to be accessible again. Event response planning will be necessary, even if Option 1 or Option 2 are constructed, because neither berm option protects against damming of Portage River.

The primary advantage of this option is the low cost. Clearing and maintaining the road should not involve significant additional effort, especially if there are already crews on-site to clear a Portage River blockage.

The primary disadvantage is loss of access along Anderson Lake Road until the road section is restored. Seton Portage would need to be accessed via Mission Mountain Road from Lillooet.

5.6.3. Cost Estimate

Table 5-8 provides a conceptual-level cost estimate for the Whitecap Creek mitigation options. The cost estimates are intended for options comparison purposes only.

These are order of magnitude estimates, with expected variance from approximately -50% to +100%. The estimates are developed to support a comparison between options, and should not be used to set budgets for the mitigation works.

Each cost estimate is based on estimated quantities (e.g., volume of earthworks) and an assumed unit cost (Appendix I). More detailed cost estimates should be developed at the next stage of design, based on updated quantities determined for the selected design option, and improved unit cost estimates. Costs associated with operations and maintenance of the mitigation options have not been estimated, but may be a significant consideration.

Table 5-8. Conceptual-level cost estimate for Whitecap Creek mitigation options.

Proposed Option	Construction Cost
1 – Short berm	$290,000
2 – Long berm	$1,070,000
3 – Event response	$0

The maintenance and restoration costs following an event are expected to be similar for all options, and would include debris removal from Whitecap Creek and Portage River channels, erosion protection repair, and restoration of the TDC access road. Option 2 may have the highest maintenance cost of all options due to its longer length.

5.6.4. Discussion

The measures outlined above focus on the protection of Anderson Lake Road. Mitigation that would prevent bank erosion or damming of Portage River would likely cost substantially more than the value of any damage that they would prevent, because the estimated annualized economic damages on the fan are only $8,300/year.

The mitigation solutions proposed for Whitecap Creek involve both structural and nonstructural options. Based on the discussion above, BGC proposes that Option 3 is preferable from a cost-benefit point of view, if the main objective of the design is to prevent or limit closure of Anderson Lake Road. To summarize:

- Alternate access to Seton Portage is available by Mission Mountain Road from Lillooet.
- The 100 Anderson Lake Road residence will be moved from the Whitecap Creek fan in spring 2018.
- Assuming the cabin is moved, there is negligible life loss risk on Whitecap Creek and economic damages are low, so major structural mitigation options are difficult to justify.

- Educational and warning signs should be installed at the campground on the upper fan or the campground should be closed.
- The life-cycle cost of Option 3 is much lower than the costs of Option 1 or 2.
- None of the three options substantially reduce the risk of damming of Portage River, which could cause flooding of Anderson Lake Road, even with the short or long berm in place.
- All options would require additional funding to clear sediment from Portage River, if the river dams.
- If Options 1 or 2 are pursued, future design stages would also need to address many of the technical challenges identified in Section 4.7.7.

The SLRD, Tsal'alh and other organizations should confirm that BGC's assumptions are correct, especially concerning the design objective.

5.7. Summary

Whitecap Creek is subject to debris floods. These events express themselves with particularly high peak flows, especially if the debris flood is triggered by an LDOF. On the fan of Whitecap Creek, debris floods result in fan inundation, bank erosion and channel aggradation both in the creek and Portage River. High flow velocities and transported boulders associated with debris floods can impact buildings, while associated bank erosion can undercut buildings and lead to them toppling into the creek.

High magnitude debris floods on Whitecap Creek could also potentially divert Portage River into the presently developed areas along Seton Portage Road. Such floods are believed to have led to the over-steepening of the fan edge of Bear Creek in the past. Such an event, while not modeled specifically, could create more damage than analyzed in this report. It is thus crucial that some heavy machinery be available during times in which debris floods are likely to occur in order to re-establish the Portage River channel as soon as possible.

The risk assessment indicates that debris flood risk on Whitecap Creek is acceptable for individuals and groups, provided that the 100 Anderson Lake Road residence is relocated. Average annualized building damage is approximately $8,300.

Two structural mitigation options were evaluated (berm construction), with the objective of deflecting debris floods away from the Portage River bridge. Both options would reduce the likelihood of Anderson Lake Road and the Portage River bridge being inundated and the CN railway being eroded. A third option, event response, is preferable from a cost-benefit point of view, if the main objective of the design is to prevent or limit closure of Anderson Lake Road. However, none of the three options substantially reduce the risk of damming of Portage River, which could cause flooding of Anderson Lake Road, even with the short or long berm in place.

Climate change will likely result in a higher frequency of debris floods on Whitecap Creek combined with a moderate increase in debris flood magnitude. In absence of mitigation, this will result in more frequent road closures and potential damming events for Portage River.

6.0 SPIDER CREEK

6.1. Introduction

This chapter presents the results of the Spider Creek hydrogeomorphic assessment. Analysis and modelling of debris floods on Spider Creek showed that even very large, low frequency events were unlikely to impact residential areas. For this reason, risk analysis and mitigation design were not completed for Spider Creek.

6.2. Previous Events on Spider Creek

6.2.1. Documented Events

According to eye witnesses Spider Creek witnessed events in 1961 to 1963 and 1982 or 1983. No other events have been documented historically. Additional details on the events are included in Appendices A and D.

6.2.2. Air Photograph Interpretation

Air photographs between 1948 and 2012 were reviewed to look for evidence of debris floods on Spider Creek (Drawings 07 and 08). Due to the thick vegetation along the stream channel, it was difficult to determine if debris floods had occurred in the channel and the channel planform could not be mapped. A summary of the observations is included in Appendix D.

However, as no events could be discerned though the dense tree canopy, the implication is that there were no events of sufficient magnitude to destroy the riparian vegetation belt. This includes the eye witness accounts of debris floods that reportedly occurred between 1961 and 1963, and 1982 or 1983. Therefore, the return period of damaging events should be adjusted to at least 50 years.

6.2.3. Dendrogeomorphology

Five possible debris-flood dates were inferred from the dendrogeomorphology analysis on Spider Creek, with an approximate return period of 20 years over the period of record dating back to the early 1990s. The detailed results of the analysis are presented in Appendix D.

6.3. Frequency-Magnitude Relationship

The following methods were used to establish the F-M relationship at Spider Creek:

- Dendrochronology to identify debris flood dates within approximately 150 years
- Flood frequency analysis and adjustments for peak discharges associated with debris floods
- LDOF modeling to test if the empirical peak flows appear reasonable.

The F-M relationship of clear water floods and debris floods is summarized in Table 6-1.

Table 6-1. Flood and debris-flood magnitude for different return periods at Spider Creek.

Return Period (years)	Annual Probability (%)	Sediment Volume Best Estimate (m^3)	Clear Water Peak Discharge (m^3/s)	Debris-flood Peak Discharge (m^3/s)	Process
10 to 30	3 to 10	13,000	25	-	Flood
30 to 100	1 to 3	17,000	55	-	Flood
100 to 300	0.3 to 1	20,000	95	140	LDOF
300 to 1000	0.1 to 0.3	24,000	140	290	LDOF
1000 to 10,000[1]	0.1 to 0.01	28,000	165	500 to 1000	LDOF

Note:
1. A 1000 to 10,000-year return period time frame was chosen at Spider Creek watershed because a narrower range could not be defined.

6.4. Impacts of Climate Change

With climate change, Spider Creek, much like Whitecap Creek is subject to a substantial increase in the frequency of extreme rainfall events and a moderate increase in their magnitude (intensity). In addition, higher temperatures and a drying trend during summer will make the forests covering large portions of the Spider Creek watershed more susceptible to wildfires. Those increase the volume of runoff, make runoff "flashier" (higher and narrower hydrograph peaks) and introduce additional sediment to the creek. In combination, these effects will likely increase both the frequency as well as the magnitude of debris floods on Spider Creek. Those increases are still very difficult to quantify given the state of climate modeling and, most importantly, its translation into sediment F-M relationship.

In how far climate change will manifest itself in an increase in either the frequency or magnitude of LDOFs is still very speculative. The reason for the uncertainty is that the effects of higher rainfall rates and more frequent extreme events on deep seated landslides are poorly understood and would require substantial investigation of the potentially unstable rock masses in question. Such investigations, however, could not be justified given the low risk potential on Spider Creek fan. However, with the projected increase in the frequency of high intensity rainfall, and thus runoff, it is possible that the existing landslide in the upper Spider Creek watershed could have more frequent secondary failures leading to more frequent, albeit smaller LDOFs. Those, as BGC's modeling confirms, are unlikely to affect development on the Spider Creek fan.

6.5. Hazard Analysis

Table 6-2 presents the results from Spider Creek hazard analysis, including a description of potential impacts to Spider Creek road and culvert. Larger return period debris floods were modeled with the numerical software package FLO 2D (see Section 3.2.6); model results are shown on Drawing 12. Smaller return periods were not modelled because the flows remain confined within the Spider Creek channel.

Table 6-2. Results from numerical debris flood modelling based on the 2017 LiDAR-generated DEM and interpretations by BGC.

Return Period (Years)	Spider Creek
10-30	• Flow will stay in Spider Creek channel and reach Portage River • Possible blockage of Spider Creek Road culvert
30-100	• Flow will stay in Spider Creek channel and reach Portage River • Portage River possibly being deflected into opposing low-lying floodplain to the North • Likely blockage of Spider Creek. Road culvert and overtopping with access loss
100-300	• Flow will stay in channel and reach Portage River • Portage River likely being deflected into opposing low-lying floodplain to the North • Very likely blockage of Spider Creek Road culvert and overtopping with access loss
300-1000	• Flow will flood lower (undeveloped) terraces • Portage River very likely being deflected into opposing low-lying floodplain to the North • Erosion expected at northern river terraces adjacent to Portage River floodplain • River channel change downstream of confluence • Likely destruction of Spider Ck. Road crossing
1000-10,000	• Flow may overtop paleo-terraces (for 1000 m^3/s scenario only) and impact two structures on the eastern paleofan • Portage River very likely being deflected into opposing low-lying floodplain to the north • Erosion expected at northern river terraces adjacent to Portage River floodplain • Likely destruction of Spider Creek Road crossing

6.5.1. Bank Erosion Assessment

Bank erosion was estimated for the 1000-year return period debris flood using the methods described in Section 3.4. The lower 500 m of Spider Creek was divided into six reaches based on differences in channel width and slope. Bank erosion was estimated for each reach, producing a range of erosion estimates (Table 6-3). The estimates for each reach were also used to generate the erosion contours shown in Drawing 12.

Table 6-3. Bank erosion estimates on the Spider Creek fan.

Return Period (T) (years)	Annual Probability (%)	Debris Flood Peak Discharge (m^3/s)	Bank Erosion (m)[1]	Comments
1000 to 10,000	0.01	600	9 – 55 (40)	Significant erosion; mostly confined to the modern floodplain on the east side of the creek but extends into a portion of the lower Spider Creek terraces and the Bear Creek fan (highly uncertain).

Note:

1. Median estimated value provided in brackets.

6.5.2. Landslide Dam Outbreak Flood (LDOF) Analysis

Similar to Whitecap Creek, Spider Creek appears susceptible to LDOFs. BGC searched for previous landslide dams in the upper watershed, constructed representative cross-sections and modeled LDOFs for various scenarios. The respective return periods cannot be determined empirically and are thus supported by judgment only. The results of the LDOF analysis were used to inform the development of the frequency-magnitude relationship.

6.6. Risk Analysis

Given that only the largest conceivable event (a 1,000 to 10,000-year return period event) on Spider Creek has the potential of reaching two buildings at a low intensity (< 1 m flow depth), a quantitative risk assessment was not warranted for Spider Creek.

6.6.1. Safety Risk

Drawing 12 displays modelled hazard scenario results for Spider Creek and Drawing G11 displays the potential bank erosion extent. As shown on Drawing 12 and Drawing G11, only the largest credible scenario (Q=1,000 m^3/s) is considered likely to impact structures, with flows expected to inundate the eastern portion of the fan. Modelled flow intensities are all less than one ($I_{DF} < 1$). Consequences of such flows are anticipated to include sediment and/or water damage with low potential for loss of life. As such, safety risk is expected to fall within the tolerable or broadly acceptable range.

6.6.2. Economic Risk

This section describes economic risk from building damage for the Spider Creek area. BGC estimated the building damage cost for the 1,000-year return period scenario as approximately $70,000. Average annualized building damage is approximately $70 based on the 1,000-year return period scenario damage. Estimated building damage costs are based only on a portion of assessed building values and do not include damage to contents or inventory. In addition, costs of cleanup and recovery, are not included.

No businesses were identified in the Spider Creek study area.

6.6.3. Loss of Access

The culvert at Spider Creek on Spider Creek Road will likely be overwhelmed by floods exceeding its capacity of approximately 14 m^3/s. This corresponds to a flood return period of <3 years. Floods carrying excessive gravels or large organic debris will block the culvert, but their specific return periods cannot be estimated with confidence. Blocking of the culvert would lead to loss of access to the properties east of Spider Creek. Conceptual Mitigation Design

The results of the risk assessment suggest that mitigation design is not required for Spider Creek, given the current distribution of development.

The potential for blockage of the Spider Creek culvert can be managed through regular cleaning, to avoid progressive infilling with sediment. BGC understands that this is being done by local residents. Spider Creek culvert could be replaced by a bridge with higher clearance, but given that it has not been destroyed in the recent past, such effort may not be warranted.

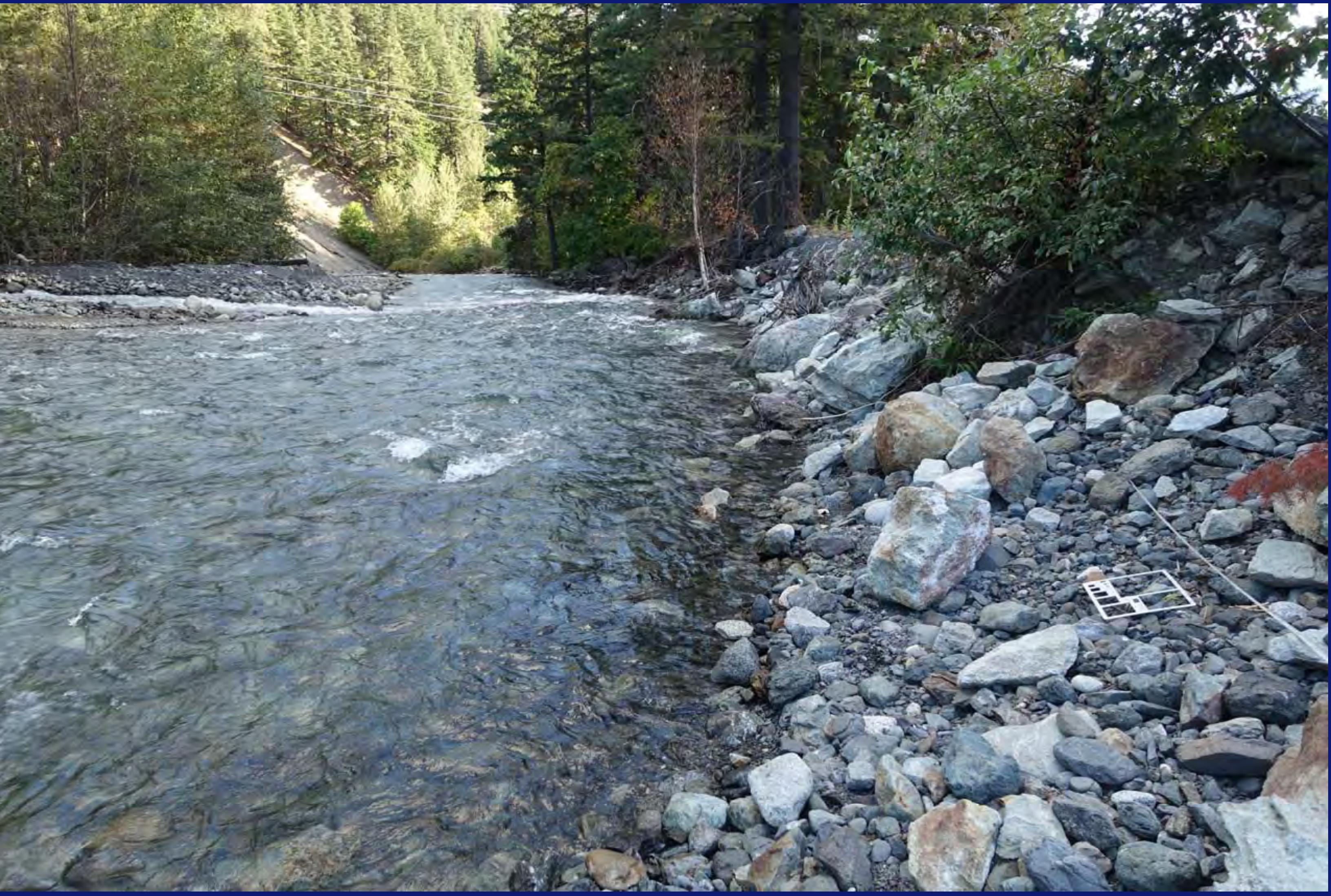
6.7. Summary

Spider Creek differs from Whitecap and Bear Creek in that it does not have a fan. Instead it discharges directly into Portage River. Paleofan surfaces are visible on either side of the creek. These became inactive when Seton Lake water levels dropped, presumably in response to a valley glacier in the Fraser Valley at Lillooet. This led to incision of Spider Creek into its early Holocene deposits.

Spider Creek watershed is capable of producing severe LDOFS. Those were modeled to understand the possible peak discharge on the lower channel of Spider Creek, to determine if such flows exceed the present channel capacity and could avulse into nearby residential areas, and to estimate the amount of bank erosion that could occur along the creek.

Only a very conservative scenario was estimated to reach residential areas. This scenario assumes the breach of a 1000 to 10,000-year return period landslide dam with no downstream attenuation.

Life loss risk is negligible for this scenario, and associated economic losses are low ($70 annualized damage cost). This implies that mitigation measures would likely exceed the value of the assets to be protected. In combination with the very low life loss risk, this indicates that mitigation measures are likely not warranted.



7.0 PORTAGE RIVER

7.1. Introduction

This chapter presents the results of the Portage River hydrogeomorphic assessment including review of documented events, air photo interpretation, and hazard analysis. Detailed hydraulic modeling and risk analysis were beyond the scope of this assessment. This would involve complex lake level modeling and flood routing.

7.2. Previous events on Portage River

7.2.1. Documented Events

Documented flood and bank erosion events on Portage River are summarized in Table 7-1 and Appendix A. The documented erosion events occurred downstream of the Seton Portage Road crossing where Portage River flows to the southeast (Drawing 06). Evidence of bank erosion at this location is also observed in the air photos (Drawings 07 and 08).

Table 7-1. Documented events on Portage River.

Date	Description	Reference
1972	Flooding on Portage River from Anderson Lake where people living beside the Anderson Lake Road bridge were reportedly temporarily displaced from their residences.	Pers. Comm. Tsal'alh meeting September 11, 2017
1986	Flooding of Portage River caused approximately 12 m of bank erosion on the south side of Portage River. As a result of the bank erosion, the house at 901 Spider Creek Road (Drawing 02) reportedly lost approximately half its yard area.	Randy James, Tsal'alh, September 28, 2017 email
1998	Flooding of Portage River led to bank erosion on the south side of Seton River washing out a section of Spider Creek Road. The cost to repair the road was approximately $25,000. No geotechnical or engineering assessment was completed.	William Alexander, Tsal'alh, Oct. 4, 2017 email

Several long-time (i.e., 30 years) residents were asked if they had ever noted flooding of Portage River that affected development, but they had not (e.g., Frank Richings email, December 1, 2017). The assumed reason for infrequent flooding upstream of the Seton Portage Road crossing is threefold: First, the river is incised into its alluvial bed between 2 and 3 m downstream of the Whitecap Creek confluence which allows for high peak flows to pass through the community without leading to overland flooding. Second, the railway embankment rises 2 m above the modern floodplain for a distance of 730 m (between 590 m and 1320 m downstream from Anderson Lake), affording additional flood protection. A majority of existing development is located in the lee of the embankment (see Figure 7-2 and Drawing 02). Third, Anderson Lake acts to attenuate floods by reducing the peak of the inflow hydrograph through lake storage. Therefore, floods may be of longer duration, but are of lower magnitude.

Portage River banks consists of coarse, poorly-sorted alluvial gravels and boulders with maximum grain sizes up to 0.8 m. These boulders are believed to have been transported by Whitecap Creek as there are no boulder sources with this size class nearby. The banks lack true cohesion and are thus susceptible to bank erosion. However, the large boulders embedded within the alluvial deposits provide substantial flow resistance. Even if undercut, these boulders will fall into the river, slowing flow along its margins and counter-acting erosion, which tends to occur due to basal scour.

7.2.2. Air Photograph Interpretation

Air photographs were interpreted between 1948 and 2012 for channel changes and signs of floods on Spider Creek (Drawings 07 and 08). A summary is provided in Table 7-2.

Table 7-2. Air photo observations of Portage River.

Air Photo Year	Observations
1948	Sediment is observed within the river channel at the toe of eroding bank some 300 m downstream of the Seton Portage Road bridge.
1951	Downstream of the Seton Portage Road bridge, the channel has increased in width and there is a large island deposited in the middle of the channel. There are islands forming and channeling widening at the mouth of the river at Seton Lake. Severe erosion along Spider Creek Road (approximately 25 m of bank erosion) relative to 1948 conditions.
1964	Downstream of the Seton Portage Road bridge, the channel has split into two around an island. The channel has significantly widened and several islands have formed at the mouth of the river at Seton Lake.
1965	Generally consistent with the 1964 air photo.
1972	The photo resolution is too coarse to map the river channel, but the river appears to have widened at the mouth of the river at Seton Lake.
1975	There is a fresh erosion scarp downstream of the Seton Portage River bridge. A berm appears to having been constructed to prevent flow from flooding a northern channel.
1987	There is a fresh erosional scarp downstream of the Seton Portage River bridge. Bank erosion at the 901 Spider Creek Road property and channel widening at the mouth of the river at Seton Lake.
1997	Erosion at the toe of the landslide downstream of the Seton Portage River bridge. Channel widening near at the mouth of the river at Seton Lake. The smaller channel around the island downstream of the eastern road bridge appears to be dry.
2005	Channel widening near at the mouth of the river at Seton Lake. The mouth of Portage River has shifted approximately 75 m south.
2012 (Digital Globe satellite image)	A channel bar has been built in the main channel downstream of the eastern road crossing near Spider Creek Road. Channel widening near at the mouth of the river at Seton Lake.

Upstream of the railway bridge the channel remains in a consistent location, but downstream the channel has a meandering planform and changes location throughout the record. There is also an active landslide on the left (north) bank of the Portage River, approximately 180 m downstream of the Seton Portage River bridge, that is present throughout the air photos. The historic channel locations are shown in Drawing 06.

In summary, there are three main fluvial processes occurring in Portage River, downstream of the Seton Portage Road bridge (Figure 7-1):

- An avulsion (i.e., shift in the channel location) in the section immediately downstream of the bridge
- Bank erosion at the outside of meander bends
- Island formation and river widening in the section upstream of Seton Lake.

Upstream of the Seton Portage River bridge, no substantial fluvial hazards were identified. The left (northern) bank consists of fluvial-glacial sediments and is being undercut by Portage River. This provides a continuous source of sediment, but does not show signs of deep-seated landsliding.

Each of these potential hazards is discussed in more detail in Section 7.3.

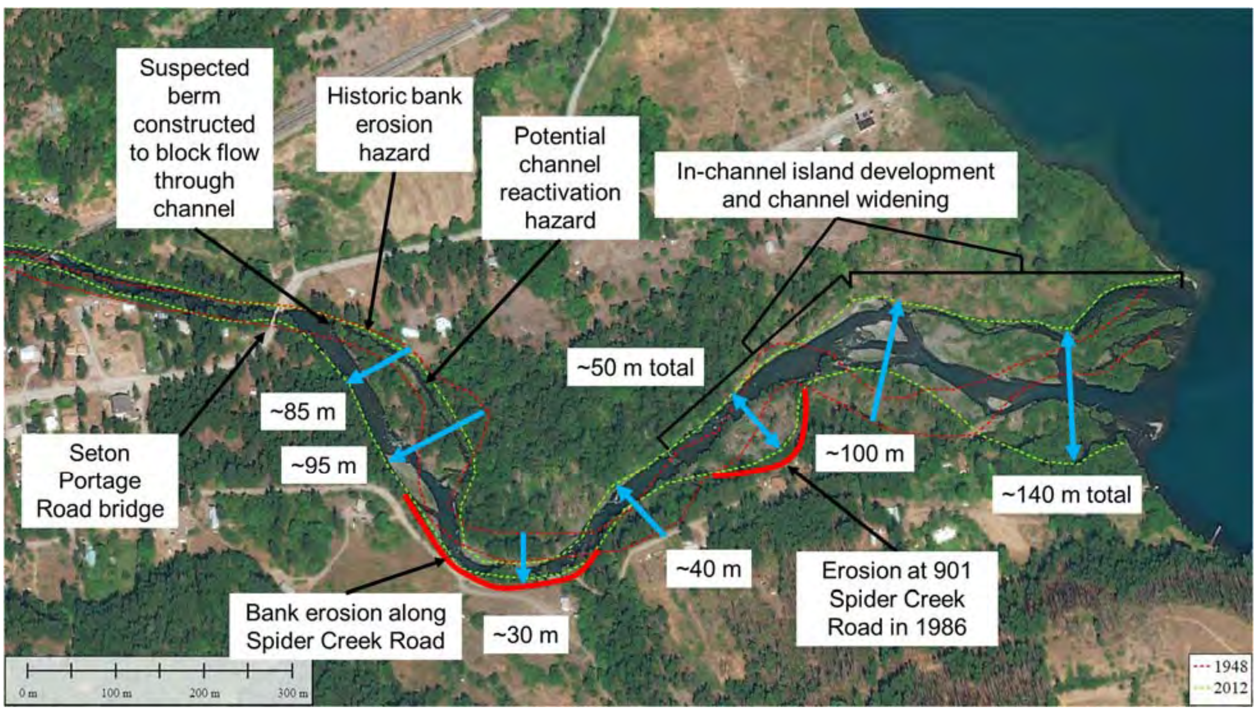


Figure 7-1. Portage River hazards near the mouth at Seton Lake. Blue lines represent total bank movement between the 1948 air photo (red dashed line) and the 2012 satellite image (green dashed line). The solid red lines represent areas of bank erosion hazard adjacent to Spider Creek Road and the 901 Spider Creek Road house. The background is a 2012 satellite image.

7.3. Hazard Analysis

7.3.1. Flooding from Whitecap Creek

As discussed in Section 5.0 and shown on Drawing 11, a debris flood on Whitecap Creek may cause flooding along Portage River. Figure 7-2 shows a cross-section of the approximate extent of Portage River flooding that may arise from a 1000 to 3000-year Whitecap Creek debris flood. The safety and economic risks of this event were included in the Whitecap Creek analysis.

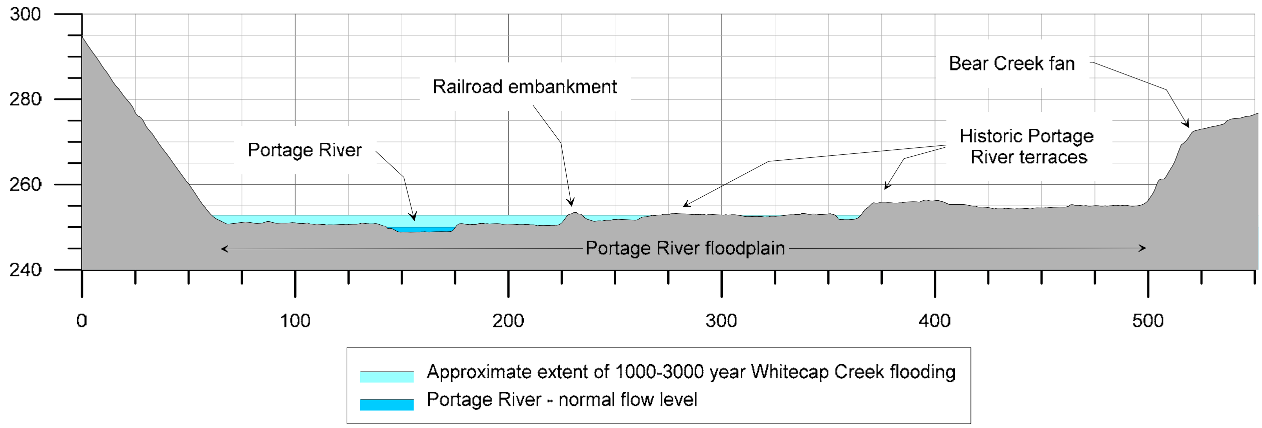


Figure 7-2. Cross-section through the Portage River floodplain about 350 m downstream of the Whitecap Creek confluence (2x vertical exaggeration).

Flooding upstream of Whitecap Creek will depend on whether Portage River becomes blocked with debris from Whitecap Creek; the Portage River discharge at the time of the blockage; and how fast the blockage is being removed by emergency staff. The latter depends on the availability of heavy machinery and its operators. Buildings within the study area on Anderson Lake, and on Portage River upstream of the Whitecap Creek confluence are all located at least 10 m above the current lake level, and would not be directed impacted by the flooding. Also, Anderson Lake is very large, so lake levels would rise slowly, decreasing the likelihood of impact to other buildings around the lake.

7.3.2. Hazards Below the Seton Portage Road Bridge

Three main hazards have been identified in the Portage River downstream of the Seton Portage Road bridge, based on an analysis of air photos and satellite imagery from 1948 to 2012. First, the channel position has shifted toward the west in the section immediately downstream of the bridge. If the river was to re-occupy the eastern side channel, bank erosion could be reactivated along the side channel.

Second, there has been progressive bank erosion toward the south along a river bend adjacent to Spider Creek Road. The maximum rate of erosion was 12 m/year during the period from 1948 to 1951. This erosion has affected Spider Creek Road with previous riprap placement required (Figure 7-3). Erosion at a meander bend further downstream has also affected a portion of the lot at 901 Spider Creek Road (Figure 7-1).

Figure 7-3. Bank erosion at Spider Creek Road. Photo by BGC dated September 13, 2017.

Finally, the river has widened significantly in the section immediately upstream of Seton Lake. In this section, Portage River loses confinement into a broad low-lying braided floodplain and aggrading delta into Seton Lake (Figure 7-4). Since 1948 the Seton Lake delta has progressed up to 70 m eastward into the lake, likely due to the deposition of suspended sediment. During this period islands have also formed within the river, and the channel has widened from approximately 40 m to 140 m directly upstream of the lake. At the moment BGC cannot identify reasons for this widening with certainty, but we speculate that it may be a result of coarse sediment depositing on the river bed upstream of the delta, forcing the flow to deviate around mid-channel islands. The frequency of sediment input may have increased as a result of inputs from Whitecap Creek, or erosion of the banks downstream of the Seton Portage River bridge. Given that sedimentation rates have not been measured over time, both theories are speculative.

Figure 7-4. Portage River at the outlet to Seton Lake. This area is subject to in-channel island formation and channel widening. Photo by BGC dated September 13, 2017.

7.4. Summary

BGC identified several hazards downstream of the Seton Portage Road crossing. These hazards include the potential for avulsion (channel switching) and erosion immediately downstream of the bridge, bank erosion at the outside of meander bends, and extensive channel widening near the river mouth. Historical erosion within this section of Portage River has impacted infrastructure in the past. In 1986, a residential lot was eroded and in 1998 Spider Creek Road was undercut. Similar events impacting Spider Creek Road and residential development are likely to occur in the future. The most likely impacts are due to erosion at the outside of meander bends, and channel widening near the lake inlet due to sediment deposition and island formation at the upstream end of the delta. Additional work would be required to estimate the frequency, extent and risk of future bank erosion events.

8.0 CONCLUSIONS AND RECOMMENDATIONS

8.1. Introduction

This integrated hydrogeomorphic assessment focused on Bear/Pete's Whitecap, and Spider creeks as well as Portage River. Hazards were quantified and mapped, risk to loss of life and economic losses were quantified and conceptual level mitigation measures presented and compared to reduce risk.

Seton Portage exists due to a dynamic interaction mostly between Whitecap and Bear Creek. This interaction is manifested in extremes. High magnitude debris floods on Whitecap Creek may be able to divert Portage River into the presently developed areas along Seton Portage Road. Such floods are believed to have led to the over-steepening of the fan edge of Bear Creek in the past. Large debris flows on Bear Creek, however, can mimic this effect and in turn push Portage River back towards the north closer to its present position.

8.2. Bear and Pete's Creek

Bear Creek and its tributary watershed Pete's Creek are subject to debris flows. Bear Creek can jump its course and flow into Pete's Creek and vice versa. Due to a high clay content and a comparatively small boulder size they can travel further than comparative debris flows with similar volumes in areas with lower or no clay content and larger boulders. Debris flows with return periods between 10 and 30 years can reach the Whitecap development and development along Cresta Road. Debris flows with higher return periods are very likely to travel beyond to and beyond the sharply defined fan edge where they can lead to damage and potentially loss of life.

The risk assessment indicates that up to 30 persons could lose their lives in a single debris flow (the 1000 to 3000-year event). The risk assessment for individuals suggests that 59 structures exceed risk tolerance criteria developed and applied elsewhere. For group risk which describes the total risk to all people affected for all debris-flow scenarios, we conclude that it well exceeds commonly accepted risk thresholds. Average annualized building damage is approximately $140,000. These findings suggest that mitigation measures are in order to reduce risk to tolerable levels.

Three potential risk reduction measures were compared. Two of those divert debris either towards the west and into Anderson Lake, or to the east towards the joining fans of Bear and Spider creeks. One option aims to capture debris closer to the fan edge. Upon comparison of these options, Option 3 (Basin and Distal Berms) is favoured.

Climate change will likely increase debris flow frequency and magnitude. Science has not advanced to a stage where those increases can be reliably quantified. However, such changes are likely to lead to an increased risk compared to the present risk. Given the uncertainty with the debris-flow magnitude estimates associated with long return period debris flows that govern the design of mitigation works, it is unlikely that the projected changes in volume would require design alterations. It would, however, likely require more frequent maintenance in the form of basin cleanouts.

8.3. Whitecap Creek

Whitecap Creek is subject to debris floods. These events express themselves with particularly high peak flows, especially if the debris flood is triggered by an LDOF. On the fan of Whitecap Creek, debris floods result in fan inundation, bank erosion and channel aggradation both in the creek and Portage River. High flow velocities and transported boulders associated with debris floods can impact buildings, while associated bank erosion can undercut buildings and lead to them toppling into the creek.

High magnitude debris floods on Whitecap Creek could also potentially divert Portage River into the presently developed areas along Seton Portage Road. Such floods are believed to have led to the over-steepening of the fan edge of Bear Creek in the past. Such an event, while not modeled specifically, could create more damage than analyzed in this report. It is thus crucial that some heavy machinery be available during times in which debris floods are likely to occur in order to re-establish the Portage River channel as soon as possible.

The risk assessment indicates that debris flood risk on Whitecap Creek is acceptable for individuals and groups, provided that the 100 Anderson Lake Road residence is relocated. Average annualized building damage is approximately $8,300 (approximately 17 times less than on Bear Creek).

Two structural mitigation options were evaluated (berm construction), with the objective of deflecting debris floods away from the Portage River bridge. Both options would reduce the likelihood of Anderson Lake Road and the Portage River bridge being inundated and the CN railway being eroded. A third option, event response, is preferable from a cost-benefit point of view, if the main objective of the design is to prevent or limit closure of Anderson Lake Road. However, none of the three options substantially reduce the risk of damming of Portage River, which could cause flooding of Anderson Lake Road, even with the short or long berm in place.

Climate change will likely result in a higher frequency of debris floods on Whitecap Creek combined with a moderate increase in debris flood magnitude. In absence of mitigation, this will result in more frequent road closures and potential damming events for Portage River.

8.4. Spider Creek

Spider Creek differs from Whitecap and Bear Creek in that it does not have a fan. Instead it discharges directly into Portage River. Paleofan surfaces are visible on either side of the creek. These became inactive when Seton Lake water levels dropped, presumably in response to a valley glacier in the Fraser Valley at Lillooet. This led to incision of Spider Creek into its early Holocene deposits.

Spider Creek watershed is capable of producing severe LDOFS. Those were modeled to understand the possible peak discharge on the lower channel of Spider Creek, to determine if such flows exceed the present channel capacity and could avulse into nearby residential areas, and to estimate the amount of bank erosion that could occur along the creek.

Only a very conservative scenario was estimated to reach residential areas. This scenario assumes the breach of a 1000 to 10,000-year return period landslide dam breach with no downstream attenuation.

Life loss risk is negligible for this scenario, and associated economic losses are low ($70 annualized damage cost). This implies that mitigation measures would likely exceed the value of the assets to be protected. In combination with the very low life loss risk, this indicates that mitigation measures are likely not warranted.

8.5. Recommendations

This section first lists key recommendations for decision makers in the text box, followed by greater elaboration of the individual recommendation components in Sections 8.5.1 to 8.5.3:

Recommendation Summary for Decision Makers

1. Engineering Design: Several steps are necessary by the SLRD and Tsal'alh before mitigation design can proceed. Those include decisions on tolerable risk, decision criteria not analyzed and a review of available funds and their distribution amongst the study creeks. Once these decisions are made, the series of engineering design steps listed in Section 8.5.1 should be followed.
2. Policy: An area structure plan (ASP) should be established based on the hazard mapping presented in this report. A municipal development plan could be created that designates flood zones and their respective use as well as outlines provincially sponsored flood mitigation on Portage River. Qualified professionals should be given guidance by the SLRD on how to conduct future development-related studies.
3. Additional Studies: Two additional studies are recommended: The first is a Sonar study that would provide input to a risk assessment of landslide-generated tsunamis on either Anderson or Seton Lakes. The second is a detailed flood study of Portage River and the adjacent lakes.

8.5.1. Studies to Support Engineering Design

Figure 3-9 summarizes the components required to arrive at a final mitigation design. The present study included Project Scoping and Conceptual Design (Phases 1 and 2) and elements of Options Assessment (Phase 3).

The choice of the final design will require the following steps beyond those already undertaken:

- Adoption of risk tolerance criteria for individual and group risk and possibly annualized economic risk.

- Decision of how other factors presently not considered formally in the risk assessment such as loss of access, services, impact to culturally important sites should inform the location, type and scale of risk reduction measures.
- Determination of available funds for the entire Seton Portage area and decision on how these funds should be distributed amongst the three creeks.

The last step will then be the basis of adjusting the scale of the measures proposed in this report to match the budget limitations. This approach may lead to design that still exceeds the chosen risk tolerance criteria. However, geohazard mitigation resource limitations are a reality in BC. The goal would be to maximize risk reduction within the constraints of the available budget. In this context, it is worthwhile to not that mitigation will benefit stakeholders who have thus far not contributed to this study, such as CN Rail and BC Hydro, both of who have facilities traversing the Seton Portage area. Therefore, negotiations on joint funding may be desirable.

Following the decision on total available funds for mitigation, the following steps are recommended (Figure 3-9).

- Select a preferred mitigation concept or combination of concepts
- Determine the layout of mitigation structures
- Conduct field investigation of subsurface conditions as applicable to the chosen mitigation measures
- Preliminary hydraulic design and design of auxiliary structures such as spillways, fords, channels
- Determination of load scenarios, design loads and impact forces
- Consideration of failure mechanism and design weaknesses
- System testing with the numerical models that were used in this report for consistency
- Assessment of residual risks that will remain following design implementation
- Design drawings, cost estimates and design documentation.

8.5.2. Policy

This section is intended to provide some policy guidance to the SLRD with respect to current and future development in Seton Portage. Such guidance should be embedded within the framework of existing guidelines (such as the APEGBC 2012 Guidelines on Flood Assessments in a Changing Climate), the 2004 Ministry of Water Land and Air Protection (MWLAP) guidelines and existing SLRD policies.

The following general guidance is provided by BGC.

Area Structure Plan (ASP)

Area structure plans (ASPs) are a high-level land use plan that provides an area an area specific framework for future subdivision and development. They identify a conceptual layout for general land uses, utility infrastructure, roads, public spaces and recreation. In terms of the geohazards encountered at Seton Portage, this area structure plan would designate areas for which specific studies are required. These areas could be designated now based on the geohazard mapping for this study, and be updated once mitigation measures have been implemented. Area structure plans should address the entire area of Seton Portage and could be separated by creek. However, given the interconnectedness of creeks, it would be beneficial if a single area be designated in which hazard should be considered in the construction of new buildings and infrastructure. Such area designation could be based on Drawing 13, which is the composite hazard map.

Municipal Development Plan

A municipal development plan could be created for Seton Portage. This plan could have the following elements as they pertain to flooding:

1. Development within designated flood zones shall be designed to protect buildings and habitable spaces in addition to protecting the natural function of water bodies.
2. Development on the 200-year return period floodplain could be limited to parks, trails and essential utilities that do not materially impede the natural function of the floodplain.
3. Seton Portage would be working with the Province to maintain appropriate mitigation for Portage River relative to the identified flood risks.

BGC's study did not include a standard flood frequency and inundation study for Seton Portage, however, this could be completed under a separate contract. It should, however, include sedimentation aspects given the strong sediment source from Whitecap Creek and should include bank erosion expected for a 200-year return period flood.

With respect to steep creeks (namely Whitecap, Bear/Pete's and Spider Creek), the SLRD could establish the following guidance:

1. Within the area structure plan in which hazard zones are delineated, consultations zones could be defined for which group risk is being calculated. Development in hazard zones could not be allowed to exceed the set individual risk criteria for new development unless appropriate mitigation could be demonstrated that would reduce residual risk to below the defined tolerance criteria.
2. Any additional development within the areas designated as hazardous is prohibited without appropriate mitigation such that the group risk would not increase.
3. Economic risk assessments may be required to provide context for considering benefits of new development in light of existing geohazard risks and support decision making. In particular, these may be required in areas potentially subject to flood inundation where life loss risk is low, and economic risk is the controlling factor for decision making.
4. Where steep creek risks are to be assessed, the appropriate methods shall be determined in light of existing guidance documents by a professional in consultation with the SLRD and the Province. The assessment should be specific to the type of hazard, the proposed development and local site conditions.
5. Steep creek risk reduction for new development is focused on risk avoidance first. Off-site hazard mitigation could be permitted as an approach to reduce risk to tolerable

thresholds where it can be demonstrated that land use provides a net positive community benefit.

6. A development proposal would require a set of specific elements that address how geohazard risks be addressed.
7. Any development or mitigation works should not cause any material adverse impact on other properties.
8. Mitigation works active, or passive, local or off-site, must be designed and constructed in accordance with appropriate engineering guidelines.
9. Critical facilities such as emergency services or essential municipal utilities should not be located within designated hazard zones.
10. Municipal infrastructure in designated hazard zones must be designed by a qualified professional engineer in accordance with existing engineering guidelines
11. Subdivision and development proposals within designated hazard zones should require adequate access and egress to all affected properties in the event of a geohazard.
12. For areas prone to bank erosion, development proposals will require a study by a qualified professional to demonstrate that the bank can be stabilized according to existing engineering guidelines.

QRP Responsibilities

When completing site-specific assessments in area structure plan in which hazard zones are delineated previously subject to regional scale steep creek risk assessments (SCRAs), the Qualified Registered Professional (QRP) is relying upon previous work. The QRP, Client and Approving Authority should be aware of the limitations of that work and this should be considered when establishing the professional services agreement.

When completing the site-specific SCRA, the QRP should identify factors that may change the level of hazard and risk compared to previous assessments, or evidence that previous assessment data and results should be updated. The following questions provide examples of factors that should be checked, but is not intended to be exhaustive:

- Was/were the previous SCRA(s) undertaken in accordance with these Guidelines?
- Do changed conditions (e.g., new geohazard events, geomorphic changes in the upper basin such as landslides, forest fires, beetle infestations, mining activities, new development, construction of risk control measures, etc.) exist that post-date previous assessments and that necessitate updates to the baseline SCRA?
- Do site-specific hazard mechanisms exist above, at, or below the proposed development site that were not identified at the scale of previous studies and should be assessed in more detail (e.g., avulsion points or localized bank erosion and instability, encroachment of the receiving river, or site alterations caused by the proposed development)?
- Do site-specific conditions affect hazard intensity (destructive potential) that were not identified at the scale of previous studies and should be assessed in more detail

(e.g., local terrain factors or site-specific alterations that change the path, velocity or depth of flows)?

- For redevelopment of existing buildings, do the renovations change the temporal probability of building occupancy compared to what was assumed in previous studies and used as the basis for risk estimates (e.g., a change from full-time to seasonal occupancy?)
- For redevelopment of existing buildings, do the renovations change the estimated level of building vulnerability to geohazard impact compared to what was assumed in previous studies and used as the basis for risk estimates (for example by adding a habitable basement with windows or doors at ground level)?
- Does proposed development densification change the number of people exposed to hazard, with a commensurate increase in group safety risk?

BGC would be pleased to collaborate with the SLRD and its stakeholders to refine these suggestions and formulate an appropriate geohazard risk management policy under a separate scope of work.

8.5.3. Additional Studies

BGC believes that two types of additional studies would be beneficial for a comprehensive assessment of all geohazards that could affect Seton Portage.

1. Anderson and Seton Lakes Sonar Study
   Most development in the Seton Portage area is located on the floodplain or low terraces of Portage River, near the shoreline of either Anderson or Seton lakes. Lakes flanked by steep-sided mountains are subject to rock avalanche-generated tsunamis as the 2005 Chehalis landslide and tsunami demonstrated (Brideau et al. 2012, Roberts et al. 2013, Roberts et al. 2014). During BGC's field visit in November 2017, it was mentioned during a Tsal'alh meeting with BGC that three consecutive 20 foot (~ 7 m) high waves were observed on Anderson Lake. The year provided was 1988 or 1989. Nothing is known about the damage it caused.
   A large (> 1 Mm^3) landslide in either lake could create a sudden and potentially very destructive tsunami. Rather than modeling tsunamis given specific source areas along Anderson and Seton Lakes that have not yet been designated, BGC proposes that a sonar study be conducted for both lakes. This study is similar to LiDAR in that it provides a very accurate image of the lake bottom. Former rock slides can be identified and their magnitude be estimated. The number of landslide deposits (if encountered) would allow an estimate of the frequency of events, while their volume could provide an estimate of the source area magnitude. The latter could be used in conjunction with identification of the associated source areas to model tsunamis and determine which portions of Seton Portage would be subject to tsunamis and could perhaps be integrated in the Area Structure Plan discussed in Section 8.5.3.

2. Portage River Flood Study
   To the best of BGC's knowledge, a flood study has not been conducted on Portage River. Such study would require detailed modeling of the behaviour of Anderson Lake in response to snowmelt and rain and the corresponding flood levels on Portage River. This study could designate the 200-year return period flood level through the 2.8 km reach of Portage River though the community and be accompanied by a bank erosion study for the 200-year return period flood. This would allow the determination of setback zones along the river channel to avoid damage by bank erosion.

8.6. Limitations

This assessment is based on the current number of dwellings and observed geomorphological conditions in the Seton Portage area. Estimated risk levels assume constant conditions. Debris fans and the processes in their watersheds are dynamic, and hazard and risk will change to some degree when floods or debris flows avulse out of the existing channel or erode new channels. Similarly, any man-made alterations of the landscape through fill placements, cutslopes or road constructions may change the distribution and intensity of debris flow and flood hazards and thus change the fan's risk profile. Modifications to development will also change the risk by changing the number and location of persons exposed to hazard. As such, to assure consistency of this report with current conditions, BGC recommends that the risk assessment be updated following debris flows or changes to the existing development. Any landscape alterations should require permits from the SLRD and First Nations and be reviewed by professionals with appropriate training in light of this risk assessment.

It is important to note that the nature of bedrock instability in the upper watersheds of Whitecap and Bear creeks is not yet sufficiently characterized for a full understanding of large landslide failure modes, volumes, and source locations. Such detailed assessment was outside the current scope of work. This uncertainty could be reduced through additional field investigation during snow-free conditions, more detailed measurement of source zone volumes, kinematic analysis of failure modes, and on-site or satellite-based monitoring to detect slope movement.

Climate change science is advancing rapidly. BGC is in the course of developing quantitative tools for the projections of changes of debris flood and debris flow frequency and magnitude, bank erosion and channel scour in collaboration with researchers at the Pacific Climate Impacts Consortium, the National Centre of Atmospheric Research in Boulder, Colorado, and researchers from the University of British Columbia. As these results become available, the current study could be updated. For the design of mitigation works, some allowance for future changes in debris flow or debris flood frequency and magnitude should be made either by adding an element of conservativism now, or by integrating flexible design elements that could be increased in scale without requiring a re-design.

Steep-sided lakes as Seton and Anderson Lakes may be subject to rock avalanche-generated tsunamis which could be particularly damaging to development on the Seton River floodplain as well as nearby low-lying terraces given their low elevation with respect to either lakes. This has not been evaluated as part of this study.

9.0 CLOSURE

We trust the above satisfies your requirements at this time. Should you have any questions or comments, please do not hesitate to contact us.

Yours sincerely,

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GLOSSARY

Term	Definition
Active alluvial fan	The portion of the fan surface which may be exposed to contemporary hydrogeomorphic or avulsion hazards[6]
Alluvial fan	A low, outspread, relatively flat to gently sloping mass of loose rock material, shaped like an open fan or a segment of a cone, deposited by a stream at the place where it issues from a narrow mountain valley upon a plain or broad valley, or where a tributary stream is near or at its junction with the main stream, or wherever a constriction in a valley abruptly ceases or the gradient of stream suddenly decreases[7].
Avulsion	Lateral displacement of a stream from its main channel into a new course across its fan or floodplain[8].
Clast	Particles of broken-down rock. These fragments may vary in size from boulders to silt-sized grains, and are invariably the products of erosion followed by deposition in a new setting[9].
Clast supported	Deposits that contain a higher proportion of clasts than matrix.
Colluvial	Applied to weathered rock debris that has moved down a hillslope by creep or by surface wash[10].
Debris	A mixture of sand, gravel, cobbles and boulders, often with varying proportions of silt and clay[11].
Debris flood	A very rapid (0.5-5 m/s velocity) flow of water that is heavily charged with debris in a steep channel[12].
Debris flow	A very to extremely rapid (0.5-50 m/s velocity) surging flow of saturated debris in a steep channel[13].
Digital elevation model (DEM)	A digital model or 3D representation of a terrain's surface[14].
Distal fan	The zone on the alluvial fan closest to the fan toe[15].
Erosion	The part of the overall process of denudation that includes the physical breaking down, chemical solution and transportation of material[16].

[6] Kellerhals and Church 1990, p.340
[7] American Geological Institute, 1972, p. 18
[8] Oxford University Press, 2008, p. 47
[9] Oxford University Press, 2008, p. 111
[10] Oxford University Press, 2008, p. 120
[11] Hungr et al. 2014, p. 170
[12] Hungr et al. 2014, p. 185
[13] Hungr et al. 2014, p. 183
[14] https://en.wikipedia.org/wiki/Digital_elevation_model
[15] Kostachuk et al. 1986, p. 475
[16] Oxford University Press, 2008, p. 200

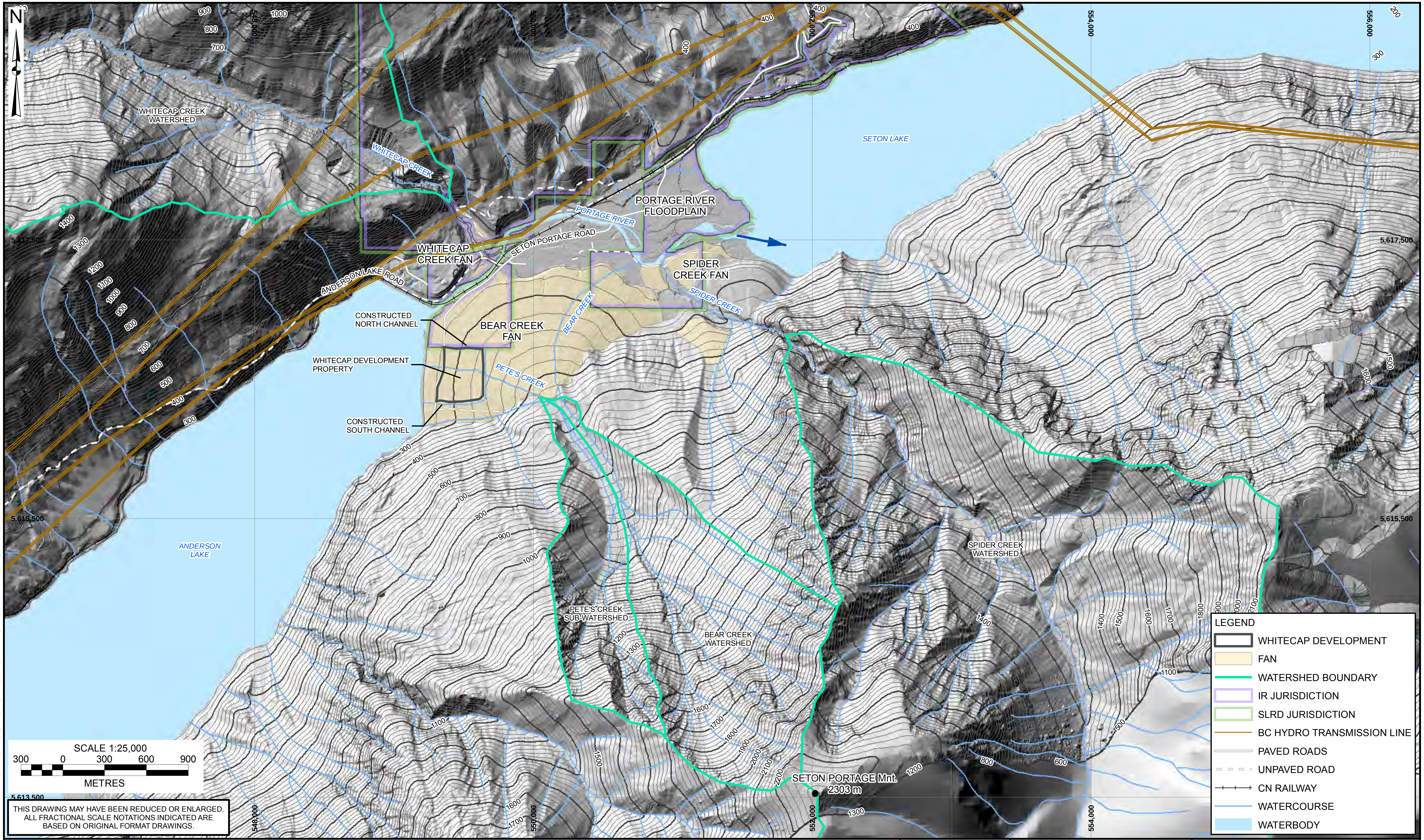
Term	Definition
Fan apex	The highest point on an alluvial fan, generally where the stream emerges from the mountain front.[17]
Fan toe	The downslope end of an alluvial fan[18].
Floodplain	The part of the river valley that is made of unconsolidated river-borne sediment, and periodically flooded[19].
Geomorphology	The scientific study of the land-forms on the Earth's surface and of the processes that have fashioned them[20].
Hydrogeomorphology	The interdisciplinary science that focuses on the interaction and linkage of hydrologic processes with landforms or earth materials[21].
Hydrology	The study of the hydrologic (water) cycle. While it primarily involves aspects of geology, oceanography, and meteorology, it emphasizes the study of bodies of surface water on land and how they change with time[22].
Inactive alluvial fan	Portions of the fan that are removed from active hydrogeomorphic or avulsion processes by severe fan erosion, also termed fan entrenchment[23]
Inverse grading	Sediment which is sorted with the finest at the base and coarsest at the top[24].
Levée	Steep-sided ridges that can be up to several metres in height. They lie outside and above the sides of a pre-existing stream channel, and can extent for many tens of metres along a channel[25].
LiDAR	Stands for *Light Detection and Ranging,* is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses - combined with other data recorded by the airborne system - generate precise, three-dimensional information about the shape of the Earth and its surface characteristics[26].
Lobe	Debris deposited over an aerial portion of the debris fan. They are often characterized by a number of arms, each ending in a "snout"[27].
Matrix	The smaller or finer grained, continuous material enclosing, or filling the interstices between, the larger grains of sediment[28].

[17] Bull, 1964, p. vii
[18] American Geological Institute, 1972, p. 743
[19] Oxford University Press, 2008, p. 219
[20] Oxford University Press, 2008, p. 241
[21] Jakob et al., 2016, p. 163
[22] Oxford University Press, 2008, p. 285
[23] Kellerhals and Church 1990, p.340
[24] Oxford University Press, 2008, p. 252
[25] VanDine, 1996, p. 9
[26] NOAA, https://oceanservice.noaa.gov/facts/lidar.html
[27] VanDine, 1996, p. 8
[28] American Geological Institute, 1972, p. 434

Term	Definition
Matrix-supported	Deposits that contain a higher proportion of matrix than clasts. As a consequence, clasts tend to not be in contact with one another.
Melton ratio	The ruggedness of the basin can be characterized by the dimensionless ratio, $H/\sqrt{A}$ (H is the watershed relief in km, and A is watershed area in km^2), which indicates how rugged the basin was at the time of maximum fan development[29].
Overbank deposit	A floodplain sediment that lies beyond the limits of the river channel and was left by floodwaters that had overflowed the river banks[30].
Proximal fan	The zone on the alluvial fan closest to the fan apex[31]
Riparian	Pertaining to or situated on the bank of a body of water, especially a watercourse such as a river[32].
Scour	The powerful and concentrated clearing and digging action of flowing air or water, especially the downward erosion by stream water in sweeping away mud and silt on the outside curve of a bend, or during a time of flood[33].
Tributary	A stream that discharges into a larger river[34].
Watershed	The area from which a surface watercourse or a groundwater system derives its water[35].
Watershed relief	The elevation difference between the highest and lowest points in the watershed[36].

[29] Melton, 1965, p. 23
[30] Oxford University Press, 2008, p. 410
[31] Kostachuk et al. 1986, p. 475
[32] American Geological Institute, 1972, p. 611
[33] American Geological Institute, 1972, p. 636
[34] Oxford University Press, 2008, p. 592
[35] Oxford University Press, 2008, p. 94
[36] Wilford et al., 2004, p. 63

DRAWINGS



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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY FLNRO – THOMPSON OKANAGAN REGION VIA UNBC, DATED OCTOBER 10, 2017. CONTOUR INTERVAL IS 20 m.
4. TRANSMISSION LINES PROVIDED BY THE SLRD. ROADS, RAILWAY AND WATERWAYS OBTAINED FROM CANVEC PROVIDED BY NATURAL RESOURCES CANADA, DATED 2011.
5. BUILDINGS DIGITIZED BY BGC USING ORTHOIMAGERY PROVIDED BY FLNRO – THOMPSON OKANAGAN REGION VIA UNBC, DATED OCTOBER 10, 2017.
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CHECKED:	SK, EM
APPROVED:	MJ

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AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
SQUAMISH-LILLOOET REGIONAL DISTRICT

PROJECT:
SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE:
SITE LOCATION MAP

PROJECT No.: 1358005
DWG No: 01

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PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: SITE FAN MAP

PROJECT No.: 1358005

DWG No.: 02

THIS BAR MEASURES 100 mm AT FULL SIZE. ALL SCALES REFERENCED TO FULL SIZE.

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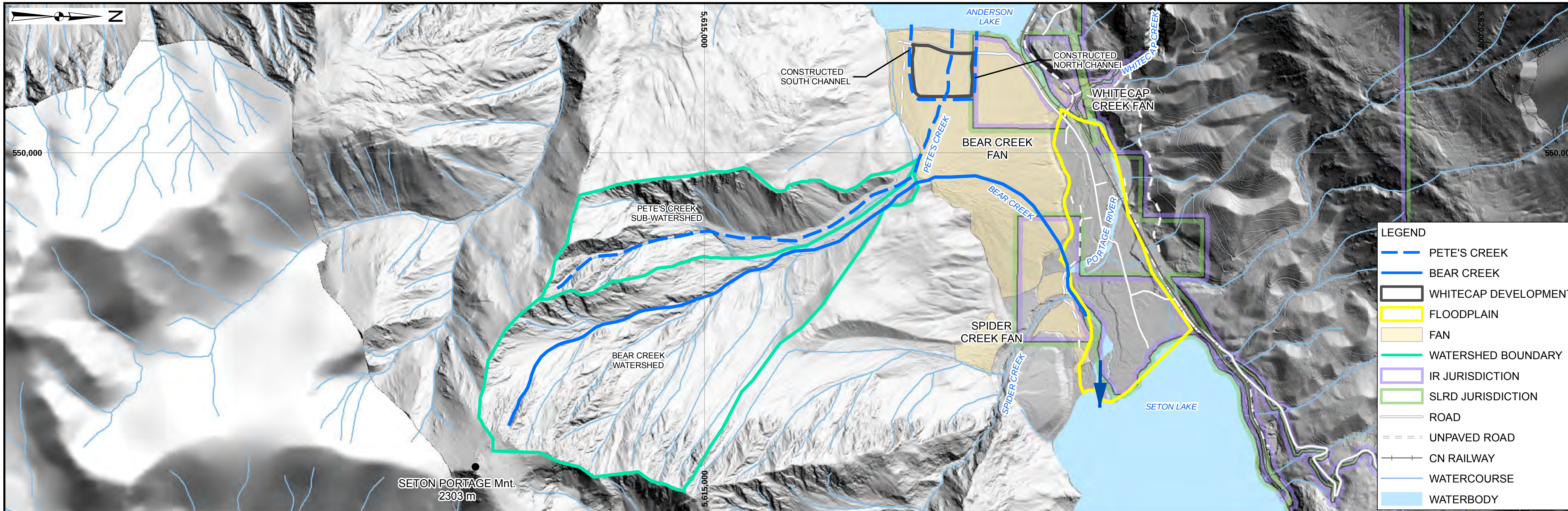

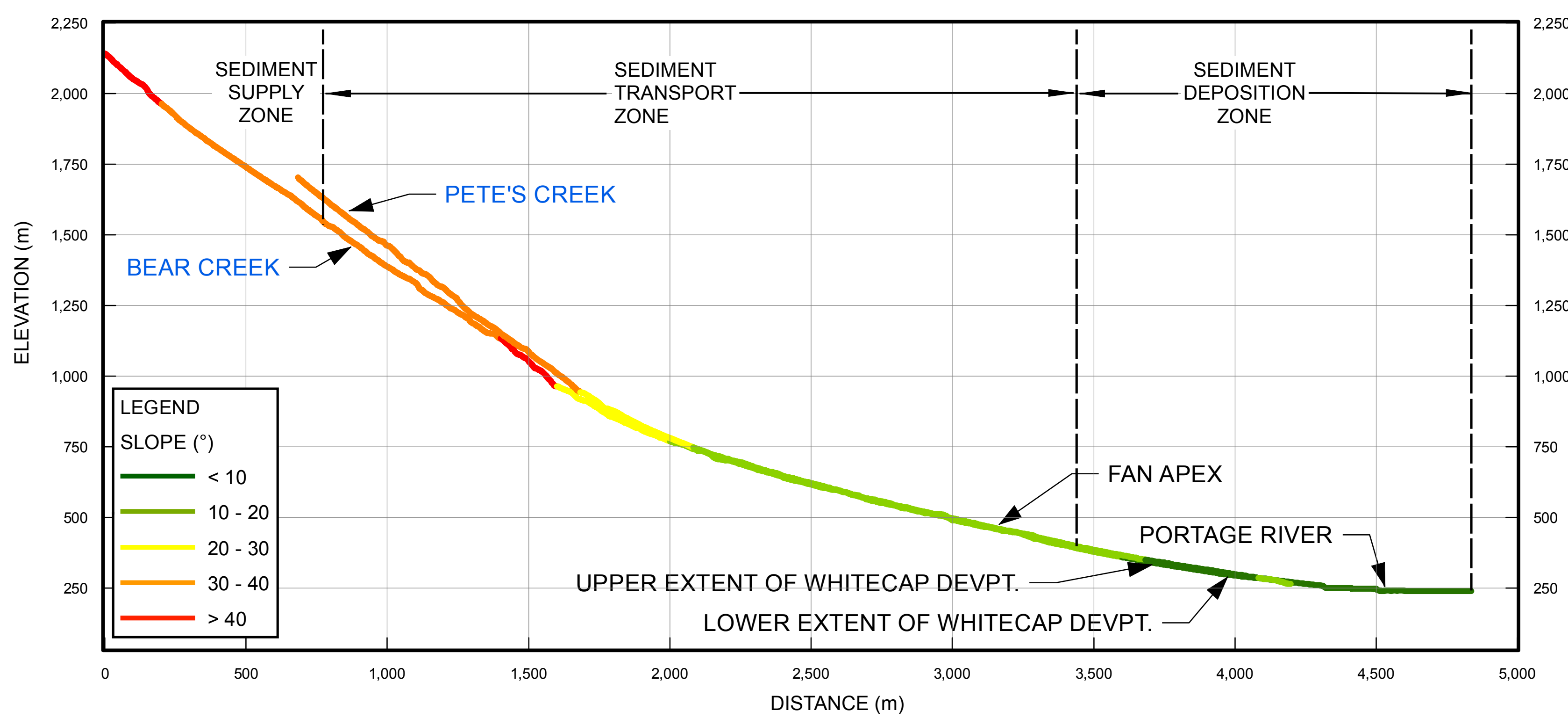

CROSS SECTION A/03

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METRES

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PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: BEAR AND PETE'S CREEKS PROFILES

PROJECT No.: 1358005

DWG No: 03

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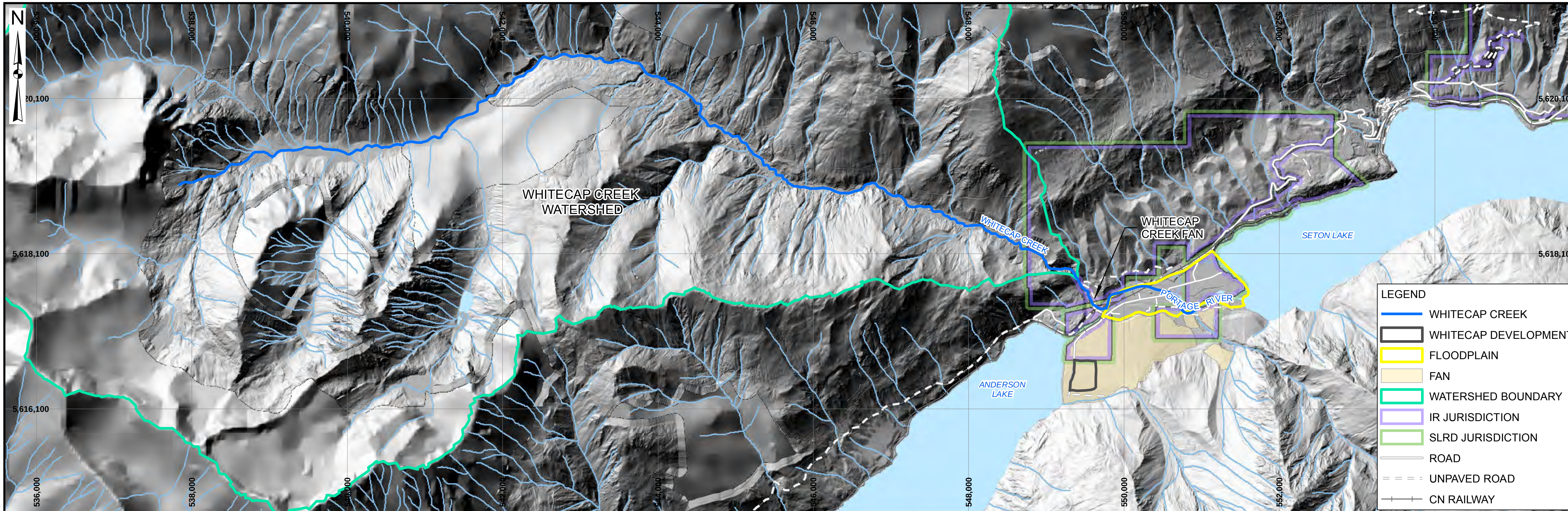

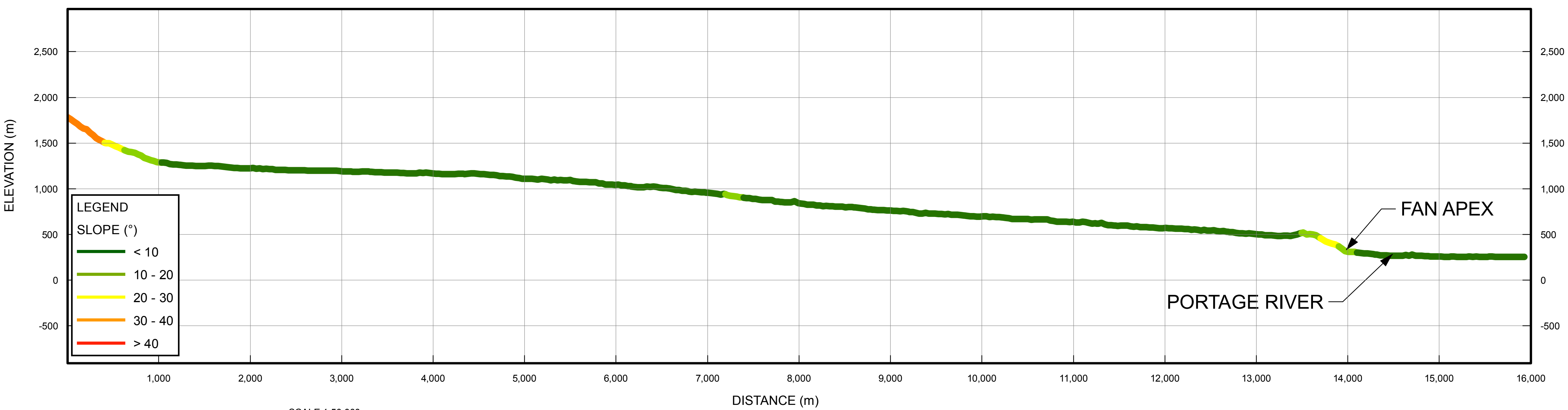

CROSS SECTION A/04

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PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: WHITECAP CREEKS PROFILE

PROJECT No.: 1358005

DWG No: 04

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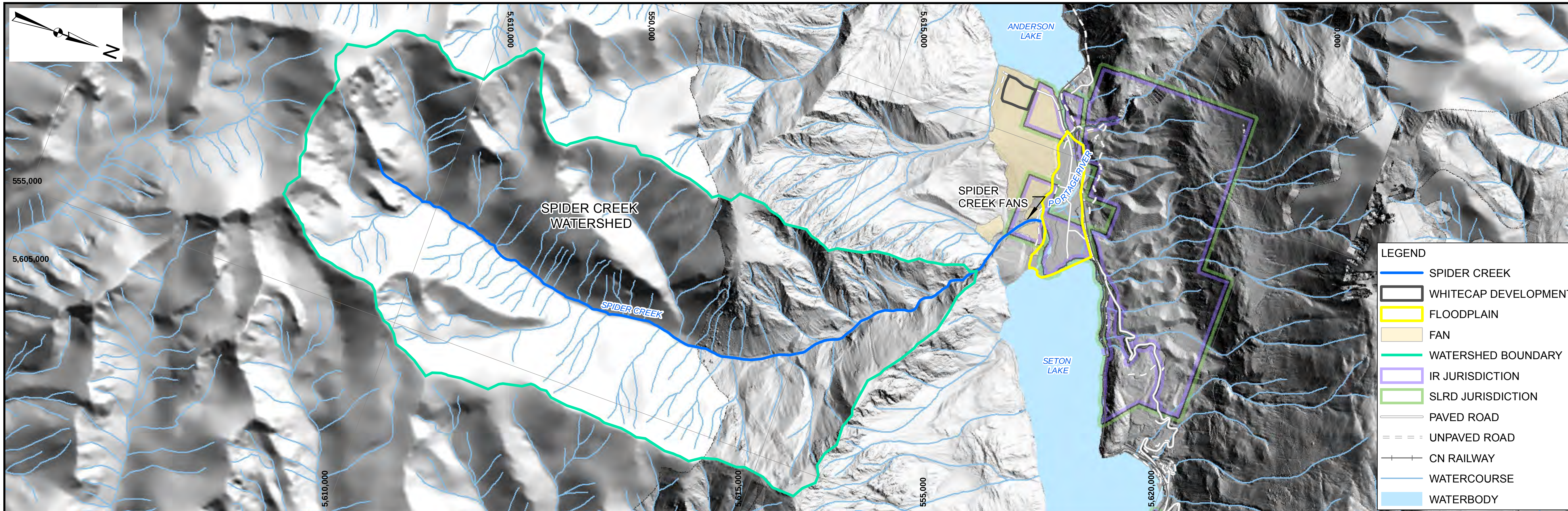

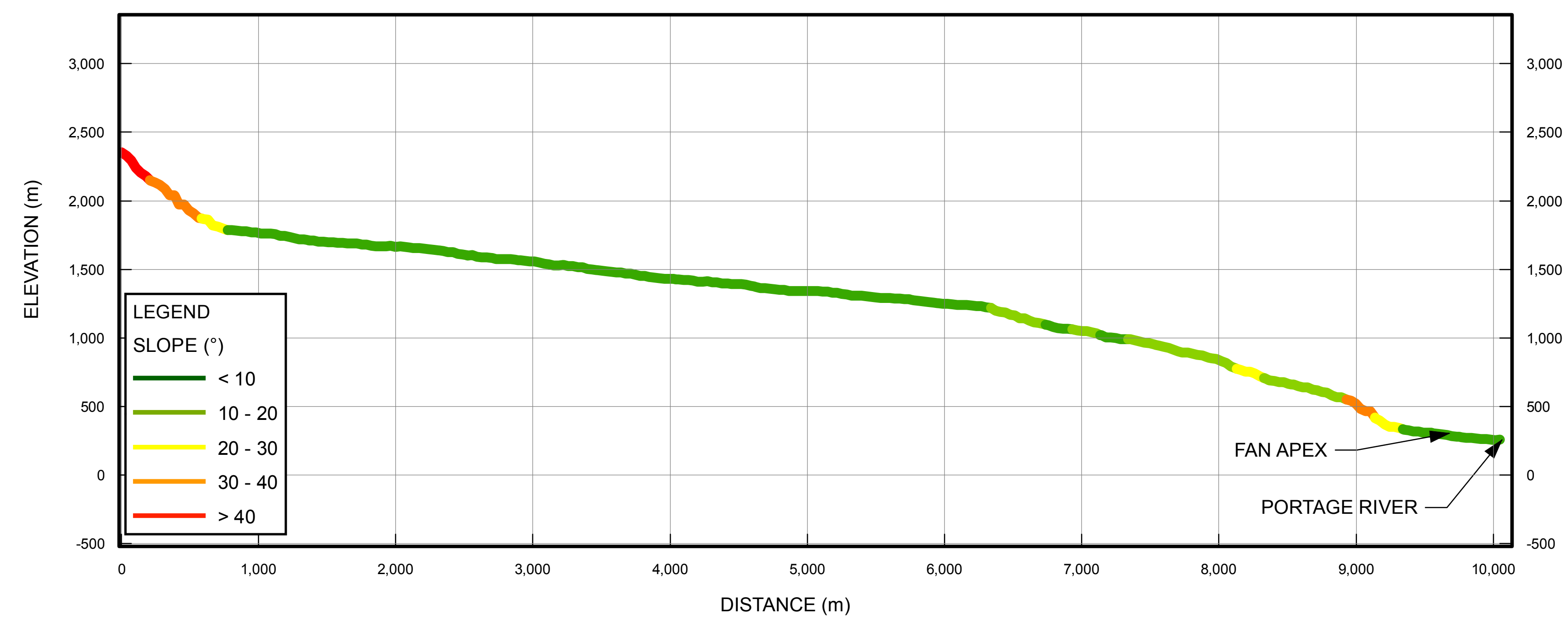

CROSS SECTION A/05

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PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: SPIDER CREEK PROFILE

PROJECT No.: 1358005

DWG No: 05

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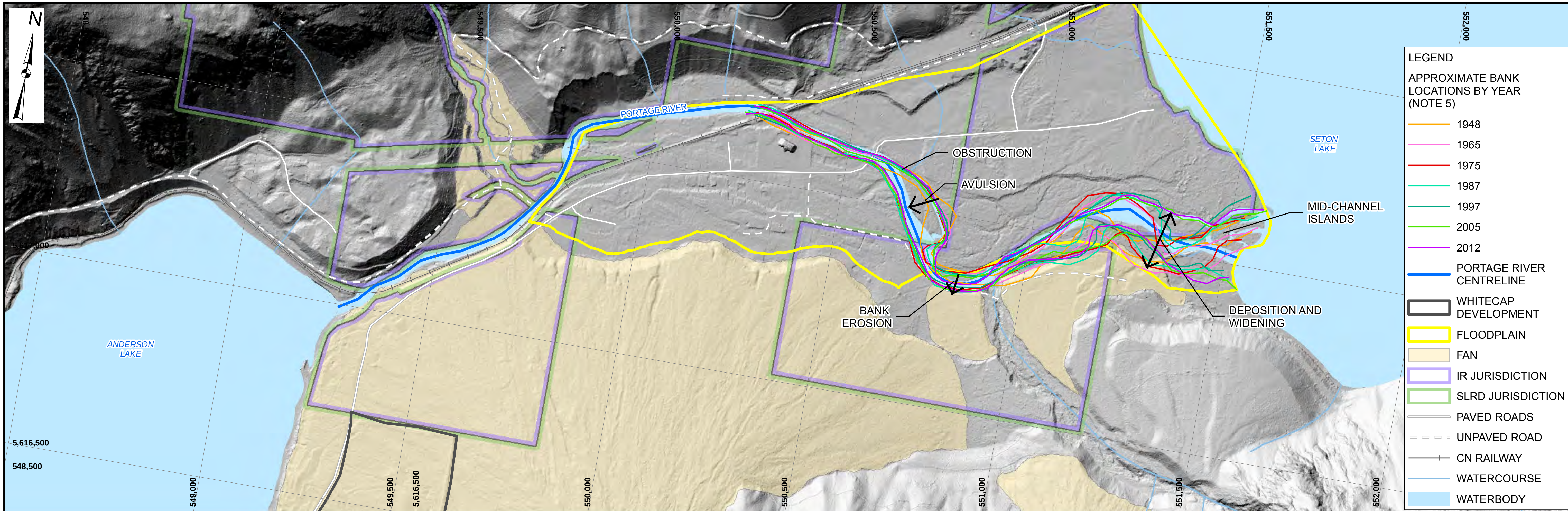

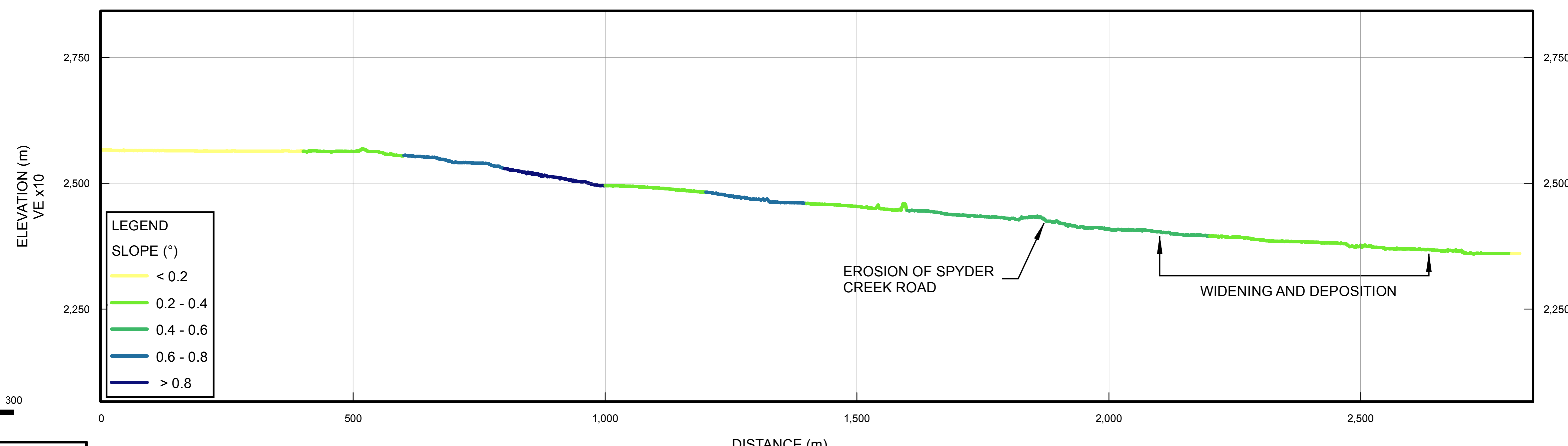

CROSS SECTION A / 06

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PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: PORTAGE RIVER PROFILE

PROJECT No.: 1358005

DWG No: 06

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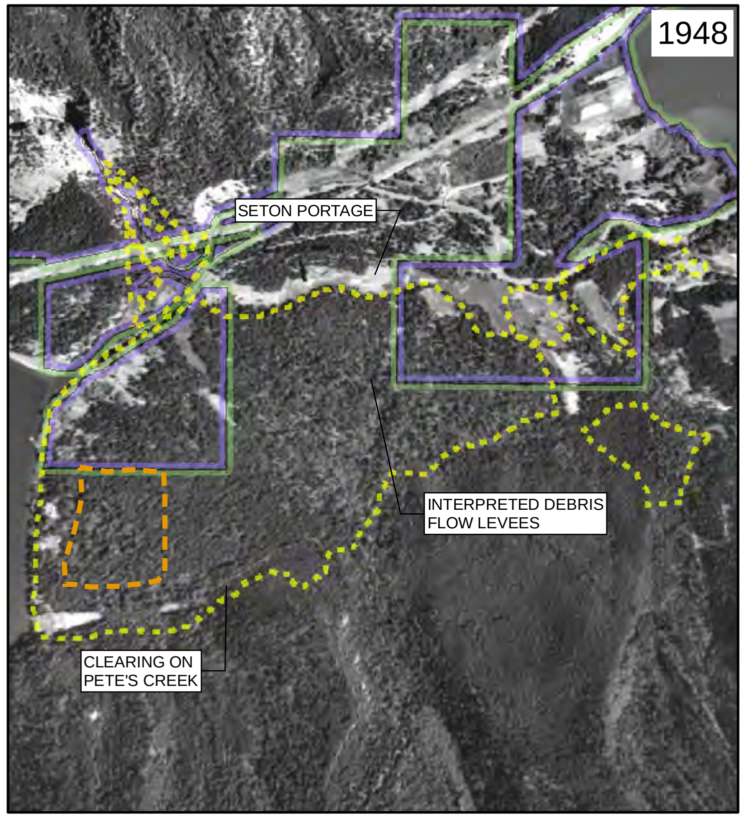

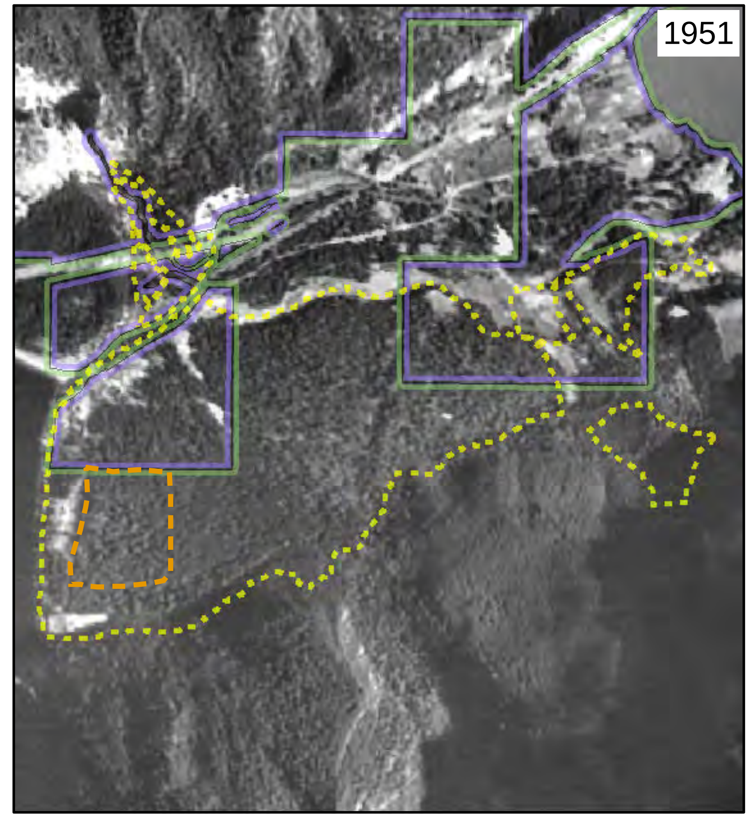

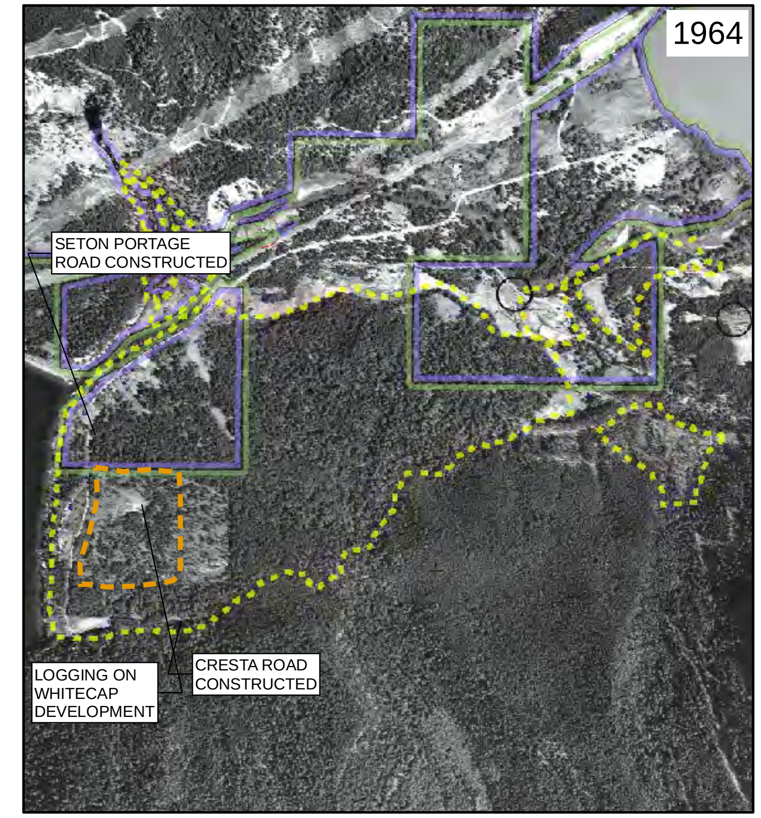

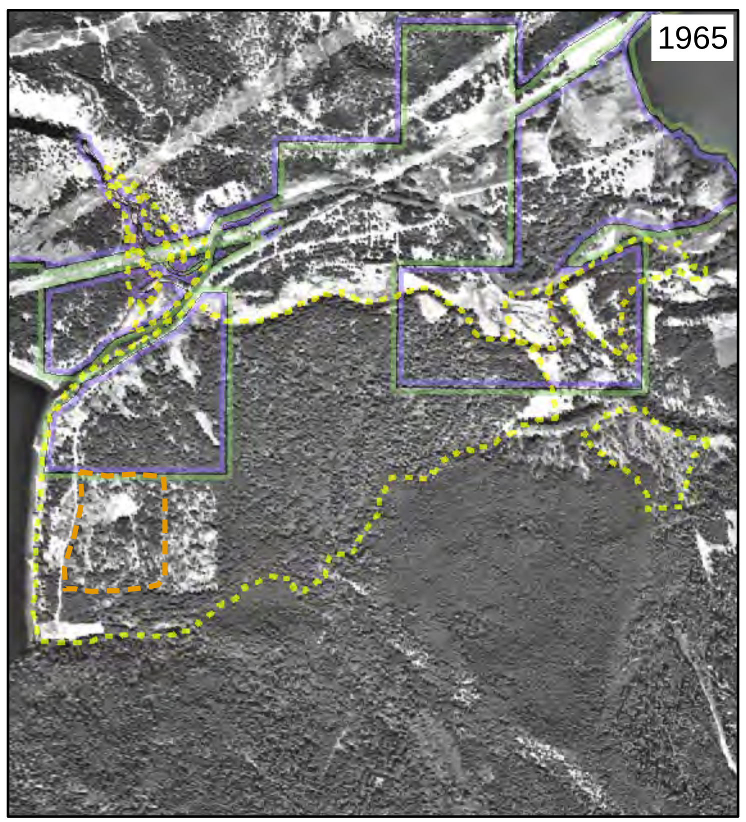

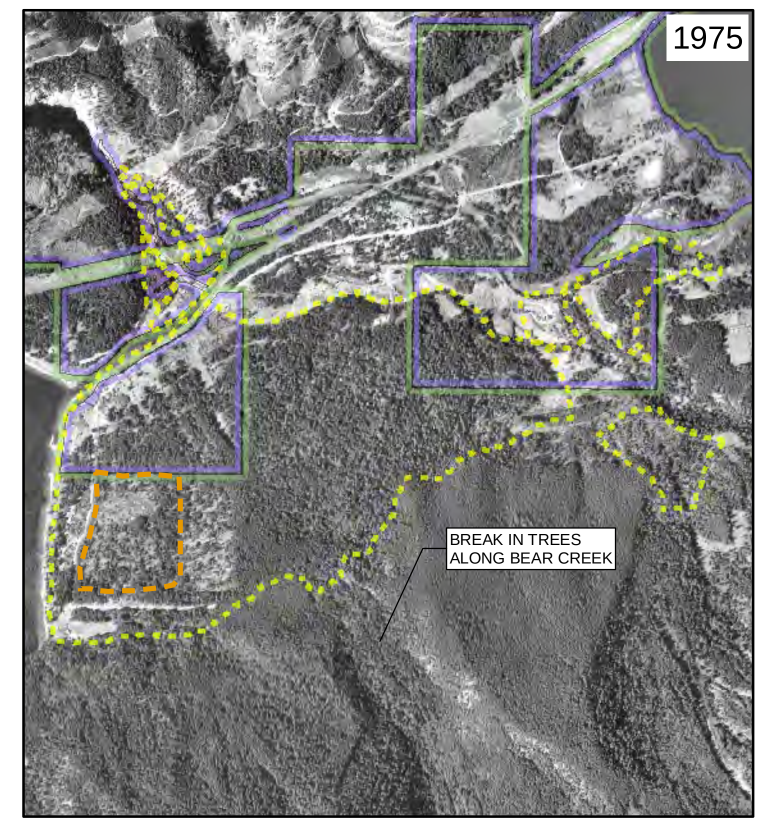

LEGEND

- WHITECAP DEVELOPMENT BOUNDARY
- FAN OUTLINE
- IR JURISDICTION
- SLRD JURISDICTION

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SCALE 1:25,000
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METRES

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4. PROJECTION IS NAD83 UTM ZONE 10N.
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CLIENT: SQUAMISH-LILLOOET REGIONAL DISTRICT

PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: HISTORICAL AIR PHOTO COMPARISON 1

PROJECT No.: 1358005
DWG No: 07

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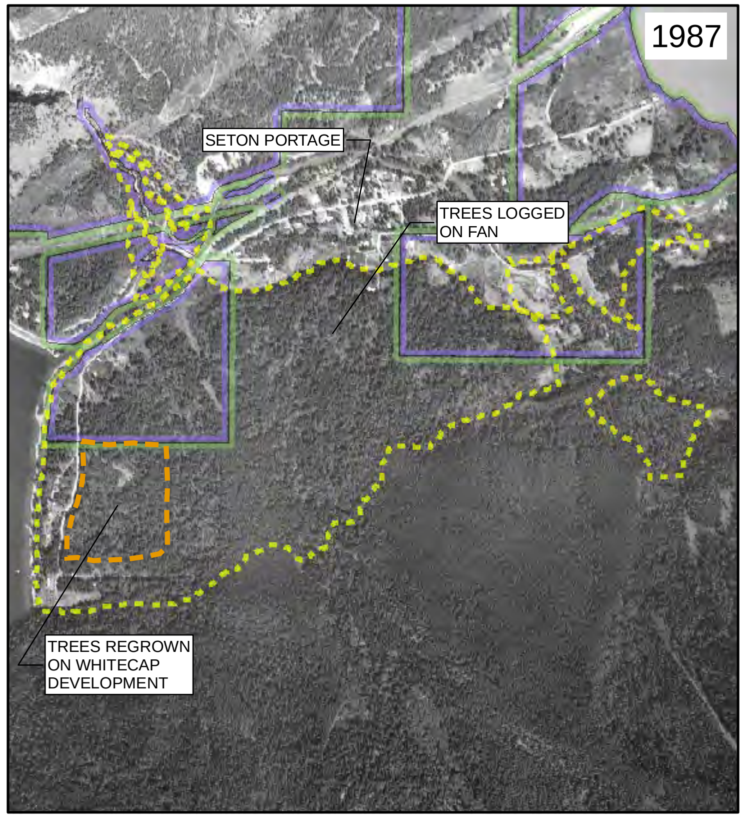

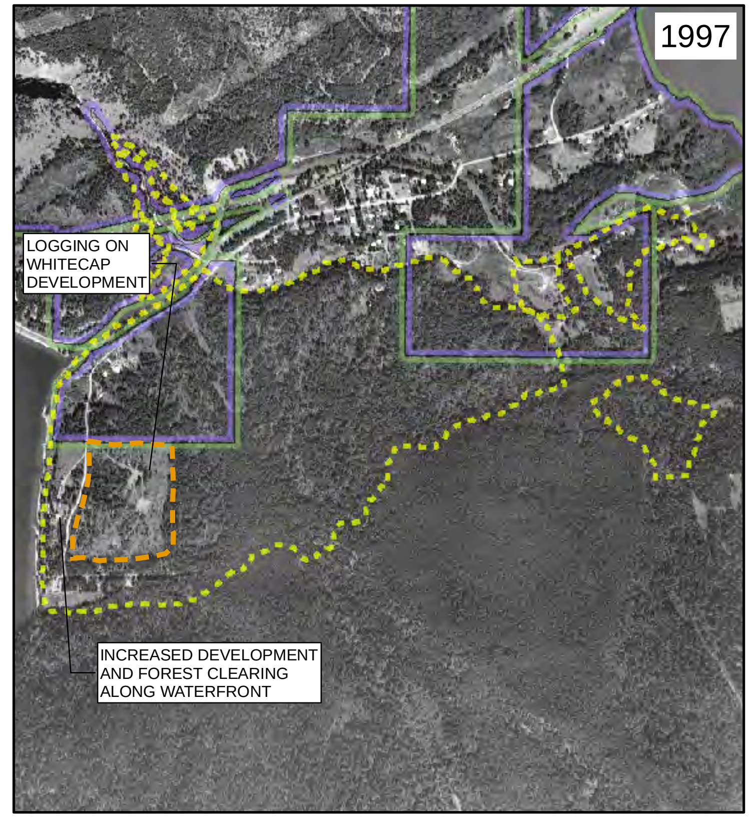

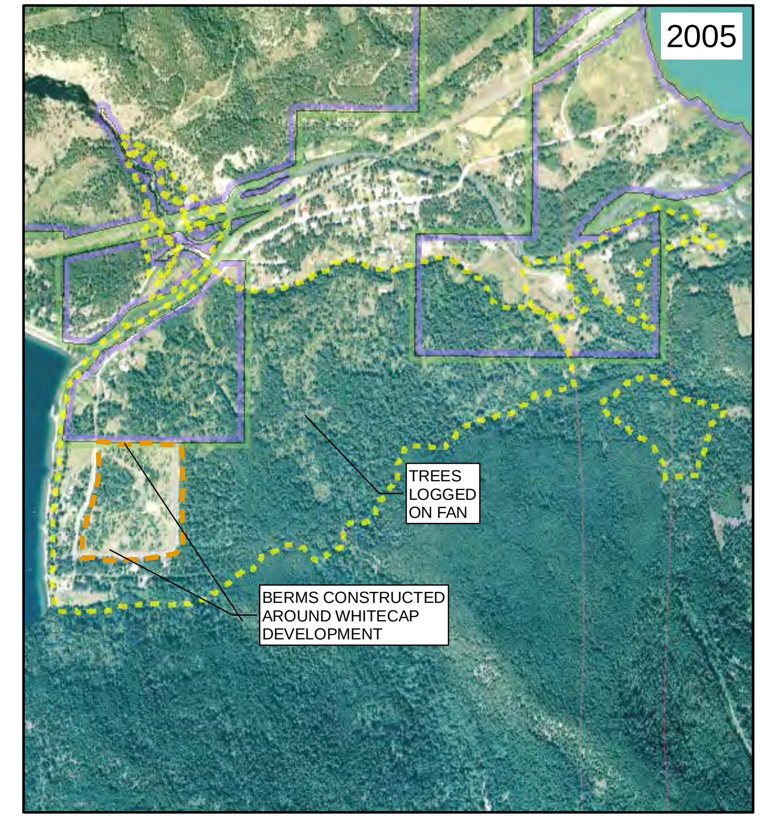

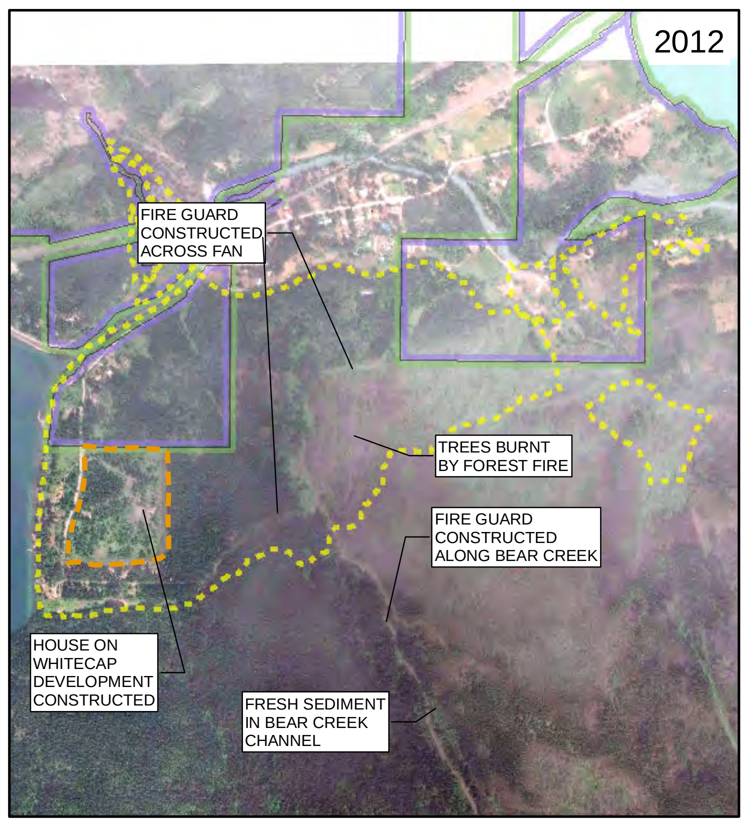

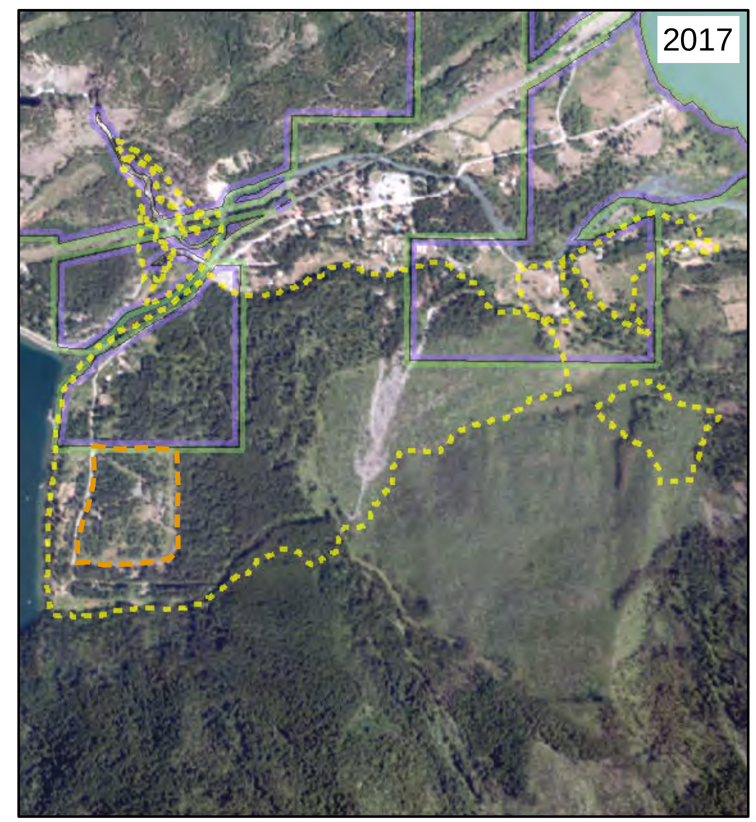

SCALE 1:25,000
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METRES

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LEGEND
- WHITECAP DEVELOPMENT BOUNDARY
- FAN OUTLINE
- IR JURISDICTION
- SLRD JURISDICTION

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PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: HISTORICAL AIR PHOTO COMPARISON 2

PROJECT No.: 1358005

DWG No: 08

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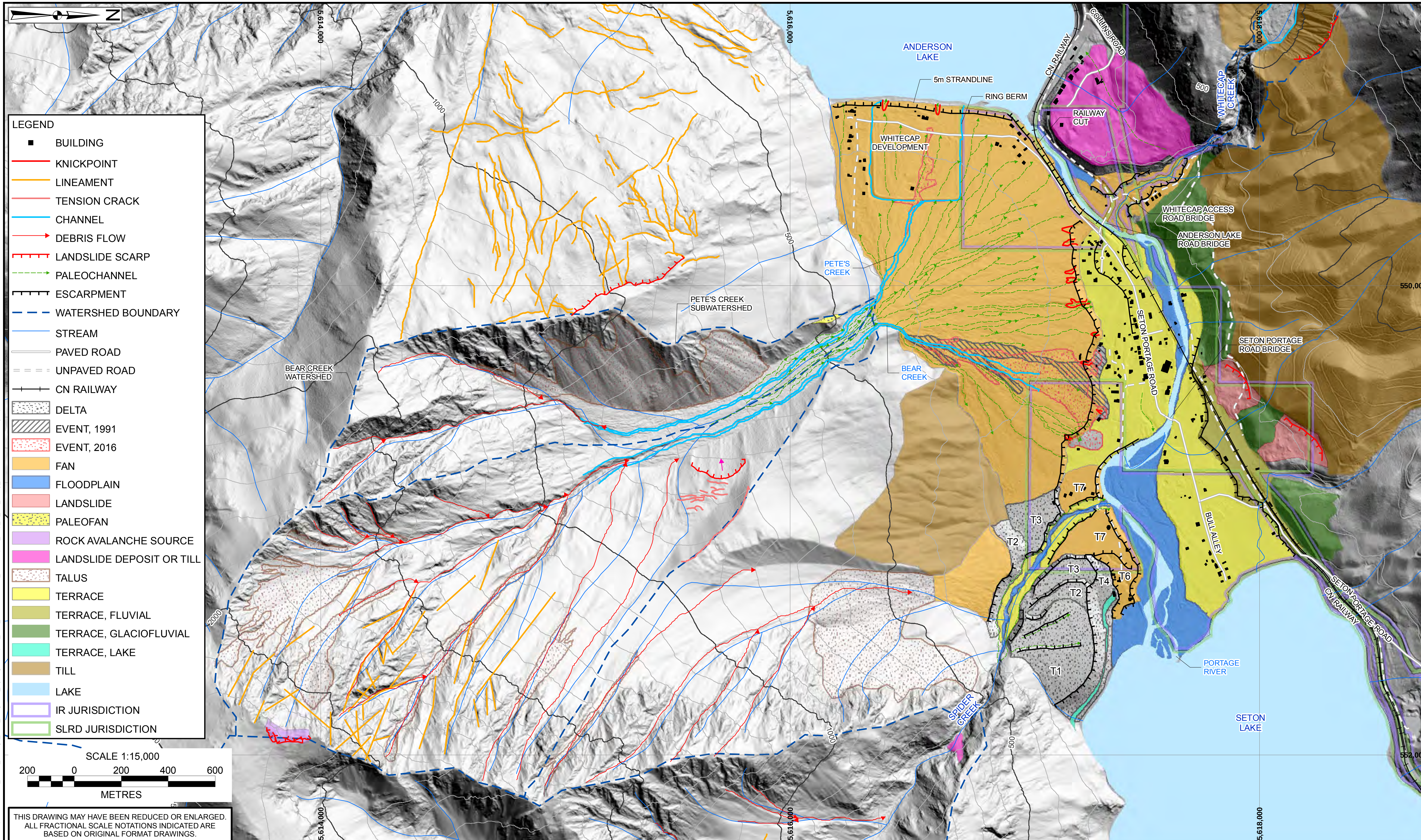

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3. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY FLNRO – THOMPSON OKANAGAN REGION VIA UNBC, DATED OCTOBER 10, 2017. CONTOUR INTERVAL IS 100 m.
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APPROVED:	MJ

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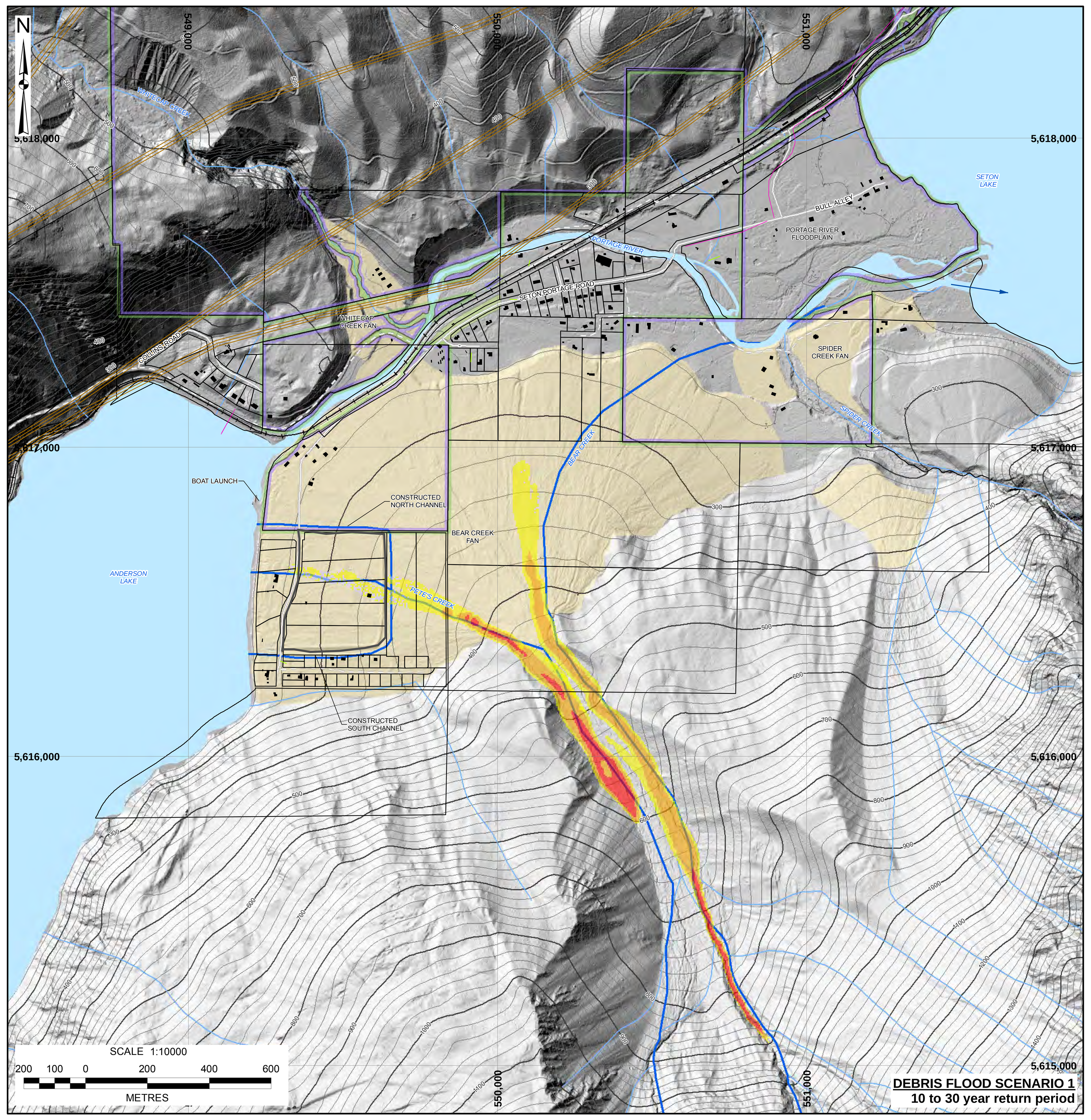
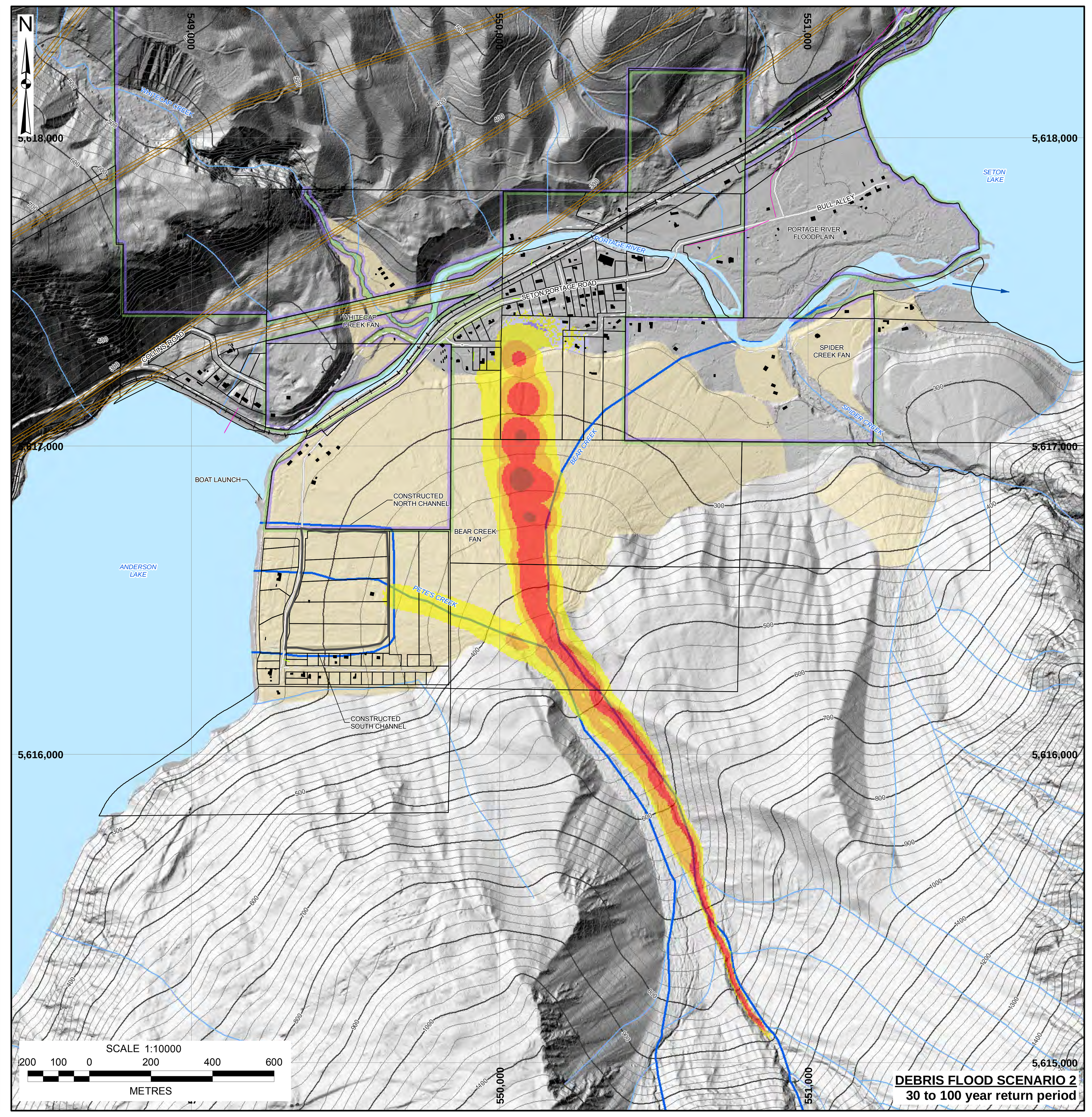
CLIENT:
SQUAMISH-LILLOOET REGIONAL DISTRICT

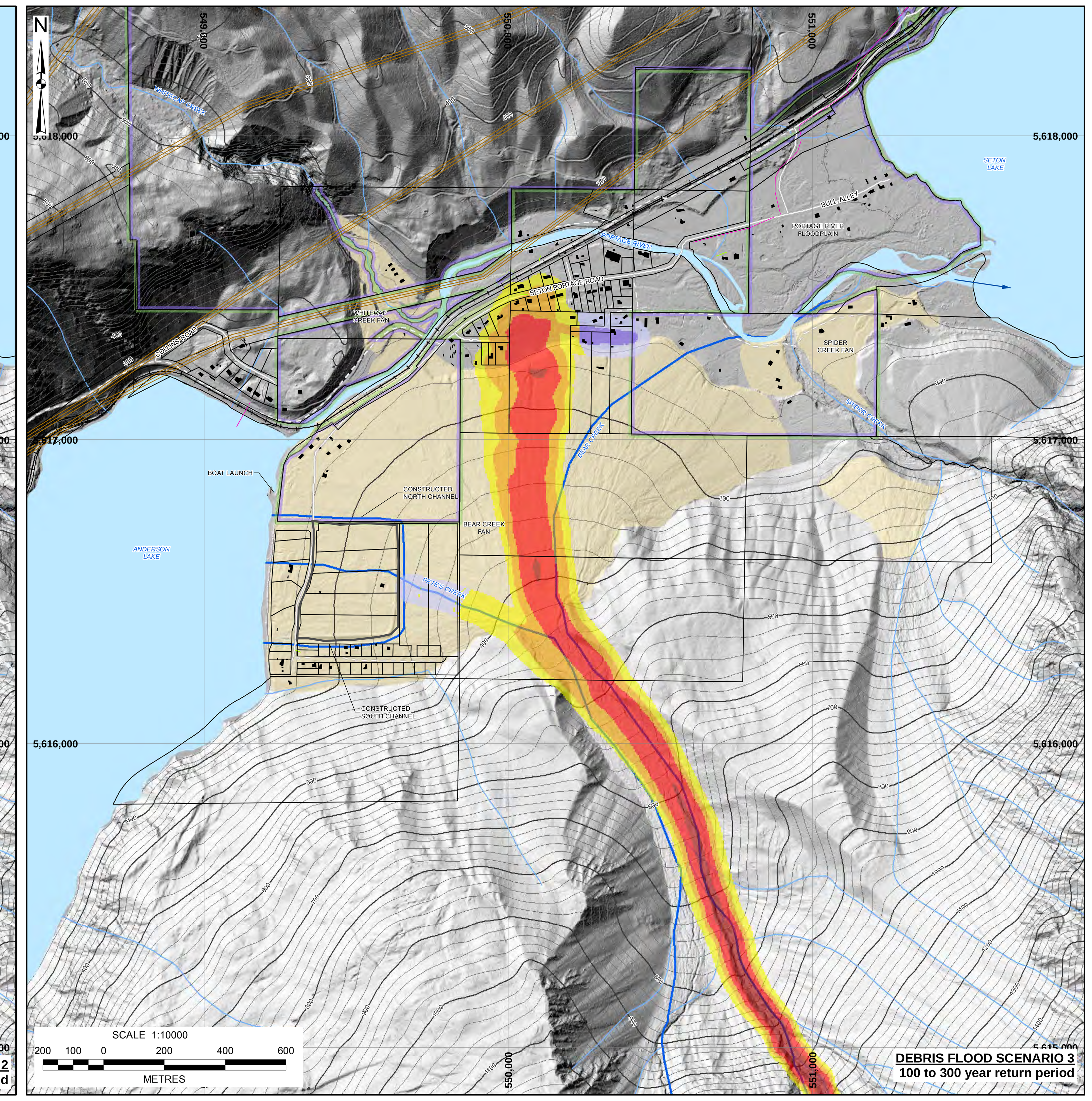
PROJECT:
SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

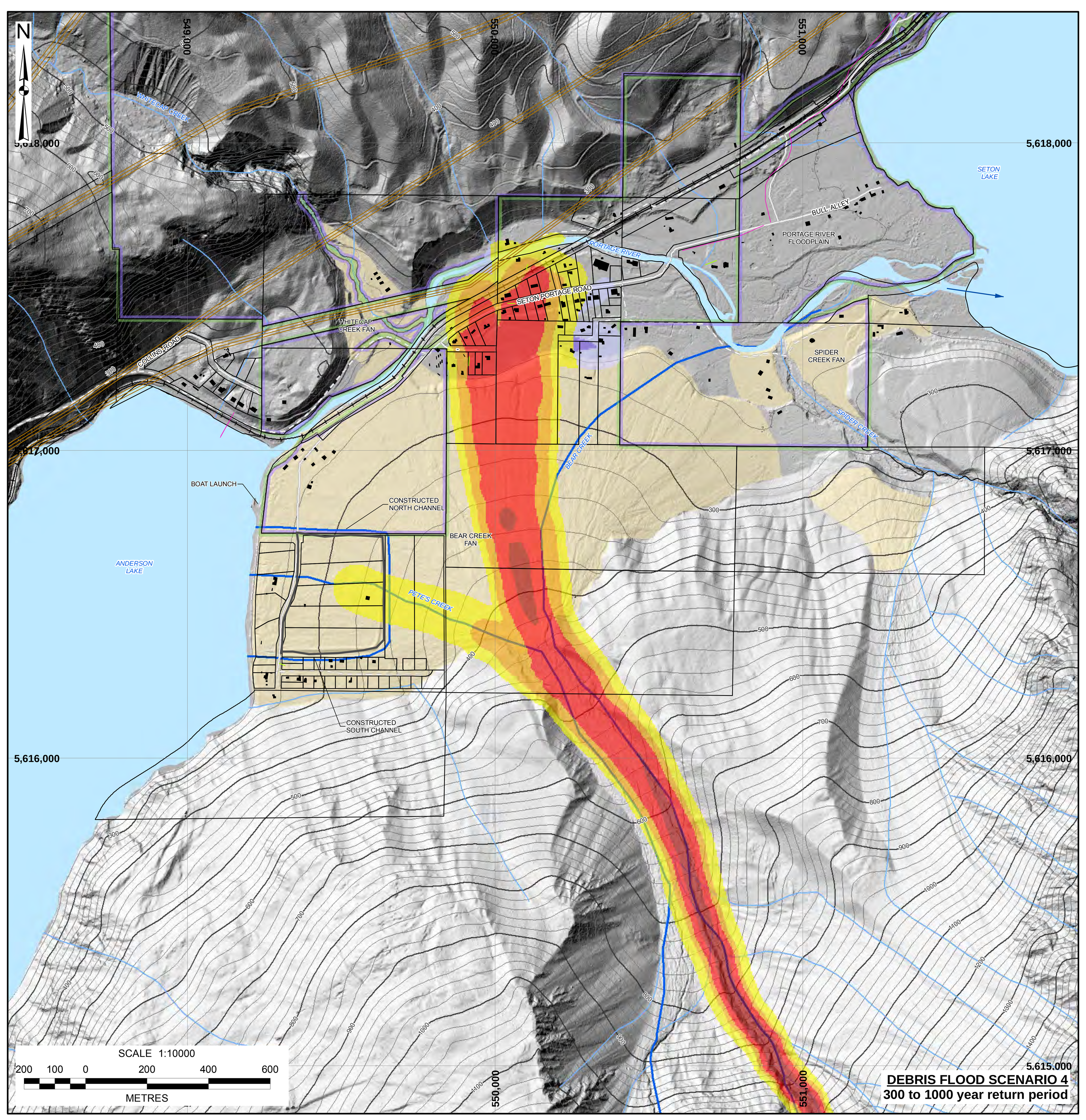
TITLE:
GEOMORPHIC MAP OF THE STUDY AREA

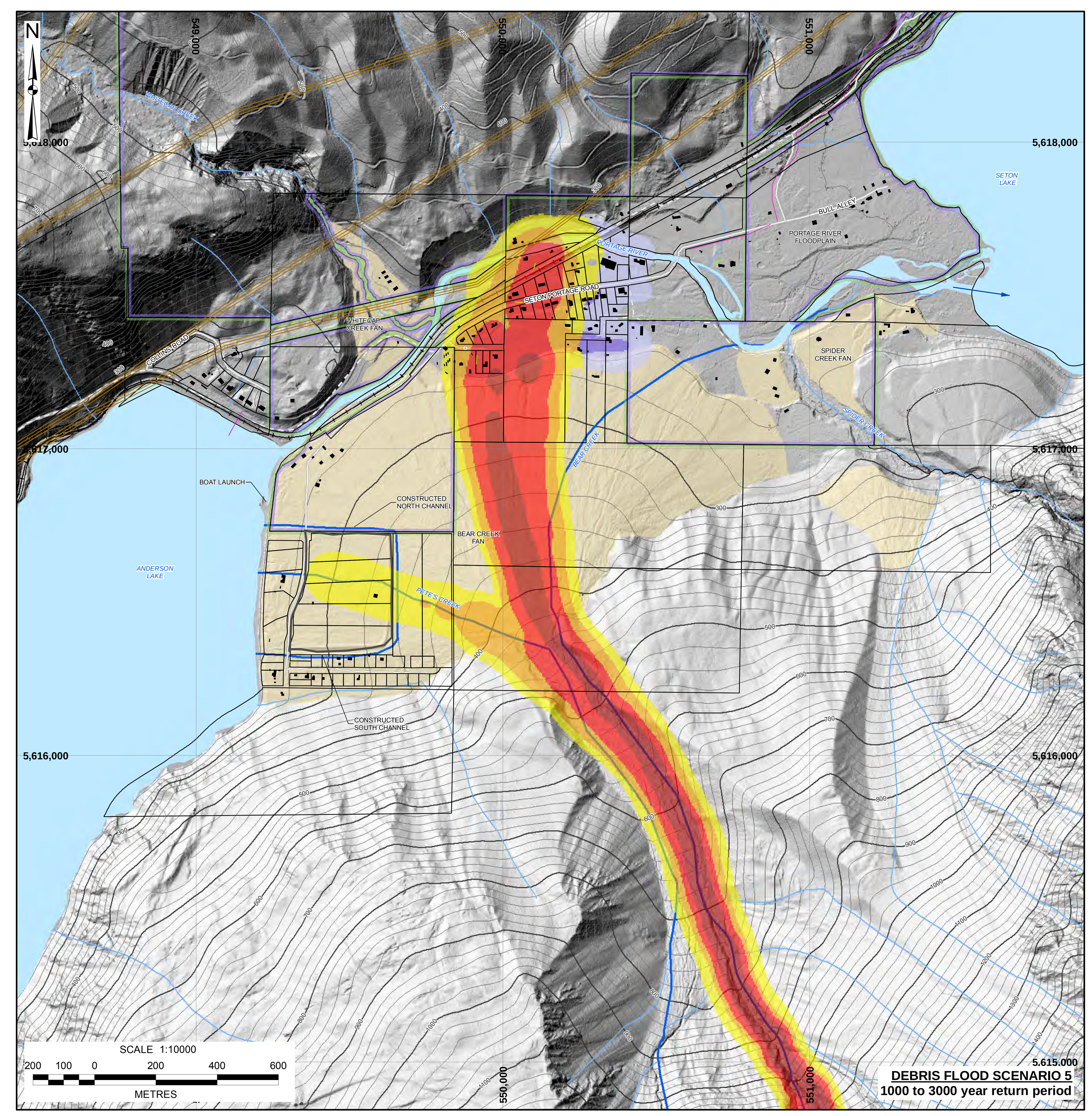
PROJECT No.: 1358005
DWG No: 09











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LEGEND

FLOW DEPTH (m) (v<1 m/s)
- <1
- 1 to 2.5
- > 2.5

INTENSITY INDEX (m^3/s^2) (v > 1 m/s)
- <1
- 1 to 10
- 10 to 100
- >100

- BUILDINGS
- PARCELS
- WHITECAP DEVELOPMENT
- SETON PORTAGE HISTORIC PROVINCIAL PARK
- FAN
- IR JURISDICTION
- SLRD JURISDICTION
- BEAR AND PETE'S CREEKS
- BC HYDRO TRANSMISSION LINE
- BC HYDRO TRANSMISSION LINE (LOCAL)
- SHAW AND TELUS LOCAL LINES
- HIGHWAY
- PAVED ROAD
- UNPAVED ROAD
- CN RAILWAY
- WATERCOURSE
- WATERBODY

NOTES:
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5. WATERCOURSES, WATERBODIES, ROADS AND RAILWAY WERE OBTAINED FROM CANVEC PROVIDED BY NATURAL RESOURCES CANADA, DATED 2011.
6. MODEL RUNS (DEBRIS FLOOD SCENARIOS) ARE LABELLED IN THE LOWER RIGHT HAND CORNER OF EACH MAP INSET.
7. THIS MAP SHOULD NOT BE RELIED UPON AT A SCALE LARGER THAN (MORE DETAILED) THAN SHOWN ON THIS MAP.
8. THIS MAP REPRESENTS A SNAPSHOT IN TIME BASED ON PROPOSED FUTURE CHANGES TO DEBRIS-FLOOD MITIGATION AND DEVELOPMENT DESCRIBED IN THE REPORT. ADDITIONAL FUTURE CHANGES (DEVELOPMENT, DEBRIS-FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
9. PROJECTION IS NAD 83 UTM ZONE 10N.
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CLIENT: SQUAMISH-LILLOOET REGIONAL DISTRICT

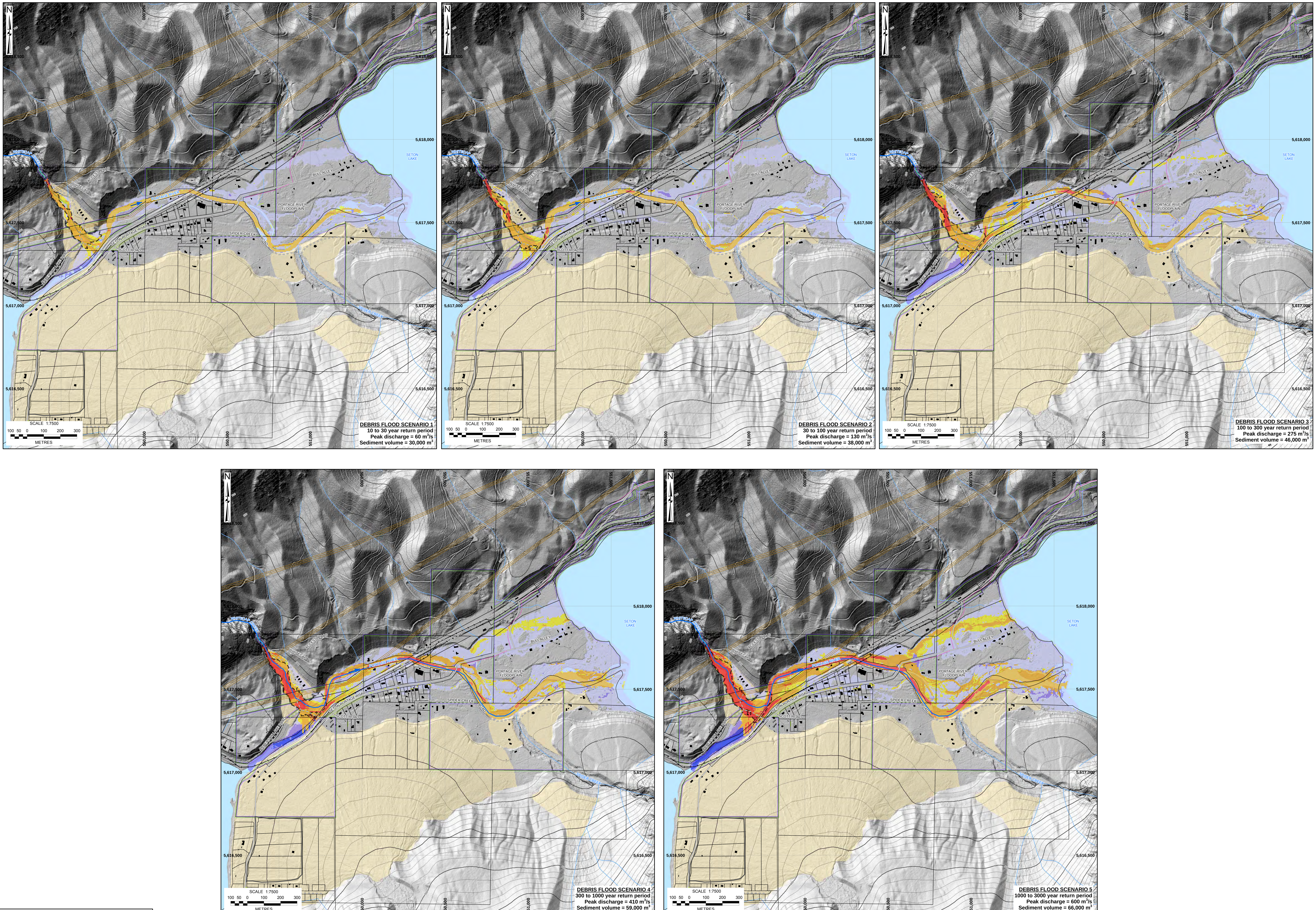
PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: DEBRIS FLOW RUNOUTS AND INTENSITY: BEAR AND PETE'S CREEK

PROJECT No.: 1358005

DWG No.: 10

THIS BAR MEASURES 100 mm AT FULL SIZE. ALL SCALES REFERENCED TO FULL SIZE



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LEGEND

FLOW DEPTH (m) ($v \le 1$ m/s)
- < 1
- 1 to 2.5
- > 2.5

INTENSITY INDEX (m^3/s^2) ($v > 1$ m/s)
- < 1
- 1 to 10
- 10 to 100
- > 100

- SEDIMENT DEPOSITION AREA (SEE NOTE 8)
- BUILDINGS
- PARCELS
- WHITECAP DEVELOPMENT
- SETON PORTAGE HISTORIC PROVINCIAL PARK
- FAN
- IR JURISDICTION
- SLRD JURISDICTION
- WHITECAP CREEK
- BC HYDRO TRANSMISSION LINE
- BC HYDRO TRANSMISSION LINE (LOCAL)
- SHAW AND TELUS LOCAL LINES
- PAVED ROAD
- UNPAVED ROAD
- RAILWAY
- WATERCOURSE
- WATERBODY

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3. PARCELS, AND UTILITIES WERE OBTAINED FROM THE SLRD. EXISTING BUILDINGS DIGITIZED BY BGC FROM ORTHOIMAGERY PROVIDED BY FLNRO – THOMPSON OKANAGAN REGION VIA UNBC, DATED OCTOBER 10, 2017. BUILDING LOCATIONS FOR POTENTIAL FUTURE DEVELOPMENT ARE UNKNOWN, BUILDINGS SHOWN ON MAP ARE REPRESENTATIVE ONLY.
4. WATERCOURSES, WATERBODIES, ROADS AND RAILWAY WERE OBTAINED FROM CANVEC PROVIDED BY NATURAL RESOURCES CANADA, DATED 2011.
5. BASE TOPOGRAPHIC DATA BASED ON LIDAR PROVIDED BY FLNRO – THOMPSON OKANAGAN REGION VIA UNBC, DATED OCTOBER 10, 2017. CONTOUR INTERVAL IS 20 m.
6. MODEL RUNS (DEBRIS FLOOD SCENARIOS) ARE LABELLED IN THE LOWER RIGHT HAND CORNER OF EACH MAP INSET.
7. WITHIN THE DELINEATED DEPOSITION AREAS, THE TOPOGRAPHY WAS INCREASED BY UP TO 3 m TO ACCOUNT FOR SEDIMENT DEPOSITION. THE VOLUME OF SEDIMENT ADDED IS SPECIFIED FOR EACH SCENARIO.
8. THIS MAP SHOULD NOT BE RELIED UPON AT A SCALE LARGER THAN (MORE DETAILED) THAN SHOWN ON THIS MAP.
9. THIS MAP REPRESENTS A SNAPSHOT IN TIME BASED ON PROPOSED FUTURE CHANGES TO DEBRIS-FLOOD MITIGATION AND DEVELOPMENT DESCRIBED IN THE REPORT. ADDITIONAL FUTURE CHANGES (DEVELOPMENT, DEBRIS-FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
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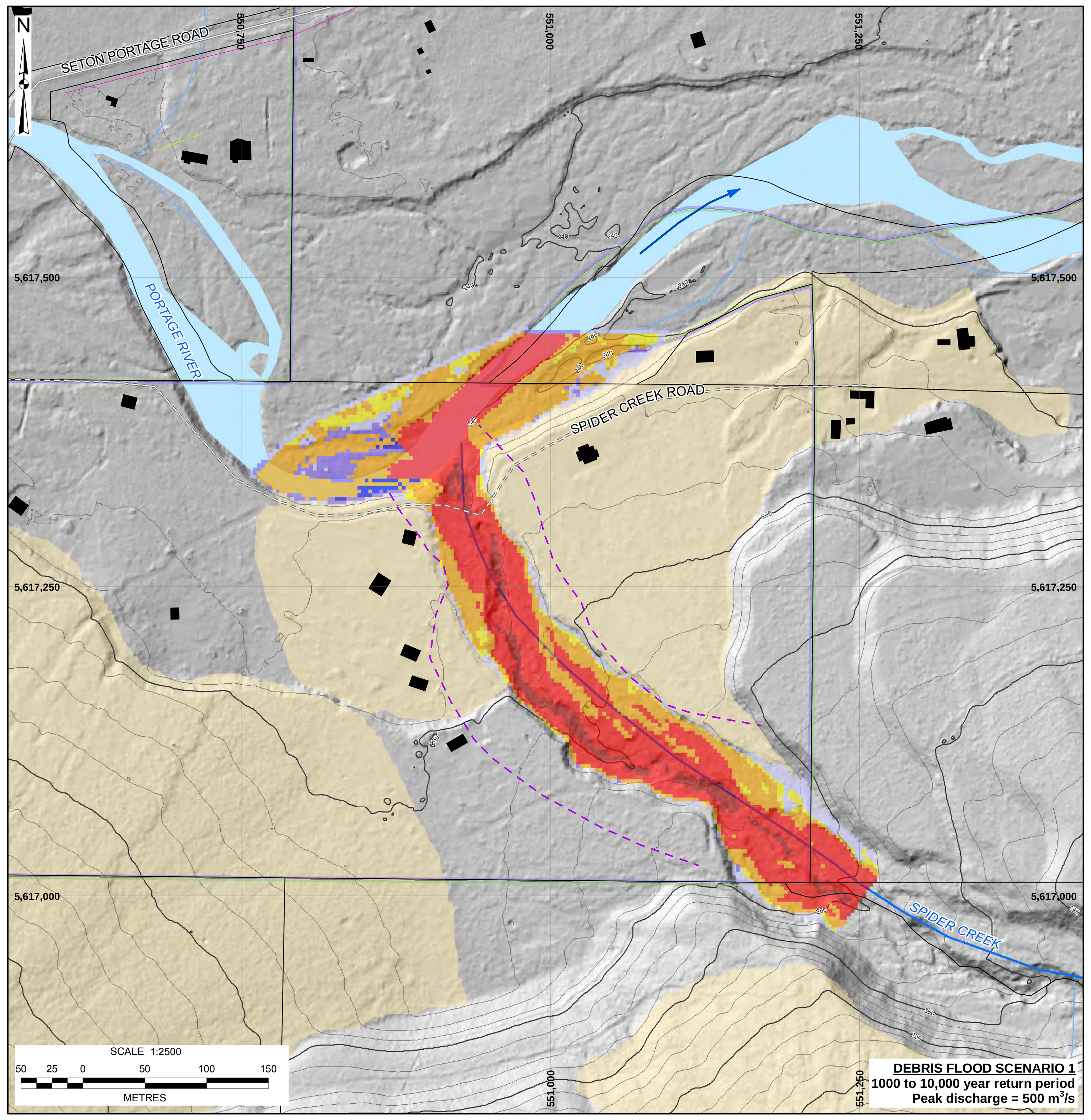
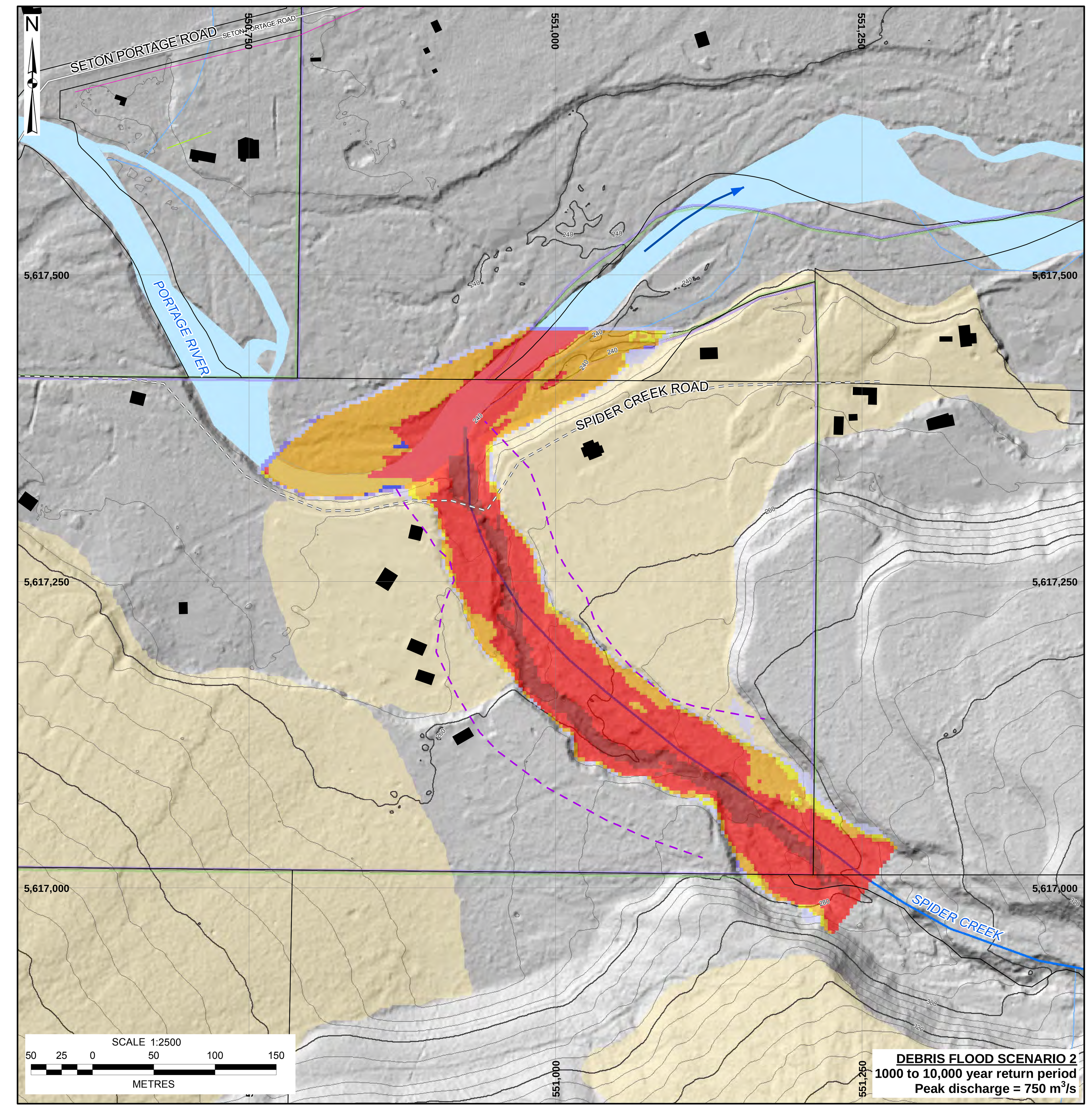
PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

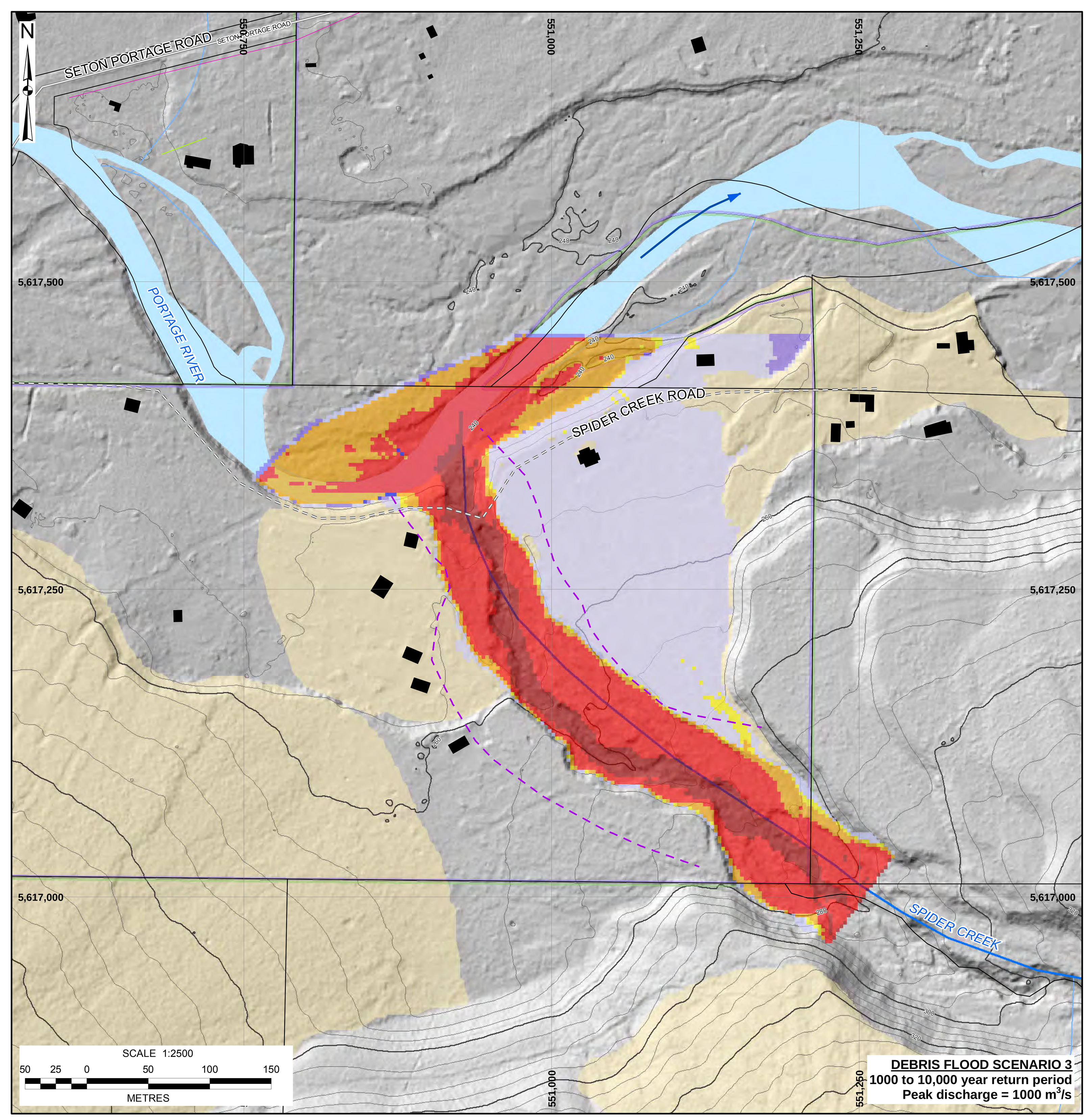
TITLE: DEBRIS FLOOD RUNOUTS AND INTENSITY: WHITECAP CREEK

PROJECT No.: 1358005

DWG No.: 11







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LEGEND

FLOW DEPTH (m) ($v \leq 1$ m/s)
- < 1
- 1 to 2.5
- > 2.5

INTENSITY INDEX (m^3/s^2) ($v > 1$ m/s)
- < 1
- 1 to 10
- 10 to 100
- > 100

- POTENTIAL BANK EROSION EXTENT 1000 YEAR EVENT
- BUILDINGS
- PARCELS
- WHITECAP DEVELOPMENT
- FAN
- IR JURISDICTION
- SLRD JURISDICTION
- SPIDER CREEK
- BC HYDRO TRANSMISSION LINE (LOCAL)
- SHAW AND TELUS LOCAL LINES
- PAVED ROAD
- UNPAVED ROAD
- WATERCOURSE
- WATERBODY

NOTES:
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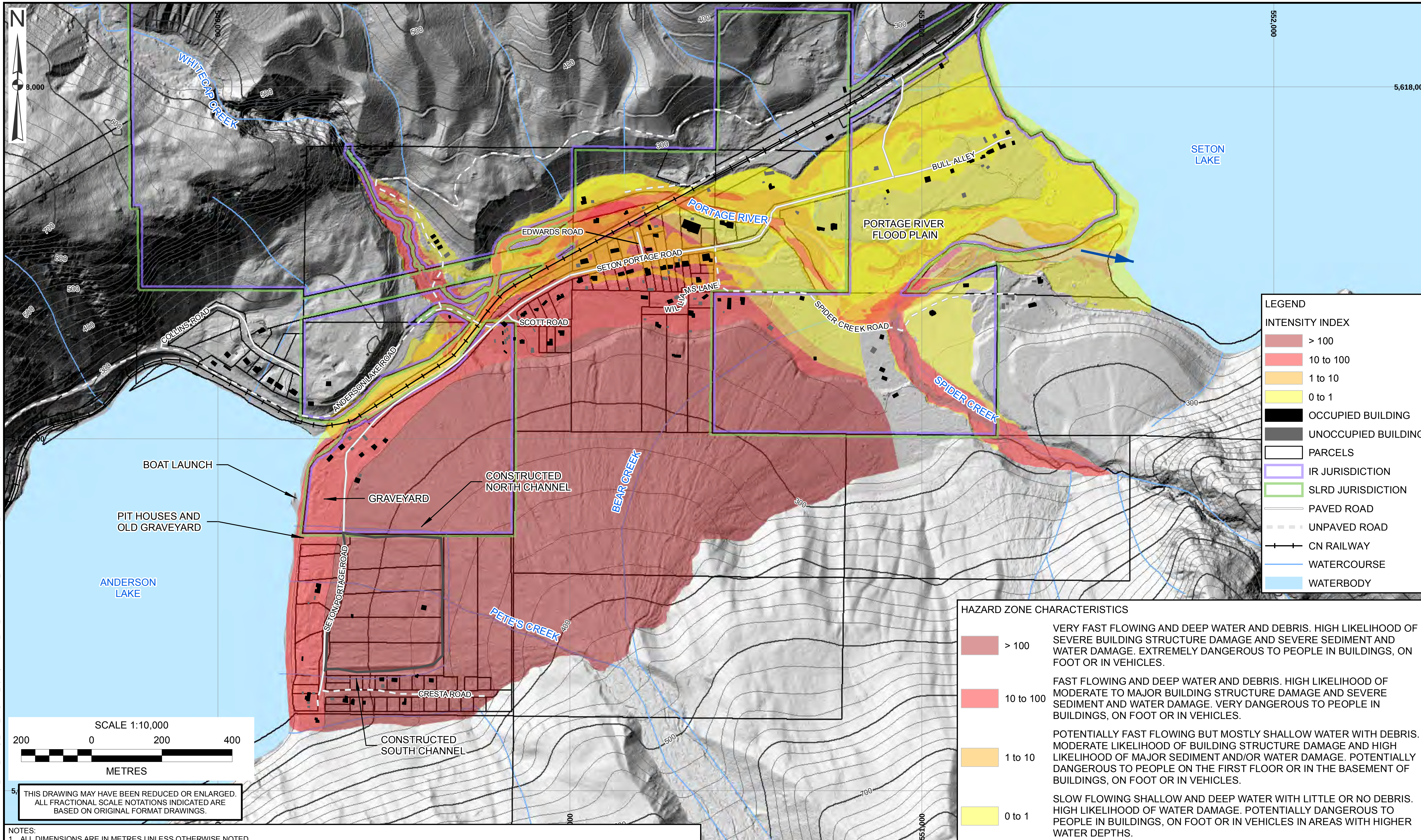
PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: DEBRIS FLOOD RUNOUTS AND INTENSITY: SPIDER CREEK

PROJECT No.: 1358005

DWG No.: 12

THIS BAR MEASURES 100 mm AT FULL SIZE. ALL SCALES REFERENCED TO FULL SIZE



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4. PARCELS AND UTILITIES PROVIDED BY THE SLRD. ROADS, RAILWAY AND WATERWAYS OBTAINED FROM CANVEC PROVIDED BY NATURAL RESOURCES CANADA, DATED 2011.
5. BUILDINGS DIGITIZED BY BGC USING ORTHOIMAGERY PROVIDED BY FLNRO – THOMPSON OKANAGAN REGION VIA UNBC, DATED OCTOBER 10, 2017.
6. PROJECTION IS NAD 1983 UTM ZONE 10N.
7. THIS MAP SHOWS MAXIMUM HAZARD INTENSITIES FOR ALL GEOHAZARD SCENARIOS ASSESSED ON WHITECAP, BEAR/PETE'S, AND SPIDER CREEKS.
8. THIS MAP REPRESENTS A SNAPSHOT IN TIME BASED ON PROPOSED FUTURE CHANGES TO DEBRIS-FLOOD MITIGATION AND DEVELOPMENT DESCRIBED IN THE REPORT. ADDITIONAL FUTURE CHANGES (DEVELOPMENT, DEBRIS-FLOOD MITIGATION, GEOHAZARD EVENTS) MAY WARRANT RE-DRAWING OF CERTAIN AREAS.
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CHECKED:	SK
APPROVED:	KH

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AN APPLIED EARTH SCIENCES COMPANY

CLIENT: SQUAMISH-LILLOOET REGIONAL DISTRICT (SLRD)

PROJECT: SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE: COMPOSITE HAZARD MAP

PROJECT No.: 1358005

DWG No.: 13

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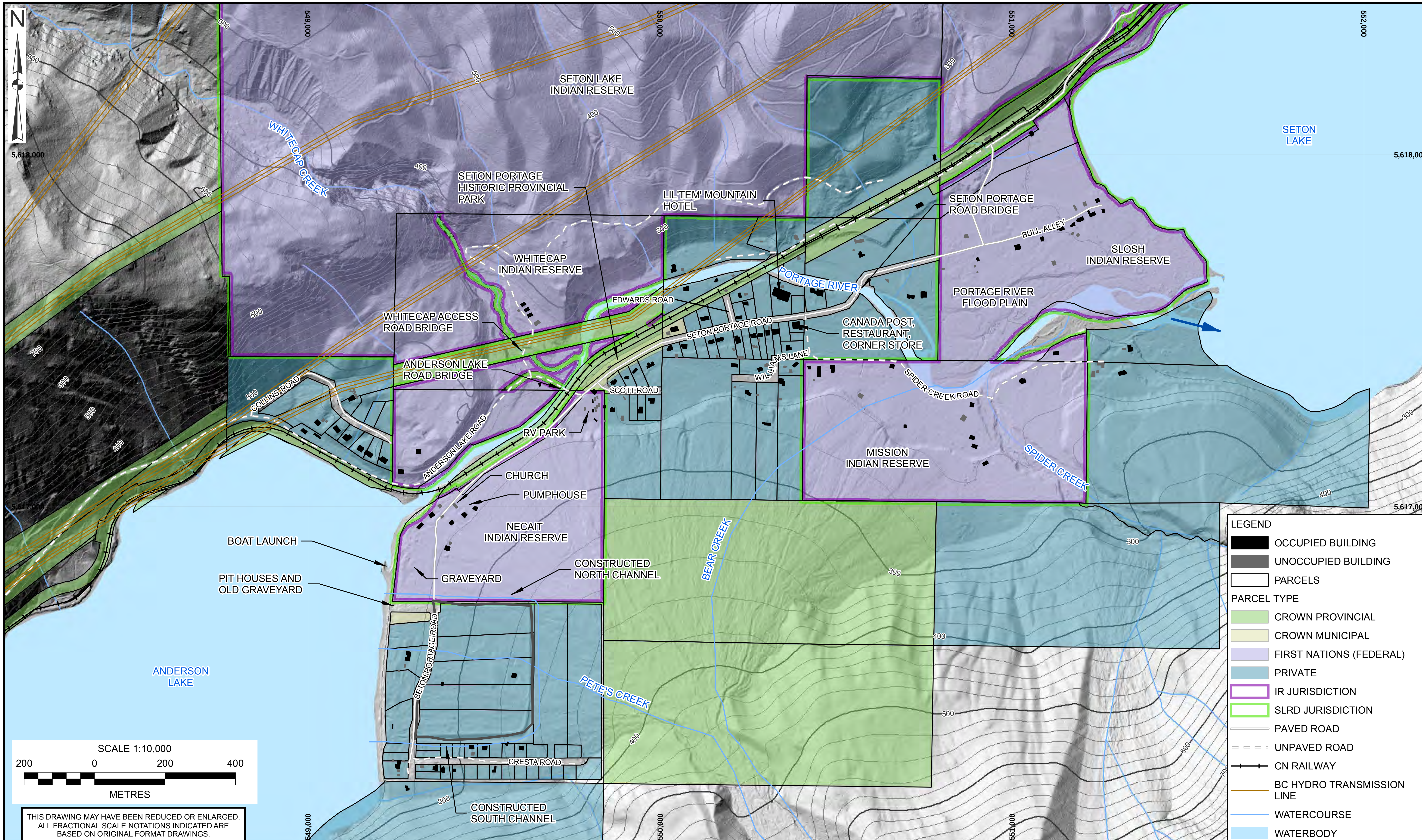

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CLIENT:
SQUAMISH-LILLOOET REGIONAL DISTRICT (SLRD)

PROJECT:
SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE:
RISK ASSESSMENT BASEMAP

PROJECT No.: 1358005
DWG No.: 14

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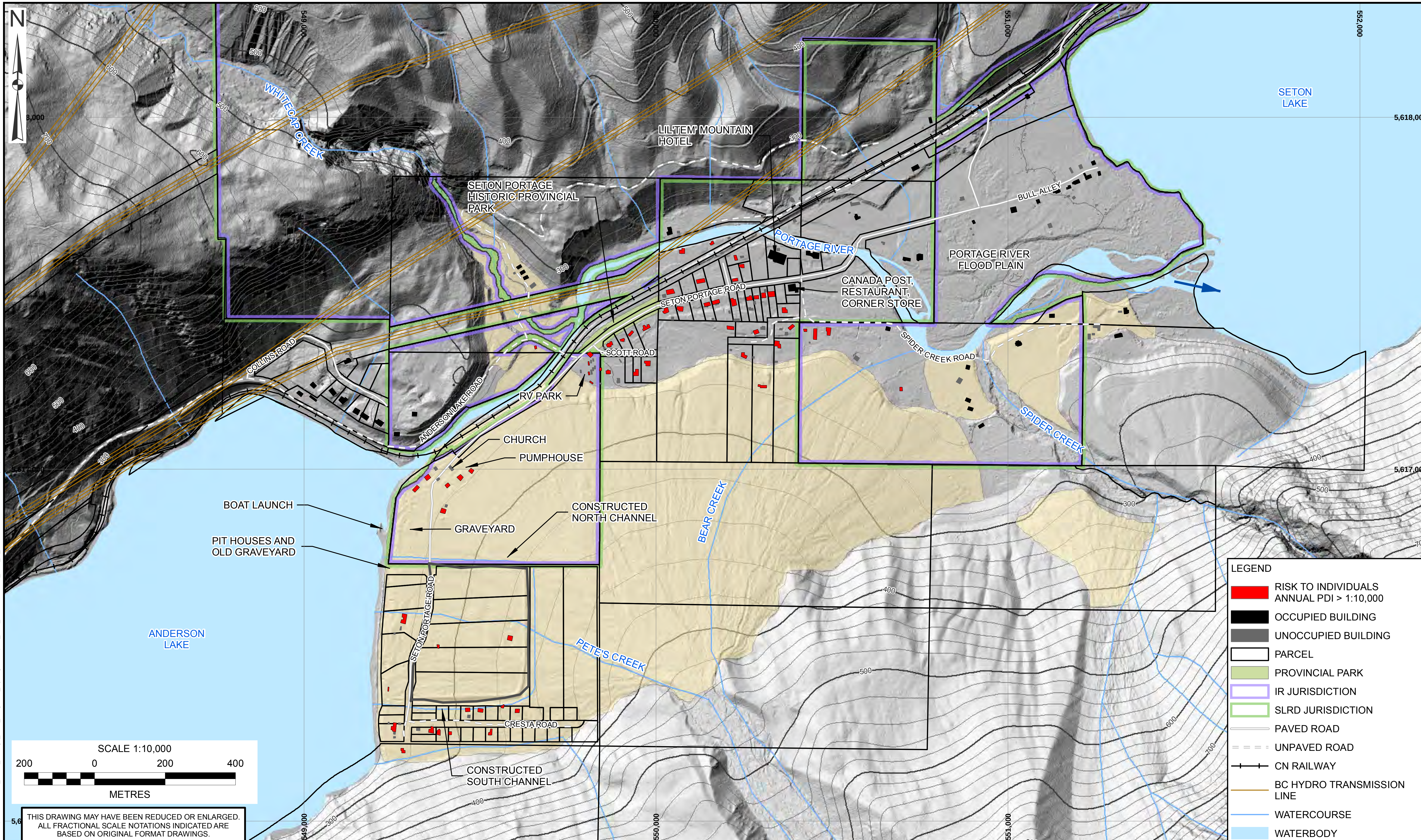

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4. PARCELS AND UTILITIES OBTAINED FROM THE SLRD. WATERCOURSES, WATERBODIES, ROADS AND RAILWAY WERE OBTAINED FROM CANVEC PROVIDED BY NATURAL RESOURCES CANADA, DATED 2011.
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CHECKED:	SK
APPROVED:	KH

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
SQUAMISH-LILLOOET REGIONAL DISTRICT (SLRD)

PROJECT:
SETON PORTAGE AREA INTEGRATED HYDROGEOMORPHIC RISK ASSESSMENT

TITLE:
RISK TO INDIVIDUALS

PROJECT No.: 1358005
DWG No.: 15

APPENDIX A
PREVIOUS EVENTS AND ASSESSMENTS

APPENDIX A – PREVIOUS EVENTS AND ASSESSMENTS

This appendix provides an overview of previous debris flows and debris floods on Bear, Pete's, Whitecap and Spider creeks.

A.1. BEAR & PETE'S CREEK

A.1.1. Anecdotal Reports

- According to a geocache website[1], Portage River was completely blocked by a huge slide originating from the Bear Creek watershed in 1907. Lillooet residents, noting that the level of Seton Lake and the creeks were lowering rapidly, went up by boat to investigate. They found the Seton Portage River blocked completely by a huge slide, and its waters flowing back into Anderson Lake. The spring freshet soon broke through the slide, and a new river channel was formed. Attempts to confirm this event by BGC were unsuccessful. It is unclear if the event occurred on Whitecap or Bear creeks. No dendrochronological dates were able to confirm the event either.
- In early spring of 1964, a debris flow occurred on Bear Creek (noted in Thurber 2004 as unconfirmed by air photos). The debris flow was reportedly triggered by a rain on snow event which triggered three simultaneous slides. The debris flow travelled at a speed of 3 to 4 mph (5 to 6.5 km/h), slow enough that people could walk ahead of the debris as it travelled down the slope. According to Mr. R. James, the debris stopped approximately 200 yards (183 m) above the church in Necait (Drawing 02), travelled over to the upper house and travelled all the way to the road at the RV park. The Casper residence was filled with approximately 6 inches (0.15 m) of debris.
- In 1974, a debris flow on Bear Creek occurred that reached the home on the northeast corner of Seton Portage Road and Cresta Road. This information is based on a conversation with a resident and no additional information is known about this event.

A.1.2. Terratech (1991)

In 1991, Terratech Western Profile Consultants Inc. (Terratech) was retained by the BC Ministry of Environment to review debris-flow hazards at Bear Creek. Their scope included a 1-day field visit, a review of debris-flow hazards to private properties, discussion of mitigation measure options, recommendations of further study.

Two debris flows occurred in 1991, one on August 19 and one on August 29. Both debris flows appeared to have reached the Portage River floodplain. Debris flow depth at the Harvey Lavigne house (Drawing 02), situated on the top of the truncated debris flow fan above the Portage River floodplain, were recorded as 0.4 to 0.5 m and had a width ranging from 10 to 15 m. As the flow arrived on the Portage River floodplain it spread, thinned and filled depressions with sand, silt and

[1] https://www.geocaching.com/geocache/GC16E8E_seton-portage-earthcache?guid=b1b6910f-f926-497a-a9cc-2ac27a65c884. Accessed December 5, 2017.

clay according to Terratech. Terratech noted that near the Lavigne house debris flows with flow depths of 1 m or greater had reached the edge of the truncated fan.

Terratech differentiated a fan apex, transport and deposition zone and mapped different channels. They characterized these zones in terms of gradient, morphologic characteristics and grain size. Terratech also interpreted the eastern portions of the fan as having relatively higher debris-flow activity and estimated that older, larger debris flows had occurred between 50 and 200 years ago. Near the fan apex, Terratech (1991a) noted that events were observed some 2 and 15 years ago, though it was not specified how these dates were derived.

The sediment volume of the 1991 event was not quantified by Terratech. However, they state that the debris flows that occurred some 50 to 200 years ago may have been as much as four times the 1991 volume.

Several mitigation alternatives were discussed by Terratech, though their report concluded that the assessment did not meet the necessary standards for the design of mitigation works. Specifically, they encouraged the development of a ‘design magnitude’. In a follow-up document (Terratech 1991b), their scope expanded and entailed: (a) advice on clear water flood channelization, (b) advice on flood-proofing the Lavigne house, and (c) to comment on meteorological and hydrologic conditions triggering landslides in the watershed.

A.1.3. LaCas (2000)

In 2000, LaCas Consultants Inc. (LaCas) and EBA Engineering (EBA) was retained by Mr. R. (Bob) Boyar of Seton Portage to provide engineering services relating to identification of the flood and debris-flow hazard on his property and to provide engineering to design mitigative works. The LaCas report made reference to previous work, including Terratech (1991).

The purpose of the assessment was to assess possible flooding and debris-flow hazards, which might impact the development, and to recommend mitigative measures to minimize the risk to acceptable levels.

LaCas (2000) made the following observations concerning debris-flow hazards on Bear Creek (paraphrased by BGC):

1. Because of the large silt and sand fine fraction, debris flows appear to be quite mobile and can run considerable distances as lobes or tongues of debris on the moderately sloping (10-15°) fan surface.
2. Stalls of surges in Bear Creek may lead to avulsions directed towards the Whitecap Development.
3. A debris flow occurred in 1991 on Bear Creek.
4. A “very old” (possibly hundreds of years) debris lobe was identified near the eastern portion of the Whitecap Development. The age was judged based on the observation by LaCas (2000) that there were no impacted trees upstream. However, a tree impact scar with an impact boulder was identified on the southeast corner of the Whitecap Development.

5. Debris flow and deposition were interpreted to be unlikely to travel far beyond the southeast corner of the Development because of the low gradient of the slope (9°), and the lack of effective channel confinement.
6. LaCas (2000) interpreted that the only apparent hazards were limited debris flow impact at the southeast corner of the property and diverted flood flow down the southern flank of the site.

Based on the above observations, the following assumptions and design principals were applied by LaCas (2000):

- The entire (100%) Bear Creek flood flow could avulse from its existing channel and flow towards the upper boundary of the Whitecap Development.
- The instantaneous peak flow accompanying a debris-laden flow could be in the range of 10 to 20 m^3/s which is about five times the 200-year return period peak instantaneous flow (Q_{i200}), or 4.4 m^3/s).
- The flood and debris flow would be directed into and contained within an excavated run-out channel parallel to the southern property line extending to Anderson Lake.
- A flood and debris flow deflection berm would separate the habitable areas from the run-out channel above Seton Road and train the debris flows along the run-out channel through to Anderson Lake.
- A continuous berm and perimeter ditch would intercept and direct land runoff to Anderson Lake without transferring hazard risk to lands outside of the Whitecap Development.
- A second-line of defense would require that a 10-m wide tree belt (no-build zone) be planted and maintained inside of the berm.
- A third-line of defense would require that all habitable areas behind the berm would be raised a minimum of 1 m above the finished grade and foundations and/or earth-fills would be protected against erosion and scour.

Based on the above, the design parameters listed in Table A-1 were used for the design of channel works and deflection berms.

Table A-1. Design parameters used for the design of channel works and deflection berms (LaCas 2000).

Process	Flow Velocity (m/s)	Flow Depth (m)	Peak Discharge (m^3/s)	Sediment Volume (m^3)
Flood	1.6	0.3	4.4	n.s.
Debris-laden flood	2.1 to 2.7	0.4 to 0.6	10-20	n.s
Debris Flow	n.s.	n.s.	n.s.	n.s

n.s. = not specified

A ditch and debris flow deflection berm was designed by LaCas (2000) to direct debris flows into the ditch from the east and south into the channel and past the Whitecap Development. The berm has a top width of 3.7 m, 3 to 4 m high with sides facing the development that slope at 1.5 horizontal (H) to 1 vertical (V), and sides facing away from the development sloped at 2 horizontal

(H) to 1 vertical (V). Further design aspects included swales across Seton Road and a 600 mm diameter culvert beneath the road. The eastern and northern portions of the property were protected by a berm up to 4 m high designed for the Q_{i200}.

According to LaCas (2000) the risk to injury or fatalities was considered minimal for a less than 10% in 50-year debris flow (approximately 500-year return period), a criterion that was used, at the time of the report, by the Ministry of Transportation as a hazard tolerance threshold[2].

A.1.4. Thurber (2004)

In 2004, Thurber Engineering Ltd. (Thurber) prepared a geotechnical hazard assessment for the proposed Necait Reserve subdivision located within the greater Seton Portage area and specifically on the southwestern portion of Bear Creek fan. The objective of the assignment was to assess geohazards that could affect the proposed subdivision and propose measures to reduce debris flow and debris flood hazards from Bear Creek.

Thurber (2004) examined the CN railroad cut downstream of the reserve and noted several metres thick units interpreted as debris flow deposits. Other debris flow units were identified on the eastern fan margins where a driveway has cut through the fan deposits. Those were noted as having thicknesses of less than 1 m to approximately 1.5 m. Specifically, Thurber (2004) conclude that: “the units show that very sizable debris flows reached the lower fan and formed some 20 m of its basal depth”. Thurber (2004) also noted that Bear Creek is a supply-unlimited basin in which a quasi-unlimited amount of debris is provided to the feeder channels that unite upstream or at the fan apex. This implies that the exceedance of a hydroclimatic threshold will invariably lead to a debris flow.

Thurber (2004) made several notes about the fan’s long-term development. The fan is sharply truncated by Portage River, which in Thurber’s (2004) opinion demonstrated erosion in the Holocene past and suggested that fan formation rates have declined over the latter part of the Holocene. This led Thurber to conclude that it is not appropriate to determine the annual rate of debris deposition by dividing the fan volume of approximately 85 million m^3 by 12,000 years (the period since deglaciation).

In Thurber’s (2004) opinion, debris flows reaching the floodplain may have occurred during the Little Ice Age, a period of colder and wetter climate from approximately 1450 to 1900 AD. Thurber further speculated that a small glacier may have existed in the upper watershed and that repeated freeze-thaw cycles may have provided higher rates of sediment to the upper basin.

The volume of a debris lobe near the proposed development was estimated at approximately 3200 m^3. The date of deposition could not be determined, but was estimated as less than 70 years based on the age of trees growing on the deposit.

Given the paucity of data, Thurber found it challenging to estimate frequency and magnitude of past debris flows reaching the proposed subdivision. In fact, stating the provincial guidance of the

[2] Note that the 10% in 50-year criterion was not associated with specific consequences, thus it forms a hazard tolerance criterion, not a risk tolerance one.

day which stipulated that design of debris flow mitigation measures need to consider the 10% in 50-year annual probability, Thurber conceded that insufficient data were available to do so, and that substantially more work would need to be done to arrive at reliable estimates. However, Thurber (2004) summarized knowledge of past debris flows as follows:

- A reported debris flow in 1964 (R. James, pers. comm. in Thurber 2004) could not be confirmed by air photograph analysis.
- A debris flow in 1991 occurred on August 13, followed by another one on August 29. The second event coincided with record rainfalls in the region. However, record rainfalls do not necessarily result in debris flows, as Thurber (2004) noted that a major rainfall event in October 2003 did not result in a debris flow. A debris flow may have occurred, however, on Pete's Creek during that time as reported by KWL (pers. comm. 2016). The debris flows of 1991 were described previously by Terratech (1991), but were not well differentiated.
- Thurber (2004), quoting Terratech (1991), concurred that the central fan had been relatively inactive but conceded that unpredictable changes on the upper fan could divert debris into the central area toward the Necait Reserve.
- Application of empirical volume prediction equations by Bovis and Jakob (1999), Thurber estimated "average" debris flows to reach volumes of 6,000 to 13,000 m^3. Assuming a deposition rate of 15 m^3/m and a 500 m long deposition zone, a 15 m^2 cross-section was back-calculated which is consistent with the observations of the 3200 m^3 debris lobe identified by Thurber upstream of the proposed Necait Reserve development.

A.1.5. BC Ministry of Forests, Lands and Natural Resource Operations (MFLNRO) (2015)

On September 22-23, 2015, MFLRNO responded to multiple events in the Seton Portage area (including Bear, Pete's and Whitecap creeks) following a significant precipitation event with total rainfall depths of approximately 30 mm (MFLNRO 2015). The Bear Creek events and initial response are summarized below:

- A debris flow originated on Bear Creek alluvial fan, which flowed northeast and impacted residences within the Mission 5 First Nations reserve. FLNRO staff toured the site to assess conditions and determine the likelihood of an immediate (i.e. within the next day or so) event. The preliminary assessment concluded that re-initiations of the debris flow was unlikely based on the observations that the primary flow area was running clear and the debris flow deposits were in the process of drying. A follow up site visit was completed by MFLNRO geomorphologist Tim Giles. His findings are summarized in MFLNRO (2016b) and in Section A.1.6 below.
- During the same period, a debris flow also flowed in a westerly direction on the fan that overtopped and damaged the berm, designed by LaCas (2000), locally known as Whitecap Dike. At the request of the SLRD, FLNRO staff inspected the berm and provided recommendations to restore it. FLNRO staff noted that the during the 2015 debris flow event the berm only partially protected the development as the diversion trench rapidly filled with debris that could not be transported away. FLNRO staff also noted that the

alignment of the debris flow path was perpendicular to the berm alignment, and that it was likely that the momentum of the debris flow allowed the material to overtop the berm resulting in damage to the downstream slope. FLNRO recommended that accumulated debris on the outside of the berm be removed and damage to the crest of the berm be repaired as soon as possible. These repair works were completed August 24, 2016. FLNRO also recommended that the SLRD consider increasing the capacity of the berm by modifying either the bypass trenches or the crest of the berm.

A.1.6. MFLNRO (2016b)

Tim Giles, P.Geo., regional geomorphologist with MFLNRO, has visited the Bear Creek fan on several occasions. In a personal correspondence to BGC (November 30, 2016), he provided the following key observations (paraphrased by BGC):

- Air photos from 2010, 2013, 2015 and 2016 suggest a slight deepening and widening of the Bear Creek channel at the apex.
- On the lower Bear Creek fan the main channel is becoming more prominent, clearly defined by high levees for that are visible further downstream compared to 2010.
- In 2010, little sediment was transported in the main channel upstream of the fan apex.
- In 2009, the channel was crossed by a fireguard. The re-contoured channel shows signs of a smaller flow passing through it in 2010. Approximately 150 m upstream of the fire break a debris flow deposit was identified that avulsed and deposited debris amongst the trees, but no recent deposit was identified on the fan surface.
- In 2013, debris flows ran out across the fan surface but did not flow below the truncated fan surface above the Seton River floodplain. In the upper channel, some of the debris avulsed from the channel and was deposited across a wide area amongst the trees. A trim line can be seen on the air photo. However, the trim line is substantially lower in elevation compared to the 2015 event.
- In 2015, debris flows on Bear Creek ran down the steep face onto the Seton River floodplain in several locations and the channel at the fireguard crossing became deeper, wider and more clearly defined. The mid-slope depositional area amongst the trees was covered by a thicker and wider deposit with channel incised through the sediments. The trim line at the fan apex was missing as the whole channel appeared to have been filled with debris. On the fan surface and down to the steep face onto the floodplain, the deposits appeared thicker and more widespread compared to the upper fan.
- In 2016, the runout again crossed the fan surface and reached the floodplain, leaving larger deposits in residential areas. Based on the visible deposit extent, the fan channel at the apex showed signs of a large event passing through. The deposits on the fan obliterated those of the 2015 debris surface but covered a greater area.

In summary, Mr. Giles believes that the channels are advancing downstream onto the fan surface, which enhances debris-flow mobility and thus increases hazards to the distal fan portions.

A.2. WHITECAP CREEK

A.2.1. Anecdotal Reports

- In 1973 or 1974 and 1977, debris flood events on Whitecap Creek occurred blocking Portage River. This was also believed to have occurred in the 1920s-40s, when the people of Lillooet reportedly came over to see why Seton Lake was dropping (pers. comm. Randy James).
- Mr. Nathan Adrian recalled four debris flood events on Whitecap Creek, two events in the 1980's (specific dates unknown), one event in 2015 and one event in 2016 (both coincident with the events on Bear Creek described above). Tsal'alh elders also recalled numerous events have occurred on Whitecap Creek, but did not remember specific dates. According to FLNRO, the Tsal'alh retained Northwest Hydraulic Consultants Ltd. (NHC) to assist with remediation following the 2015 event.

A.2.2. Seton Portage-Tsal'alh District Chamber of Commerce (1992)

On August 30, 1991 BC Rail diverted Whitecap Creek due to the fact that the creek was overflowing its natural bank resulting in damage to B.C. Rail's railbed. A letter from the Seton Portage-Tsal'alh District Chamber of Commerce to the Ministry of Environment dated July 8, 1992 indicates the diversion resulted in erosion and gravel filling of Seton Creek (also known as Portage River) negatively impacting spawning grounds and increasing the flooding risk to downstream properties.

A.2.3. MFLNRO (2015)

On September 22-23, 2015, a debris flood and channel avulsion occurred on Whitecap Creek that isolated and/or damaged an access road, four residences, and an office building and introduced a significant amount of debris into the Portage River. The avulsion occurred approximately 250 m upstream from the confluence of Portage River. The avulsion may have been caused by high streamflow or entrained debris in the flow (or a combination of both). The new flow path damaged the road and bridge servicing an office building and three dwellings[3] and also damaged an over 15-year old deflection berm on the lower reach of Whitecap Creek. Debris transported by Whitecap Creek deposited in Portage River resulting in complete blockage for approximately 170 m.

On September 23, the Tsal'alh cleared the Whitecap Creek channel and re-established flow back to the previous channel alignment. Based on an average width of 17 m and depth of 3 m, the estimated volume of material deposited in the Portage River channel was in excess of 8,500 m^3. The blockage prevented outflow from Anderson Lake, caused flooding around the lakeshore and threatened CN rail bed integrity. As such, emergency works to excavate the Portage River channel were undertaken. An initial 1 m wide inlet channel was created on September 23 and

[3] An additional dwelling downstream of Anderson Lake road was damaged (see Photo 11 in MFLRNO 2015).

MOTI unplugged the bridge opening and widened the channel with mechanical excavation on September 24. A rock weir was installed near the upstream end of the channel to act as a control point to prevent excessive downcutting of the channel[4]. MFLNRO recommended that spoil piles along both sides of the Portage River created during channel blockage excavation be removed. This work appears to have been undertaken. MFNLRO also recommended that a qualified engineering professional be retained to evaluate the condition through the blockage reach and to make recommendations on how to proceed with any further remediation works. NHC was retained to prepare a remediation plan; however, for various reasons, the works were not constructed and the subsequent 2016 high flow event destroyed the previous emergency/interim works (Ball 2016).

A.2.4. NHC (2016)

Some time on or after January 5, 2016, NHC developed sketches of a conceptual flood mitigation system for Whitecap Creek, in response to the September 2015 event (NHC, 2016). The sketches were completed by NHC's Kamloops offices; the version that BGC received was otherwise unattributed. The proposed mitigation design involved the following components:

- Excavation of the channel bed and west/right bank
- Construction of a berm along the west bank, using the fill excavated from the bed and bank
- Riprap protection of the berm
- Dredging of the area under the Tsal'alh Development Corporation (TDC) access road bridge, to increase capacity, or raising of the bridge deck.

The channel mitigation was proposed to initiate about 200 m upstream of the TDC access road bridge. In this reach, the berm would block off the avulsion channels. Downstream of the bridge, two alignments were proposed: one along Anderson Lake Road and an alternate option along the side of the creek. NHC's sketches are on file at BGC if additional information is required.

A.2.5. MFLNRO (2016a)

On November 10, 2016, MFLNRO responded to an avulsion event that occurred on Whitecap Creek following a significant regional precipitation event (MFLNRO 2016a). The events and initial response are summarized below:

- A channel avulsion occurred on Whitecap Creek that damaged an access road and residence, and isolated the Tsal'alh office and campground. The avulsion occurred approximately 250 m upstream of the confluence with Portage River. Local residents and MOTI staff estimated that the deposited material resulted in an approximately 75% blockage of Portage River. On November 9 and 10, the Tsal'alh cleared the original Whitecap Creek channel and re-established flow back to the previous alignment. In order to re-establish access to the Tsal'alh office and campground, a berm was constructed on

[4] BGC understands this rock weir was removed in the Spring of 2016 (J. Ball, MFLNRO, email, October 31, 2017).

the right bank (looking downstream) of Whitecap Creek at the location of the avulsion. The approximately 1 m high berm was constructed using local material (sand/gravel, boulders and woody debris) without adequate compaction and according to MFLNRO should be considered temporary.

- Partial blockage of Portage River Creek occurred and downstream of the Anderson Lake road bridge (Figure A-1). MFLNRO discussed the requirement to remove the deposited material with DFO and Tsal'alh. The flow velocity of Portage River was observed to remobilize the material deposited by the Whitecap Creek avulsion, therefore it was decided that mechanical excavation would not be required.
- Deposition of material and erosion of the left bank approach embankment occurred on both sides of Anderson Lake bridge. Immediately following the event, the road was cleared of debris and the eroded embankment was temporarily infilled to allow vehicle traffic. More permanent repair and armouring of the eroded area was completed on November 18. Triton Environmental Services (Triton) was retained as the Qualified Environmental Professional to monitor the work. Details of the work are summarized in Triton (2016).

Following their assessment, MFLNRO made the following recommendations:

- The abutment of the Tsal'alh office access bridge over Whitecap Creek be evaluated by a geotechnical engineer as soon as possible and suitable warnings established to notify users of the hazard.
- The dwelling located on the south side of Anderson Lake Road be relocated.
- Tsal'alh consider completion of NHC's design proposal for the Whitecap remedial works issued in January 2016.

Figure A-1. Before (left) and after (right) photos of the Seton River bridge at the base of Whitecap Creek following the 2016 event (photos provided by MOTI).

A.2.6. SLRD (2016)

According to the SLRD (2016), following the September 22, 2015 debris flood event on Whitecap Creek, the water levels in Anderson Lake rose by approximately 1 m. Emergency response works to re-open the Seton River channel allowed water to resume draining from Anderson Lake and relieved the immediate threat of flooding in Seton Portage; however, the pre-event capacity of the Seton River was not restored. In December 2015, the SLRD was made aware that water levels in Anderson Lake remained elevated by approximately 1 m. The SLRD began engaging with the Province to find a solution to the issue. According to MFLNRO (J. Ball, MFLNRO, email, October 31, 2017), no further action than what is described in MFLNRO (2015, 2016a) has been taken since the fall of 2016.

A.3. SPIDER CREEK

A.3.1. Anecdotal Reports

- In 1962 or 1963, a landslide dam outbreak flood (LDOF) occurred on Spider Creek when a landslide above the Spider Creek waterfall blocked the creek for a few hours. Mr. William Alexander reported that when the landslide dam broke, an approximately 30 foot (9 m) high wave breached the channel and traveled northeast towards 400 Spider Creek Road.
- In 1982 or 1983, there was an event on Spider Creek at 100 Spider Creek Road (pers. comm. William Alexander). No additional information was provided.

A.4. PORTAGE RIVER

A.4.1. Anecdotal Reports

- In 1972, due to flooding of Portage River from Anderson Lake, people living beside the Anderson Lake Road bridge were reportedly temporarily displaced from their homes. BGC notes that 1972 was a notable flood year in BC.
- In 1986, flooding of Portage River caused approximately 12 m of bank erosion on the south side of Seton River. As a result of the bank erosion, the house at 901 Spider Creek Road reportedly lost approximately half its yard area.
- In 1998, flooding of Portage River led to bank erosion on the south side of Seton River washing out a section of Spider Creek Road. The cost to repair the road was approximately $25,000 and no engineering assessment was completed (William Alexander, Tsal'alh, October 4, 2017 email).

A.5. ANDERSON LAKE

A.5.1. Anecdotal Reports

In 1988 or 1989, three approximately 20 foot (6 m) waves were observed in Anderson Lake. There were no observations of an aerial landslide that may have created the waves. This observation was reported by one gentleman at a September 11, 2017 meeting of BGC with the Tsal'alh. This event, however, could not be corroborated by other members of the Tsal'alh.

A.6. INCIDENTS OF FLOODS, LANDSLIDES AND ROCK FALL AROUND PEMBERTON, 1808-2006

Septer (2006) data-mined newspaper and published literature to create a provincial record of flooding and landslide activity. This data catalogue was reviewed to develop a record of event generating storms affecting the Pemberton area, as these storms are candidate storms for triggering landslides on Seton Portage.

For Pemberton, the first record is the Meager Creek 1931 debris flow related to October rains. Other significant events are major flooding on Lillooet River in October 1940, 1984 and 2003, and events in 1981 and 1991 that destroyed bridge crossings on Rutherford Creek. The incidents of flood, rock fall or landslides around Pemberton are listed below:

- October 1931 (Meager)
- January 20-27, 1935
- October 27-29, 1937
- October 19-20, 1939
- October 17-20, 1940 (flood of record since July 19, 1918)
- July 13-15, 1946
- November 27-December 4, 1951
- December 1-3 1955
- September 5-6 1957
- April 29-30, 1959
- January 8-17, 1961
- November 20-25, 1966
- October 30-November 1, 1967
- January 12-20, 1968
- October 29, 1968
- July 22, 1975 (Devastation)
- October 29-November 6, 1975
- December 23-27, 1980
- October 27-31, 1981
- January 1-4, 1984
- October 6-12, 1984 (Preacher's quote: the biggest one since 1940)
- October 4, 1990
- November 6-13, 1990
- November 16-24, 1990
- August 7-9, 1991
- August 27-31, 1991
- October 23-24, 1992
- March 17-26, 1997
- May 31-June 1, 1997 (Gowan)
- June-July 1999
- October 16-22, 2003
- January 16-31, 2005.

In summary, Septer records 32 event storms affecting the Pemberton area between 1930 and 2006, or one every 2 to 3 years. The record is likely incomplete for the period before development in the 1970s and it is likely that more local, non-regional event storms have triggered geomorphic events at Seton Portage. As such these averages should be interpreted with caution. Moreover, debris flows or debris floods do not occur in the study area every time threshold rainfall conditions are exceeded, as some time is needed between events to recharge the channels with debris. This is a common phenomenon in debris-flow channels (Church and Miles 1987, Jakob et al. 2005), which increases uncertainty in debris-flow volume and frequency prediction.

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APPENDIX B
HYDROGEOMORPHIC FLOODS

APPENDIX B – HYDROGEOMORPHIC FLOODS

B.1. HYDROGEOMORPHIC FLOODS

Steep mountain creeks (here-in defined as having channel gradients steeper than 5%) are typically subject to a spectrum of mass movement processes that range from clear water floods to debris floods to hyper-concentrated flows to debris flows in order of increasing sediment concentration. In this report, they are referred to collectively as hydrogeomorphic[1] floods or processes. There is a continuum between these processes in space and time with floods transitioning into debris floods and eventually debris flows through progressive sediment entrainment. Conversely, dilution of a debris flow through partial sediment deposition and tributary injection of water can lead to a transition towards hyper-concentrated flows and debris floods and eventually floods.

In BC, most infrastructure on such creeks have been designed for clearwater floods with return periods of up to 200 years. This design does not account for hydrogeomorphic processes such as debris floods and debris flows in which parts of or the entire channel bed sediments are mobilized and lead to erosion of channel bed and banks and debris inundation on terminal alluvial fans (Jakob et al. 2016).

Ignoring the specific hydrogeomorphic processes that act on steep creeks can and has led to a plethora of problems, many of which are caused by the fact that culverts and sometimes bridges have not been designed for heavy sediment loads or severe bank erosion. When such culverts are overwhelmed, blockage and re-direction of waters and sediment can occur.

B.1.1. Steep Creeks

Hydrogeomorphic floods are a phenomenon of steep channels. The morphology and processes in steep channels have been described by Church (2010, 2013). Sediment transfer occurs by a continuum of processes ranging from fluvial transport (bedload and suspended load) through debris floods to debris flows. These phenomena are transitional within time and space along the channel, depending on the sediment-water mixture. To understand the significance of these different modes of sediment transfer, it is useful to consider the characteristic anatomy of a steep channel system. Steep mountain slopes deliver sedimentary debris to the upper channels by rock fall, rock slides, debris avalanches, debris flows, slumps and raveling. Landslides may create temporary dams that pond water: when the dam breaks, a debris flow may be initiated in the channel. Debris flows and debris floods characteristically gain power and material as they move downstream, debouching onto a terminal fan where the channel enters the main valley floor. Here sediment is deposited and widespread damage may occur (Jakob et al. 2016).

[1] Hydrogeomorphology is an interdisciplinary science that focuses on the interaction and linkage of hydrologic processes with landforms or earth materials and the interaction of geomorphic processes with surface and subsurface water in temporal and spatial dimensions (Sidle and Onda 2004).

The following subsections adapted from Jakob et al. (2016) provide a summary of debris flow and debris flood processes.

Figure B-1 summarizes the different hydrogeomorphic processes by their appearance in plan form, velocity and sediment concentration.

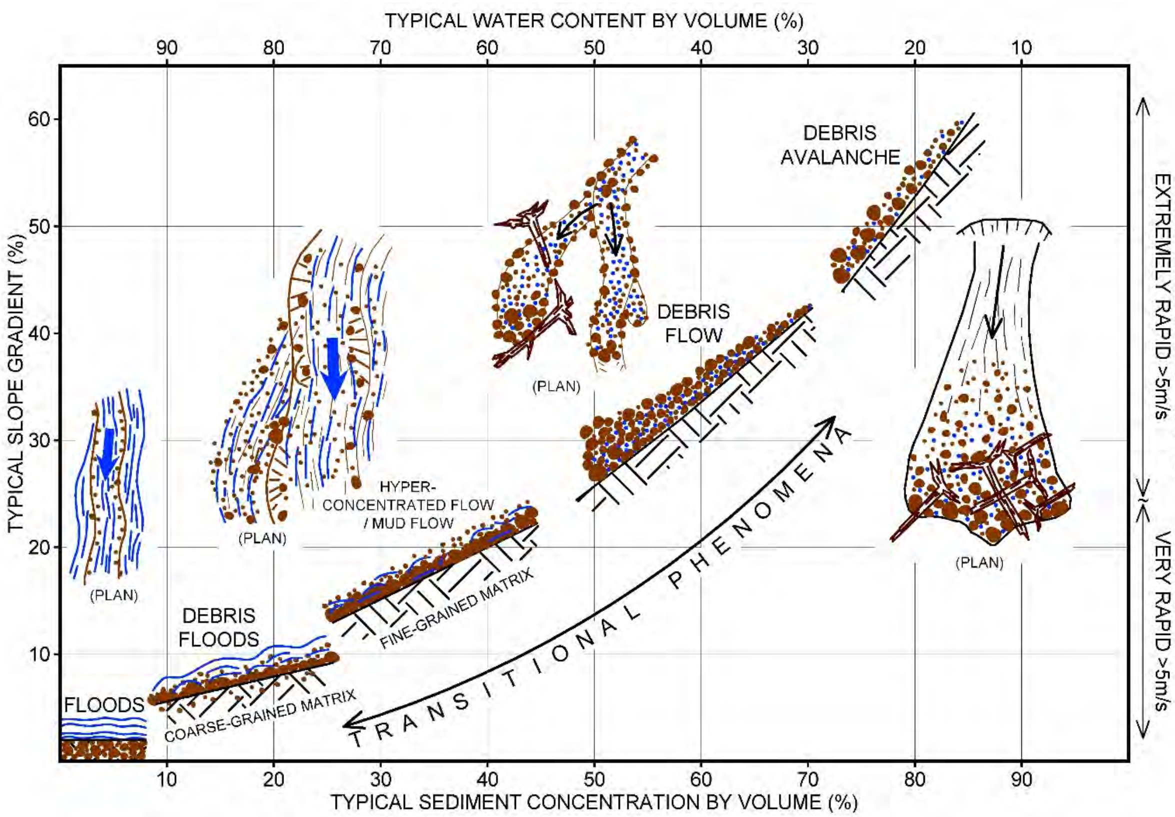

Figure B-1. Hydrogeomorphic process classification by sediment concentration, slope, velocity and planform appearance.

B.2. DEBRIS FLOW

'Debris flow', as defined by Hungr et al. (2014), is a very rapid, channelized flow of saturated debris containing fines (i.e., sand and finer fractions) with a plasticity index of less than 5%. Debris flows originate from single or distributed source areas in debris mobilized by the influx of ground- or surface water. Liquefaction occurs shortly after the onset of landsliding due to turbulent mixing of water and sediment, and the slurry begins to flow downstream, 'bulking' by entraining additional water and channel debris.

Sediment bulking is the process by which rapidly flowing water entrains bed and bank materials either through erosion or preferential "plucking" until a certain sediment conveyance capacity (saturation) is reached. At this time, further sediment entrainment may still occur through bank undercutting and transitional deposition of debris with a zero net change in sediment concentration. The volume of the flowing mass is thereby increased (bulked). Bulking may be limited to partial channel substrate mobilization of the top gravel layer, or – in the case of debris flows – may entail entrainment of the entire loose channel debris. Scour to bedrock in the transport zone is expected in the latter case.

Unlike debris avalanches, which travel on unconfined slopes, debris flows travel in confined channels bordered by steep slopes. In this environment, the flow volume, peak discharge, and flow depth increase, and the debris becomes sorted along the flow path. Debris-flow physics are highly complex and video recordings of events in progress have demonstrated that no unique rheology can describe the range of mechanical behaviours observed (Iverson 1997). Flow velocities typically range from 1 to 10 m/s, although very large debris flows from volcanic edifices, often containing substantial fines, can travel at more than 20 m/s along much of their path (Major et al. 2005). The front of the rapidly advancing flow is steep and commonly followed by several secondary surges that form due to particle segregation and upwards or outwards migration of boulders. Hence, one of the distinguishing characteristics of coarse granular debris flows is vertical inverse grading, in which larger particles are concentrated at the top of the deposit. This characteristic behaviour leads to the formation of lateral levees along the channel that become part of the debris flow legacy. Similarly, depositional lobes are formed where frictional resistance from coarse-grained or large organic debris-rich fronts is high enough to slow and eventually stop the motion of the trailing liquefied debris. Debris-flow deposits remain saturated for some time after deposition, but become rigid once seepage and desiccation have removed pore water.

Typical debris flows require a channel gradient of at least 27% (15^{o}) for transport over significant distances (Takahashi 1991) and have volumetric sediment concentrations in excess of 50%. Between the main surges a fluid slurry with a hyperconcentration (>10%) of suspended fines occurs. Transport is possible at gradients as low as 20% (11^{o}), although some type of momentum transfer from side-slope landslides is needed to sustain flow on those slopes. Debris flows may continue to run out onto lower gradients even as they lose momentum and drain: the higher the fines content, and hence the slower the sediment-water mixture loses its water content, the lower the ultimate stopping angle. The silt-clay fraction is thus the most important textural control on debris-flow mobility. The surface gradient of a debris-flow fan approximates the stopping angle for flows issuing from the drainage basin.

Due to their high flow velocities, peak discharges are at least an order of magnitude larger than those of comparable return period floods. Further, the large caliber of transported sediment and wood means that debris flows are highly destructive along their channels and on fans.

Channel banks can be severely eroded during debris flows, although lateral erosion is often associated with the trailing hyperconcentrated flow phase that is characterized by lower volumetric sediment concentrations. The most severe damage results from direct impact of large clasts or coarse woody debris against structures that are not designed for the impact forces. Even where the supporting walls of buildings may be able to withstand the loads associated with debris flows, building windows and doors are crushed and debris may enter the building, leading to extensive damage to the interior of the structure (Jakob et al. 2012). Similarly, linear infrastructure such as roads and railways are subject to complete destruction. On fans, debris flows tend to deposit their sediment rather than scour. Therefore, exposure or rupture of buried infrastructure such as telecommunication lines or pipelines is very rare. However, if a linear infrastructure is buried in a recent debris deposit, it is likely that over time or during a significant runoff event, the tractive forces of water will erode through the debris until an equilibrium slope is achieved, and the infrastructure thereby becomes exposed. This necessitates understanding the geomorphic state of the fans being traversed by a buried linear infrastructure.

Avulsions are likely in poorly confined channel sections, particularly on the outside of channel bends where debris flows tend to superelevate. Sudden loss of confinement and decrease in channel slope cause debris flows to decelerate, drain their inter-granular water, and increase shearing resistance, which slow the advancing bouldery flow front and block the channel. The more fluid afterflow (hyperconcentrated flow) is then often deflected by the slowing front, leading to secondary avulsions and the creation of distributary channels on the fan. Because debris flows often display surging behaviour, in which bouldery fronts alternate with hyperconcentrated afterflows, the cycle of coarse bouldery lobe and levee formation and afterflow deflection can be repeated several times during a single event. These flow aberrations and varying rheological characteristics pose a particular challenge to numerical modelers seeking to create an equivalent fluid (Iverson 2014).

B.3. DEBRIS FLOODS AND HYPERCONCENTRATED FLOWS

A ‘debris flood’ is “a very rapid surging flow of water heavily charged with debris in a steep channel” (Hungr et al. 2014). Transitions from floods to debris floods occur at minimum volumetric sediment concentrations of 3 to 10%, the exact value depending on the particle size distribution of the entrained sediment and the ability to acquire yield strength[2]. Because debris floods are characterized by heavy bedload transport, rather than by a more homogenous mixture of suspended sediments typical of hyperconcentrated flows (Pierson 2005), the exact definition of sediment concentration depends on how sediment is transported in the water column. Debris floods typically occur on creeks with channel gradients between 5 and 30% (3-17°).

The term “debris flood” is similar to the term “hyperconcentrated flow”, defined by Pierson (2005) on the basis of sediment concentration as “a type of two-phase, non-Newtonian flow of sediment and water that operates between normal streamflow (water flow) and debris flow (or mudflow)”. Debris floods (as defined by Hungr et al. 2014) have lower sediment concentrations than hyperconcentrated flows (as defined by Pierson). Thus, there is a continuum of geomorphic events that progress from floods to debris floods to hyperconcentrated flows to debris flows, as volumetric sediment concentrations increase. Some creeks are hybrids, which implies that the dominant process oscillates between debris floods and debris flows.

Due to their initially relatively low sediment concentration, debris floods are more erosive along channel banks and beds than debris flows; the latter can reach a sediment saturation point

[2] The yield strength is the internal resistance of the sediment mixture to shear stress deformation; it is the result of friction between grains and cohesion (Pierson 2005).

whereby bank or bed erosion is significantly reduced. Bank erosion and excessive amounts of bedload introduce large amounts of sediment to the fan where they accumulate (aggrade) in channel sections with decreased slope. In fact, debris floods can be initiated on the fan itself through rapid bed erosion and entrainment of bank materials. Because typical synoptic storm hydrographs fluctuate several times over the course of the storm, several cycles of aggradation and remobilization of deposited sediments on channel and fan reaches can be expected during the same event (Jakob et al. 2016).

Debris floods can be triggered by a variety of processes. One trigger is transition from a debris flow when lower stream channel gradients are encountered. Another trigger is exceedance of a critical shear stress threshold of the channel bed and full bed mobilization (Church 2013). More uncommon triggers are landslide dam, beaver dam or glacial lake outburst floods as well as the failure of man-made dams (Jakob and Jordan 2001; Jakob et al. 2016). Photograph B-1 is an example of a debris flood triggered by the failure of a human-made dam on Cougar Creek in Canmore, Alberta.

Photograph B-1. Example of the failure of a human-made dam on Cougar Creek shortly after the breach initiated. May 25, 1990 (Alberta Environment 1991).

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APPENDIX C
HYDROLOGY

APPENDIX C – HYDROLOGY

C.1. INTRODUCTION

Flood frequencies were analyzed as part of this work for Whitecap and Spider creeks as it informs on the choice of design events. It is noteworthy, however, that the resulting peak flow estimates were subsequently adjusted to account for debris-flood and landslide-dam outburst flood (LDOF) specific aspects that control peak flows. For Bear Creek, the flood frequency analysis (FFA) was conducted only to support possible outlet structures, as flood flow has little influence on debris flow peak flows or their respective volumes. Flood frequencies were estimated using two approaches: a regional FFA and rainfall-runoff modelling. Both methods are described below.

C.2. REGIONAL REGRESSION ANALYSIS

Regional FFAs are conducted when there are several representative hydrometric stations along a watercourse of interest or along adjacent watercourses in the area. Alternatively, this approach is also often employed when there is no representative gauge along a watercourse, such that other gauges within the same region must be used.

FFAs typically use the Annual Maximum Series (AMS) – or the maximum peak instantaneous stream flow (Q_{IMAX}) measured in each year on record – as the dataset for the analysis. Regional flood frequencies are calculated by comparing peak instantaneous flows for a given return period (e.g., the 10-year flood) at selected gauges within the region, and developing a power law equation relating the magnitude of each return period flood to drainage area. The flow associated with a return period can then be estimated at the location of interest based on the drainage area. The power law is described by the following equation:

$$Q_p = aA^b \quad \text{[Eq. C-1]}$$

where Q_p is the peak flood estimate at the location of interest for the return period *p*, A is the upstream drainage area at the location of interest, and a and b are regression coefficients developed based on the regression analysis of the selected gauges for a given return period (Watt et al. 1989).

Five gauges were selected for the regional analysis at Seton Portage. Table C-1 summarizes the characteristics of Water Survey of Canada (WSC) hydrometric stations used in the regional FFA. Some of the factors considered in the gauge selection include: proximity, drainage area, length of record, regulation by upstream lakes or dams, and similarity in flow timing. As there are few gauges within the area with similar drainage areas to the locations of interest (i.e., Whitecap, Bear, and Spider creeks) and with sufficient lengths of flow record – typically greater than 15 years – partially regulated gauges were also used in the analysis.

Table C-1. Water survey of Canada (WSC) gauges selected for the regional flood frequency analysis.

Station Name	Cayoosh Creek Near Lillooet	Bridge River (South Branch) Below Bridge Glacier	Yalakom River Above Ore Creek	Hurley River Below Lone Goat Creek	Pemberton Creek Near Pemberton
Station ID	08ME002	08ME023	08ME025	08ME027	08MG025
Latitude	50.669319	50.856220	50.91261	50.730888	50.315540
Longitude	-121.965	-123.453	-122.239	-122.942	-122.805
Basin Area (km^2)	885	144	581	312	32.4
Record Period	1914-2014	1979-2013	1983-2015	1996-2015	1987-2014
Record Length (Complete years of data)	66	35	33	20	24
Regulation Type	Regulated	None	None	None	Regulated
Location with Respect to Pipeline Crossing	25 km Southeast	85 km Northwest	25 km North	45 km West	55 km Southwest

C.3. RAINFALL-RUNOFF ANALYSIS

In addition to the regional analysis described above, rainfall-runoff modeling was also conducted for Whitecap Creek and Spider Creek using the program HEC-HMS (Version 4.2) developed by the US Army Corps of Engineers (USACE 2015). Rainfall-runoff models provide an estimate of the peak flow resulting from a precipitation event within a watershed. Inputs required for the model include:

- A rainfall distribution
- A curve number (CN), which is selected based on the soil and land cover type, and used to establish infiltration within the basin
- A time of concentration, defined as the time required for storm runoff to travel from the most remote location in the watershed to the location of interest.

For Whitecap and Spider creeks, a Type I Soil Conservation Service (SCS) standard rainfall distribution was used. The 24-hour precipitation totals specified for each return period event in Table C-2 were distributed over the 24-hour period according to this distribution. A variety of curve numbers, ranging from 60 to 75, were used in the modeling (SCS 1972). These numbers reflect characteristic curve numbers for forested areas with a range of soil types and antecedent conditions. Finally, the time of concentration was calculated for each watershed based on the selected curve number, as well as watershed characteristics such as drainage area, length, and overall gradient.

Table C-2. Total estimated 24-hour rainfall for a range of return periods at the Tsal'alh (Shalath) climate station, based on data from 1963 to 2004.

Return Period (Years)	3	10	30	100	300	1000
Rainfall (mm)	40	60	79	102	126	156

Rainfall-runoff analyses was used to estimate the magnitude of debris floods on Whitecap (Table C-3) and Spider creeks (Table C-4) which is added here for completeness and repeated in Appendix D.

Table C-3. Whitecap Creek (drainage area: 74 km²) flood frequency results.

Method	Scenario	Return Period (Years)					
		3	10	30	100	300	1000
Regional Analysis	Q_{IMAX} (m^3/s)	37	50	64	84	108	143
Rainfall-Runoff Model	Q_{IMAX} for CN_{60} (m^3/s)	14	37	67	112	167	244
	Q_{IMAX} for CN_{65} (m^3/s)	20	49	85	138	202	290
	Q_{IMAX} for CN_{70} (m^3/s)	28	63	107	169	242	340
	Q_{IMAX} for CN_{75} (m^3/s)	38	81	132	204	286	395

Table C-4. Spider Creek (drainage area: 25 km²) flood frequency results.

Method	Scenario	Return Period (Years)					
		3	10	30	100	300	1000
Regional Analysis	Q_{IMAX} (m^3/s)	26	34	45	60	78	107
Rainfall-Runoff Model	Q_{IMAX} for CN_{60} (m^3/s)	6	16	28	47	70	102
	Q_{IMAX} for CN_{65} (m^3/s)	8	21	36	58	84	121
	Q_{IMAX} for CN_{70} (m^3/s)	11	27	45	71	101	142
	Q_{IMAX} for CN_{75} (m^3/s)	16	34	56	86	120	164

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APPENDIX D
FREQUENCY-MAGNITUDE ANALYSIS

APPENDIX D – FREQUENCY MAGNITUDE ANALYSIS

D.1. INTRODUCTION

This appendix contains technical methodological detail and how these methodologies were applied to determine the frequency and magnitude of debris flows on Bear and Pete's creeks, and debris floods on Whitecap and Spider creeks. Results are summarized in condensed form in Sections 4, 5 and 6 in the main report. The emphasis of this appendix is on Bear Creek, because it has by far the highest risk potential compared to the other two creeks. Fortuitously, it also contains the greatest wealth of information that can be used to decipher its frequency-magnitude (F-M) relationship.

The structure of this appendix mirrors the main report, with separate sections for each study creek, due to the different methods that were applied in each case.

D.2. FREQUENCY-MAGNITUDE MODEL

There are no commonly applicable rules in Canada to define the range of hazard event frequencies or return periods that should be considered in a geohazard assessment. However, regulatory guidance and/or legislation worldwide mandate a range from several tens of years up to 10,000-year return periods. For example, in British Columbia, the current guidance to Ministry of Transportation and Infrastructure (MoTI) approving officers is that a 10,000-year return period be considered for all life-threatening landslide processes (MoTI 2009). Similarly, hazard tolerance criteria developed by Cave (1992) suggest consideration of up to a 10,000-year return period for new subdivisions. This guidance contrasts with a more nuanced approach developed for the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC 2012) "Guidelines for Legislated Flood Assessments in a Changing Climate". In those guidelines, the scale of future (and existing) development to be protected guides the return periods to be considered. For example, for very high loss potential sites, which would apply to Seton Portage, the APEGBC guidelines stipulate that an event up to 2,500-year return period be considered.

These relatively high return period ranges are more conservative than the present standard of practice for hydrogeomorphic hazards in Austria and Switzerland, where return periods of up to 150 years and 300 years are considered, respectively and, in the case of Switzerland, consider residual risk for return period exceeding 300 years (Hübel pers. comm.). Rudolf-Miklau et al. (2011) provide an overview of the hazard and risk assessment guidelines in various European nations.

Regardless of the design event return period, once events have been documented and their age and volume estimated, return periods need to be assigned to individual events that allow extrapolation and interpolation into annual probabilities often well beyond those extracted from the physical record. Such record extension is necessary to develop scenarios across the return period range under consideration. These scenarios then form the basis for debris-flow and debris flood modelling and risk analysis.

In this context, judgement is required to assign magnitudes for very long return periods (thousands of years) and the degree of error is proportional to the length of the return period. This high degree of uncertainty can be addressed through secondary lines of defense or contingency plans should the channel aggrade significantly over time. Table D-1 summarizes the techniques that were applied at the three study creeks.

Table D-1. Methods to determine frequency and magnitude of debris flows and debris floods for the different study creeks.

Method	Bear and Pete's Creeks	Whitecap Creek	Spider Creek
LiDAR remote sensing	✓	✓	✓
Field investigation	✓	✓	✓
Event reconstruction	✓	✓	
Test trenching and radiocarbon dating	✓		
Dendrogeomorphology	✓	✓	✓
Regional frequency-magnitude curves	✓		
Fan volume calculations	✓		
Debris flow sediment bulking	✓		
Rainfall-sediment volume relationships		✓	✓
Flood frequency and rainfall-runoff analysis		✓	✓

D.2.1. General Assumptions and Limitations

While based on the best available data, estimates of F-M relationships that span time scales of millennia require judgment and assumptions that are subject to uncertainty. General limitations include those listed below. Specific limitations are listed at the end of each sub-section.

- Older events are covered or scoured by new ones, thus obliterating evidence
- Not all events are documented by any of the applied dating methods
- Data are often sporadic between sites and leave spatial and temporal data gaps
- Some dates from any of the dating methods applied can be ambiguous
- Land ownership and development can preclude dating in certain fan sections.

Several assumptions are required to allow the establishment of F-M relationships:

- The probability of occurrence of debris flows or debris floods during a time interval is low and the probability of two or more simultaneous events is negligible in the same main channel (see McClung 1999 who describes this for snow avalanches).
- The premise of stationarity over time (no long-term trend in the frequency of debris flows/debris floods), and that they underlie an ergodic (independence from initial conditions) stochastic process.

The above assumptions can be questioned. For example, extrapolation of high return periods from the initial record length is done with only limited information on how climatic or geomorphic watershed conditions may have changed during this time. Changes in vegetation cover, future wildfire or wildfire suppression, changes in the frequency and/or magnitude of hydroclimatic events and the occurrence of cataclysmic events such as large landslides will all influence levels of hazard and associated risk.

D.2.2. Summary

Despite these limitations, a combination of field and analytical techniques, as well as geomorphic reasoning, can reduce uncertainty and allow the derivation of a plausible debris-flow or debris-flood frequency-volume relationship. The key is to view frequency–volume estimates as credible proxies for true events rather than precise estimates. These estimates are then used to determine key consequences and risks that support risk reduction decision-making.

D.3. BEAR AND PETE'S CREEKS

D.3.1. Frequency Analysis

Debris-flow frequencies were estimated by four direct dating methods: records of previous events; air photo interpretation of photos dating back to 1948; dendrogeomorphology; and test trenching with radiocarbon dating. Each of these methods is described below.

Recorded Debris Flow Events

Table D-2 summarizes previous recorded events on Bear and Pete's Creek.

Table D-2. Previous events on Bear and Pete's Creek.

Date	Description	Reference
1907?	Landslide that blocked Portage River	Geocache (2007), not confirmed
early Spring 1964	Debris flow that travelled all the way to the road at the RV park	R. James, Tsal'alh; Thurber (2004)
1974	Debris flow reached the home on the northeast corner of Seton Portage and Cresta Road	Seton Portage resident (name unknown)
August 19, 1991	Debris flow reaching Portage River floodplain	TerraTech (1991a, b)
August 29, 1991	Debris flow reaching Portage River floodplain	TerraTech (1991a, b)
2003	Debris flow to the west that did not reach the Whitecap berm	KWL, pers. comm. (2016)
2013	Debris flows ran out across the fan surface but did not flow below the truncated fan surface above the Portage River floodplain	T. Giles, MFLNRO, email Nov. 30, 2016
September 20, 2015	Debris flows that flowed northeast and west impacting residences within the Mission 5 First Nations reserve and overtopping the Whitecap berm (Drawing 2)	MFLNRO (2015), Giles (2016)
July 30, 2016	Debris flow crossing the fan surface and reaching residential areas	Giles (2016)

According to Table D-2, there were nine debris flows in the last 110 years, which would suggest an approximate frequency of 12 years. This, however, may be an under-estimate as it is quite likely that more debris flows occurred between 1907 and 19991 than the table may suggest.

Airphoto Interpretation (API)

Air photograph analysis was conducted to:

- Identify debris-flow events, with a particular focus on events prior to 1964.
- If possible, delineate the areas of previous debris flows, in order to estimate volumes.

Air photograph interpretation also allows for identification of debris-flow source area in the upper watersheds. Eleven sets of aerial imagery were available for the Seton Portage area, including air photos from 1948 to 2005 and satellite imagery from 2012. Observations are summarized in Table D-3.

Table D-3. Observations from airphoto interpretation, Seton Portage 1948-2005.

Series	#s	Year	Scale	Observations
X195L	4-6	1948	N/A	Oblique aerial photographs limited to upper watersheds above the fan apex. Some shading on upper slopes of Bear and Pete's creek watersheds. Rockfall and debris flow tracks visible and fresh debris in the upper watershed of Bear Creek. Smaller debris flow track visible on Pete's Creek watershed. The two channels do not appear to join.
BC494	114-117	1948	1:64,246	Medium scale photo extent limited to the fan and lower to mid watershed. The uppermost slopes of Bear Creek are not visible. Photo has some shadows and is dark toned. Fresh debris flow track in Bear Creek watershed extends below waterfall to the top of the glaciofluvial deposit. Bear Creek is partially entrenched downslope of the bedrock sections of the watershed, but this is not continuous through the deposit. Smaller fresh debris flow track seen from Pete's Creek watershed. Both channels are obscured by trees onto the fan, but noted by thin breaks in the vegetation. Apparent track of Bear Creek noted by treed ridge on northern margin of fan. Below the fan apex Pete's Creek sharply turns west and flows adjacent to the southern hillslope. Houses and cleared areas are visible on the outer portions of the fan, particularly near the water's edge on Anderson Lake. A small clearing in the trees of uncertain origin is noted upstream of the most southern house on Anderson Lake.
A13251	35-37	1951	1:70,000	Small scale photos with upper watershed covered by shadows, but fan is well lit. Fresh debris flow and rockfall tracks noted through shadow in upper watershed. Pete's Creek below fan apex appears to flow in the same location as the previous photo against the southern margin of the hillslope. Apparent location of Bear Creek has not changed since the previous photo. The extent of developed areas on the fan does not appear to have increased since the previous photo.

Series	#s	Year	Scale	Observations
BC4243	19-24 141-146 183-186	1964	1:15840	Large scale photos with partial shadow cover in the upper watershed. Fresh debris flow and rockfall tracks are noted in both Bear Creek and Pete's Creek watersheds. A large tension crack in the upper Bear Creek watershed is highlighted by late snow cover in photo 183. Bear Creek does not appear to be entrenched below the waterfall. The location of the channels across the fan is partially obscured due to thick vegetation cover, but both channels appear to flow in the same location as the previous photos. Seton Portage Road and Creston Road have been constructed along the west and southern margin of the fan. Orchards are visible below the escarpment near Bear Creek. The future footprint of the Whitecap Development has been partially logged.
BC5143	143-146	1965	1:31860	Medium scale photo with well exposed fan and watersheds. Few changes from the previous photo, except for a fresh debris flow deposit from one of the Bear Creek sub-watersheds.
RSA30517	3-4	1972	1:120,000	Small scale colour photos with well lit fans and watersheds. Fresh debris flow tracks in Bear Creek watershed. Shadows obscure the smaller Pete's Creek upper watersheds. The channels across the fan are difficult to locate due to the small scale of the photo. Creston Road has been expanded further upslope and east of the former photo.
BCC7763 BCC7769	124-127 167-170	1975	1:20,000	Medium scale black and white photos with well lit fan and watersheds. Fresh debris and rockfall tracks visible on Bear Creek sub-watersheds. Much smaller debris flow tracks noted on Pete's Creek. Bear Creek is entrenched below the bedrock section. The channel locations on the fans are obscured by the thick vegetation. The logging on the future Whitecap Development has not expanded.
30BCC678 30BCC679	119-123 221-225 29-31	1987	1:15,000	Large scale black and white photos of the fan and watersheds. The photo set is partially overexposed. Fresh debris flow and rockfall tracks on Bear and Pete's Creek watersheds. Bear Creek is no longer entrenched below the waterfall. The channel locations on the fans are obscured by the thick vegetation. Small, inconsistent patches of trees have been logged on the fan. More houses have been developed along Seton Road near the Portage River.
30BCC97125 30BCC97128	81-82 134-138 19-23	1997	1:15,000	Large scale black and white photos of the fan and watersheds. The photos are overexposed on the margins. Few discernible differences in the watersheds to the previous photo, except for a small debris flow track on Bear Creek below the waterfall. The Whitecap Development has been re-logged to its present extent and some roads have been constructed.

Series	#s	Year	Scale	Observations
30BCC05 135	39-42 125-128	2005	1:20,000	Medium scale colour photos of the fan and upper watersheds. Fresh debris flow tracks of similar extent to the previous photo are visible in the upper Bear and Pete's Creek watershed. The locations of the channels across the fan are difficult to determine due to thick forest cover. The berm on the Whitecap Development has been constructed.
Digital Globe Imagery		2012	0.5 m pixel	Fresh debris flow tracks are noted on Bear Creek but not Pete's Creek watershed. Bear Creek is not entrenched below the bedrock section. Large portions of the trees on the fan, and upper Bear Creek watershed have been burnt. A fire break has been constructed across the fan, running approximately northeast to southwest, and upstream along Bear Creek. The locations of the channels on the fan cannot be determined due to the overexposure of the image. A house on Whitecap Development has been constructed. Properties adjacent to the southern berm have been developed.

In summary, it appears that the largest debris flow in the last 70 years occurred in July of 2016. Other debris flows are discernible but were too small to destroy forests. Therefore, their aerial extent cannot be measured with confidence. Given some evidence of debris flows shortly before or in 1948, this evidence calls from an adjustment of the return period estimate from historical accounts from 12 to 10 years.

Dendrogeomorphology

Dendrochronology is an absolute dating method in which annually distinct tree rings are used to determine the age of a tree. Dendrogeomorphology, a sub discipline of dendrochronology, focuses on geomorphological processes that influence tree growth. Depending on the ages of trees along the mainstem channel of a creek, and the history of disturbing geomorphic events, dendrogeomorphology can extend the frequency record of debris flows well past the air photograph record and may close the time gap between air photograph interpretation (several decades) and radiocarbon dating (century to millennia). Dendrogeomorphology can also be precise to the nearest year in dating growth disturbances, and in some cases, even the seasonal timing of growth disturbance can be deciphered (Stoffel and Bollschweiler 2008).

Dendrogeomorphological methods have been applied specifically to debris flow which can influence regular tree growth in different ways (Alestalo 1971; Stoffel and Bollschweiler 2008):

- Trees may be damaged due to impact by large boulders or logs transported by a debris flow, producing scars or shearing the tree off above the stump in extreme cases (decapitation)

- Some trees species will produce tangential traumatic resin ducts (TRDs) when scarred or decapitated[1]
- Tree growth may be reduced or increased in years following a debris-flow event due to changes in resource (water/nutrients) access
- Growth pattern may also change when a tree is tilted and produces denser (and thus darker) reaction wood to regain vertical alignment.

Because trees produce a new layer of radial growth each year, these events can be accurately dated by studying the tree's growth ring series.

Method

Nineteen trees were sampled during the field program (September and November, 2016) from coniferous trees on the Bear Creek and Pete's Creek fan. One species was sampled: Douglas fir (*pseudotsuga menziesii*). One or two cores per tree were extracted from living trees using a 4 mm increment borer. Coring is a non-destructive sampling technique and is thus preferred to felling the tree.

Retrieved samples were sanded to a high finish using 120 grit sand paper and scanned using a calibrated Epson scanner at 1600 dots per inch (dpi). The tree ring widths were measured using Regent Instruments' WinDENDRO 2012 software package (Regent Instruments Inc. 2012). WinDENDRO is a semi-automatic image analysis program, which identifies tree rings and measures the width of the yearly growth. The user inputs the outer ring year (2017 in this case), and the program counts inwards from the bark along a user-defined path. The operator is also able to review and correct the ring assignments as necessary. WinDENDRO can be superior to manual dating techniques because it facilitates verification; when errors are found, measurement image files can be easily opened, adjusted and re-saved.

Once the cores were measured, the next step in the analysis was to identify the event response features shown on each sample, for each year. The following response features were documented: tangential TRDs; reaction wood; growth variations; and impact scars. This process is known as feature identification. The results of this assessment were summarized in a spreadsheet (on file at BGC). For each year, the spreadsheet lists the trees that were damaged or impacted, and the strength of the response feature.

In conjunction with the historical air photos, these feature identification results were used to identify event years. The following criteria were used to identify an event at Seton Portage:

- At least one tree showing unambiguous scarring, and/or at least three trees showing TRDs or reaction wood.
- Presence of trees showing growth reduction with dates that match scarring or TRDs.

[1] When a spruce or fir tree is wounded, the tree forms aligned rows of resin ducts, known as tangential TRDs. TRD formation is a defense mechanism that allows the tree to compartmentalize the damaged wood. By contrast, resin ducts in pine trees do not align after damage.

Older events (prior to about 1900) were identified using less stringent criteria, since there were fewer samples available to corroborate the dates.

Results

The results of the dendrogeomorphology study on Bear and Pete's creeks are summarized in Table D-4 and further discussed in the main report.

Table D-4. Debris-flow event dates inferred from dendrochronology.

Inferred Date	Affected Samples	Corresponding Data
1885	1 scar, 1 other tree was established a few years after event	
1910	2 scars	May correspond to the 1907 event recorded on Geocache
1920	3 scars and 3 trees with germination year of approx. 1920	
1927	1 affected, 2 trees with germination year of approx. 1927	
1936	4 trees affected	
1950	2 scars, 2 other trees affected	
1956	8 trees affected	
1964	6 trees affected	Sheet mudflow event from rain-on-snow in spring; fresh debris-flow tracks observed on air photographs
1974	6 trees affected	Reported by a homeowner
1991	6 trees affected	Records of two 1991 events that reached the Seton River floodplain
2015	1 scar	Recorded event

Test Trenching and Fan Surface Observations

Test trenches and natural exposures are documented for two reasons: First, it allows a designation of deposit thicknesses which in turn helps to reconstitute the magnitude of former debris flows. Second, during test trenching, organic materials can be sampled that allow radiocarbon dating. These dates allow a reconstruction of debris-flow frequency.

Test pit (TP) descriptive logs and photographs are included in Appendix E, while the test pit locations are shown on Drawing 02. Results from test trenching are summarized in Table D-5 and Figure D-1. The last column indicates the calculated return period for the dated time frame.

Table D-5. Radiocarbon samples and dates obtained at Seton Portage.

Sample code	Lab ID	Site	Depth (m)	Material	Calendar Age (calibrated)	No. of events above sample (min.)	Min. Debris-Flow Return Period (years)
BGC-1	474067	TP1	1.2	Charcoal	1028 – 1184 CE	2	460
BGC-2	474068	TP2	1.4	Charcoal	1224 – 1298 CE	1	760
BGC-3	474069	TP2	1.4	Charcoal	1726 – 1814 CE	1	250
BGC-4	474070	TP3 notch	2.9	Charcoal	1500 – 1383 BCE	4	860
BGC-5	474071	TP5	3.0	Charcoal	1773 – 1627 BCE	2	1860
BGC-6	474072	TP5	3.0	Plant	Post 1950 CE	3	20
BGC-7	474073	TP7	0.7	Charcoal	1450 – 1635 CE	1	470
BGC-8	n/a	TP7	0.7	(not tested)			
BGC-9	n/a	TP8 (section)	10.0	(not tested)			
BGC-10	474075	TP8 (section)	10.0	Charcoal	2465 – 2778 BCE	8	580
BGC-11	474076	White house[1]	3.5	Charcoal	1134 – 1004 BCE	(not logged)	
BGC-12	n/a	White house[1]	3.5	(not tested)			
BGC-13	474078	TP10	2.0	Charcoal	664 – 770 CE	1 (200 cm)	720
BGC-14	n/a	TP10	2.0	(not tested)			
BGC-15	474079	Spider Creek	0.5	Charcoal	1734 – 1806 CE	(not logged)	
BGC-16	474080	Spider Creek		Charcoal	1392 – 1443 CE	(not logged)	
BGC-17	478121	TP-5	1.77	Sediment	1039 – 1210 CE	2	560
BGC-18	478122	TP-5	5.25	Charcoal	2056 – 1921 BCE	6	670
BGC-19	478123	TP-16	2.60	Sediment	321 – 422 CE	2	190
BGC-20	478124	TP-17	2.65	Charcoal	360 – 156 BCE	5	460
BGC-21	478125	TP-17	3.05	Charcoal	542 – 397 BCE	6	414
BGC-22	478126	TP-17	3.25	Sediment	522 – 383 BCE	7	353
BGC-23	478127	TP-18	1.65	Charcoal	328 – 204 BCE	2	1140
BGC-24	478128	TP-18	2.30	Charcoal	781 – 511 BCE	5	530
BGC-25	478129	TP-19	0.5	Sediment	1635 – 1684 CE	1	1660
BGC-26	n/a	Railway cut	3.85	(not tested)			
BGC-27	478130	Railway cut	3.85	Charcoal	781 – 511 BCE		
	Average Return Period						660

Notes:

1. 410 Spider Creek Road.
2. Two samples were collected and sent to Beta Analytic, but lab testing was not completed due to quality concerns. *CE* is Common Era (since the year 0) and *BCE* is Before Common Era, so prior to the year 0.

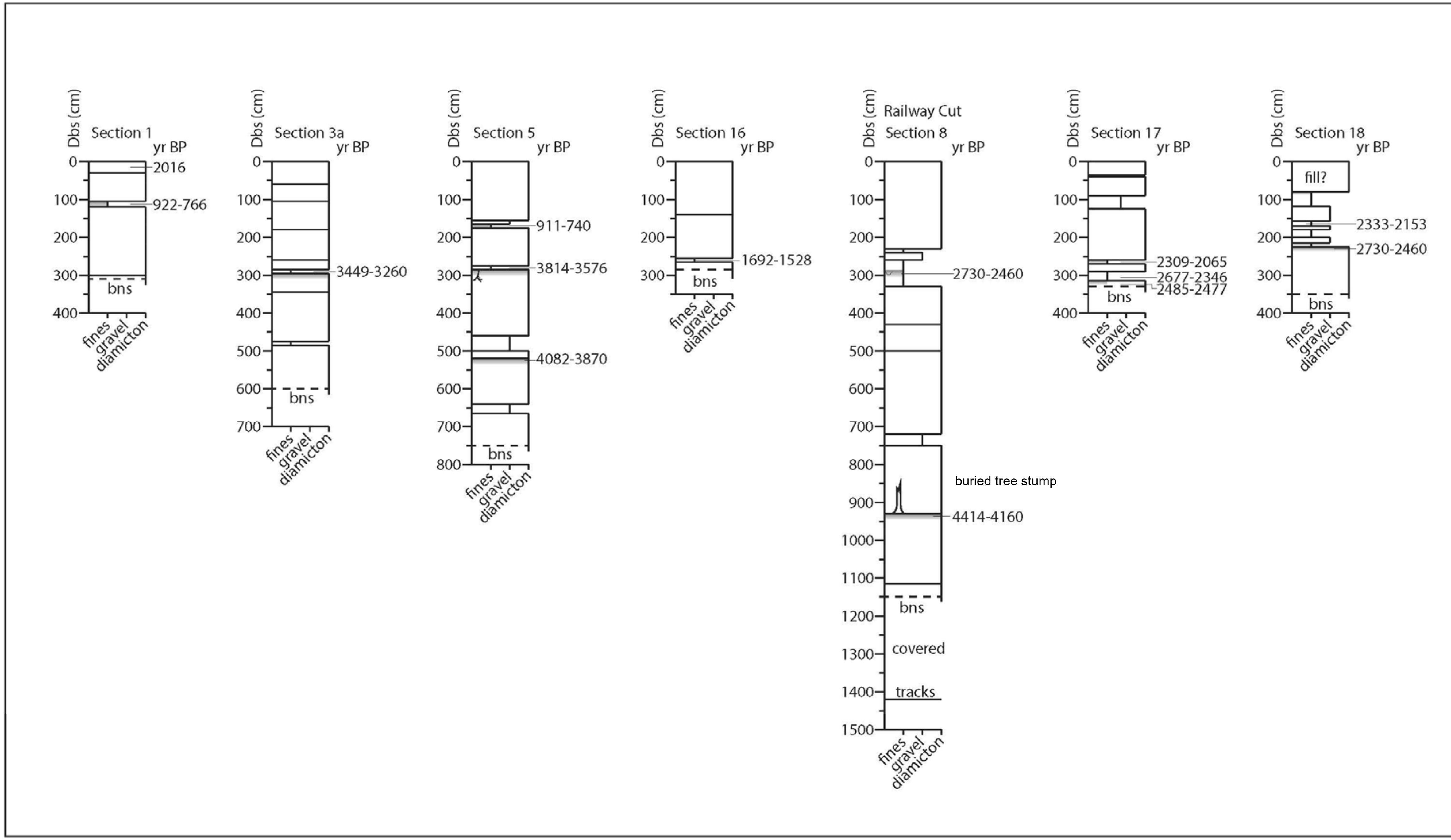

Figure D-1. Fence diagram for northeast to northwest distal portion of Bear/Pete's Creek fan showing ^{14}C dates from test trenching at Test Pits 1, 3a, 5, 8 (railway cut), 17 and 18. Debris flow thicknesses up to 2 m were encountered. "Bns" stands for "base not seen". Each white box represents a facies (fines, gravel, diamicton), diamicton refers to debris flow units. Dashed lines indicate 'base not seen'.

Table D-5 demonstrates that the average return period of sampled debris flows is 660 years, with return periods for individual sections ranging from 20 to 1860 years. This implies that individual fan sectors are inundated by large debris flows about every 700 years. For example, at TP 3 (see Drawing 02), at least four debris flows occurred over the last 3500 years, resulting in an average return period of large (estimated as at least 100,000 m^3 and within the 100 to 300-year return period class) debris flows at this location of approximately 860 years. This does not indicate the range of return period of all debris flows on Bear Creek fan, as some debris flows may be eroded, others may deposit upstream of the test pits locations, and others may deposit on different sections of the fan.

The fan edge of Bear Creek has a length of 2800 m. The estimated average width of a single debris flow is approximately 400 m. This implies that, on average, there is room of 7 debris flows along the fan perimeter. Since large debris flows are unlikely to follow the same path (as it will be elevated after events), the average frequency of large debris flows reaching the truncated fan edge is 100 years.

D.3.2. Magnitude Analysis

Frequency analysis techniques have shown that small (< approximately 20,000 m^3) debris flows on Bear and Pete's creeks have about a 10-year return period, and large debris flows have about a 100-year return period. The next step is to quantify the magnitude of these debris flows, both in terms of debris volume and peak discharge.

The following sections describe the magnitude analysis techniques that were used on Bear and Pete's creeks, including historical volume estimates, point-source volume estimation, test-trenching and peak discharge estimation.

Historical Volume Estimates

Historical event volumes are helpful because they allow numerical model calibration and provide a sense of the severity of a recent event. Event volume estimates were not included in previous studies of events on Bear and Pete's creeks; however, event areas were delineated in 1991 (Terratech) on Bear Creek and in 2016 by SLRD staff.

BGC retraced the events delineated by Terratech and SLRD staff (1991 and 2016), traced the area of the 2016 debris flow based on 2017 LiDAR imagery in Global Mapper, and estimated the thickness of the deposits from field evidence. Table D-6 summarizes the results of this analysis.

Table D-6. Estimated debris-flow volumes on Bear Creek.

Event Date	Mapped By	Area (m^2)	Thick-ness (m)	Best Est. Volume (m^3)	Uncertainty (%)	Volume Range (m^3)
Aug. 19 and 29, 1991	Terratech	58,000	0.5	34,000	50	24,000-51,000
Sept. 22/23, 2015 (Pete's)	SLRD/BGC	9,560	0.4	3,800	20	3,000-4,600
July 30, 2016*	BGC	116,000	0.5	58,000	30	41,000-75,000
July 30, 2016 (Pete's)		-	-	1,100	20	900-1,300

*Note that the 2015 and 2016 events followed very similar trajectories and can thus not be distinguished exactly.

Landslide Point Source Input Volumes

At Bear Creek, two types of debris flows are conceivable:

- The first is the so-called "firehose effect" in which debris flows initiate by high runoff descending from Bear Creek and impacting the upper steep fan. The rapidly flowing water will entrain debris until fully saturated (at approximately 50 to 75% sediment concentration). In this debris-flow type, no debris source volume need to be accounted for. These debris flows likely have volumes of less than 100,000 m^3.
- Second are debris flows triggered by point source failures in the main head waters or tributaries in which a debris avalanche or rock slide triggers a debris flow through either impact loading (undrained loading) or through liquefaction of a sliding debris mass.

Point source volume ranges were assigned based on LiDAR interpretation, helicopter-based inspection of potential failure zones in inaccessible areas, and field observations. In the upper watershed of Bear Creek, BGC identified a large potential point source, shown on the hillshade in Figure D-2, and in the photographs in Figure D-3 and Figure D-4. Previous large debris flows are believed to having been initiated by similarly sized rock slope failures that are now no longer visible.

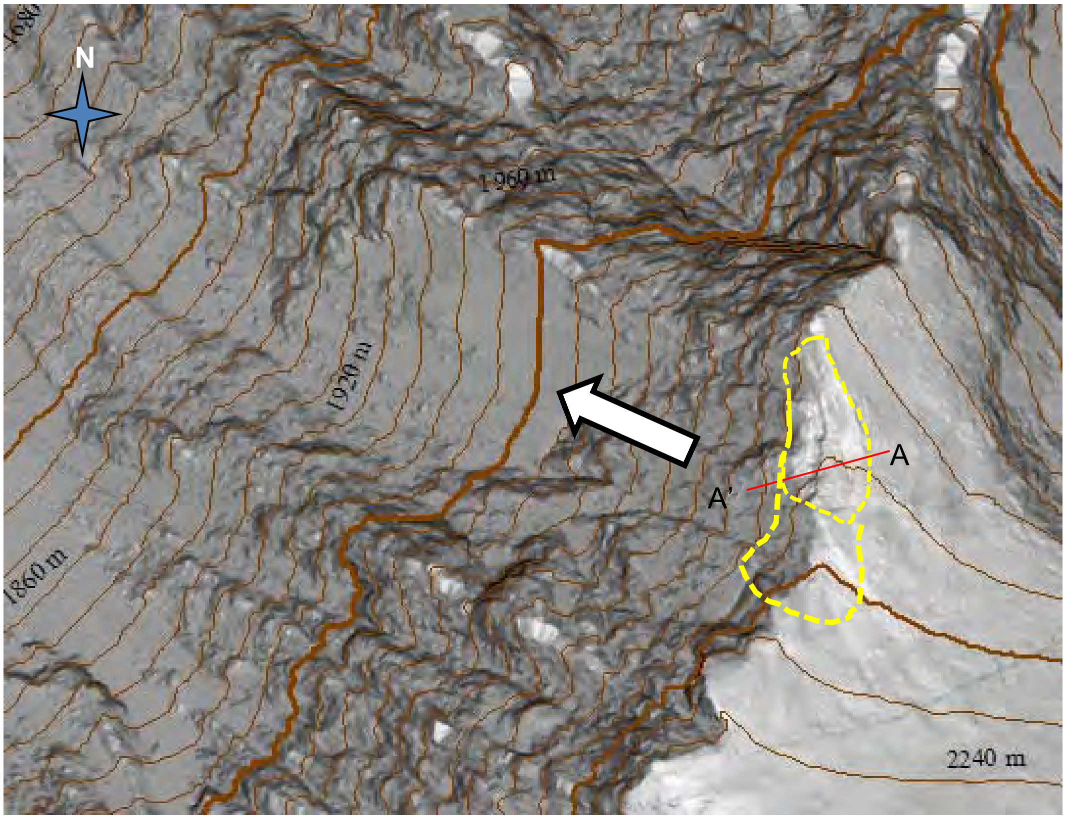

Figure D-2. Potential rock slide sources for debris-flow initiation in the upper Bear Creek watershed at approximately 2190 m elevation, delineated in yellow. Location of cross-section is shown in red.

The areas shown in yellow are approximately 5,000 m^2 (smaller area), and 10,000 m^2 (larger area). A thickness of 10-15 m was estimated by drawing a cross-section across the rock mass; the cross-section is shown in Figure D-5.

Figure D-3. Looking north and downslope at the top of the potential point source, delineated in yellow. Photo: BGC September. 13, 2017.

Figure D-4. The rock mass in the vicinity of the point source has a steeply dipping joint set (~ 45 º). Photo: BGC September 13, 2017.

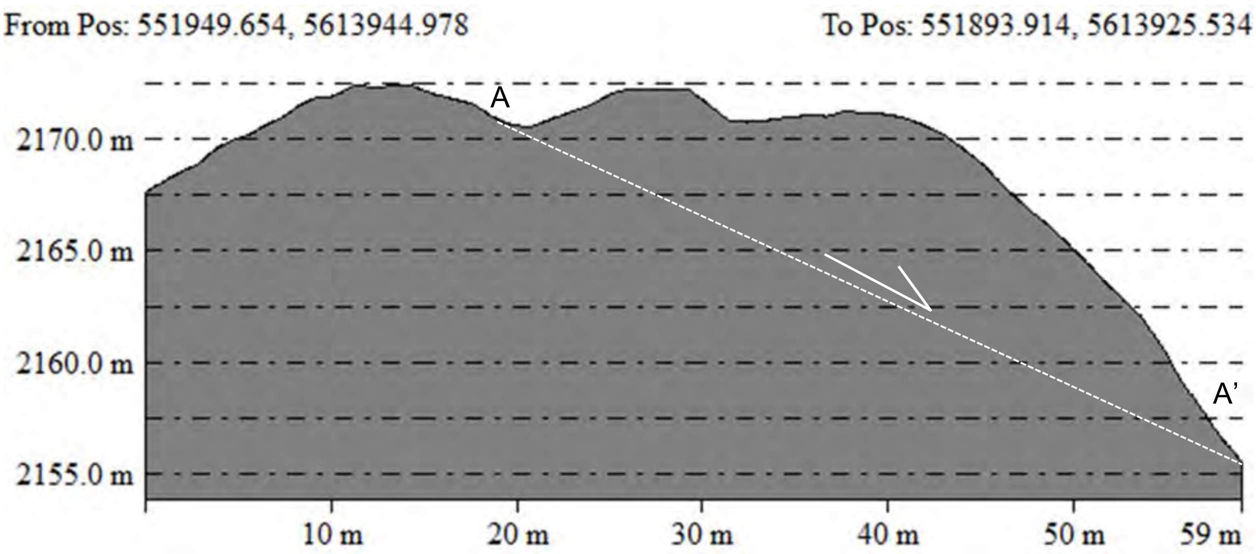

Figure D-5. Profile through the upper rock slope shown in Figure D-2.

Using the range in areas and thicknesses, BGC estimated a total rock mass volume of 50,000 to 150,000 m^3. This mass may fail sequentially, in pieces, or in one single event.

Other point sources are conceivable, such as the large talus slope on the western portion of the upper watershed. Given that there are no visible previous failures associated with this slope though, constituting a volume is associated with substantial uncertainty.

D.3.3. Debris-Flow Frequency-Magnitude Relationship

Introduction

The principle challenge of debris-flow assessment lies in establishing a reliable frequency-magnitude relationship (FMR). For longer return periods, this requires a combination of several absolute dating methods, test trenching, hydrology, sedimentology and determining fan volume above a dated horizon and comparing it with the sum of all debris flows.

In areas where comprehensive studies on debris-flow or debris-flood frequencies and magnitude have been conducted, a normalization based on fan area or fan volume can be applied to approximate FMR without the need for in-depth field investigation (Jakob et al. 2016). This analysis was conducted at Bear Creek. These relations, however, should only be applied in similar environment and morphometrically similar watersheds. As few detailed FMR studies have been conducted in the drier environments of southwestern BC, the results of this analysis were compared with the different frequency and magnitude analyses conducted herein to gain confidence.

Methods

Nine detailed debris-flow hazard and risk assessments have also been completed in southwestern BC for different clients by BGC and Cordilleran Geoscience over a period of approximately 15 years.

The hazard assessments in BC entailed the reconstruction of detailed FMRs for debris floods and debris flows. Various methods were applied to decipher magnitudes and frequencies of past events. For each project, an F-M curve was established. The individual F-M curves from the nine regional projects were normalized by fan area and plotted on the same graph (Figure D-6). A best-fit line was then plotted and a predictive equation extracted. An upper credible limit was also fit to the data.

The regional relations predict the sediment volume (V_S) in m^3 generated in various return period (T) events and normalized by fan area (A_f) in km^2. Each relation is applicable for return period events ranging from approximately 10 to 3000 years, noting that in some cases the minimum return periods exceed 10 years. Return periods > 3000 years are too speculative with respect to their sediment volumes to be included in this analysis.

The resulting regional debris-flow relation (Equation D-1) has a coefficient of determination (R^2) of 0.65.

$$V_S = A_f[54{,}230 \ln(\mathrm{T}) - 161{,}714] \quad \text{[Eq. D-1]}$$

Results

Equation D-1 was applied to Bear Creek (Figure D-7). Initially, the Pete's Creek results were prorated by watershed area (factor of 0.26) (BGC 2016, Figure D-7). Upon fieldwork in September and November of 2016, BGC found that the fan portion of Bear and Pete's creeks cannot be distinguished morphologically and given that one creek can avulse into the other. Therefore, BGC chose to combine the frequency-magnitude into one curve.

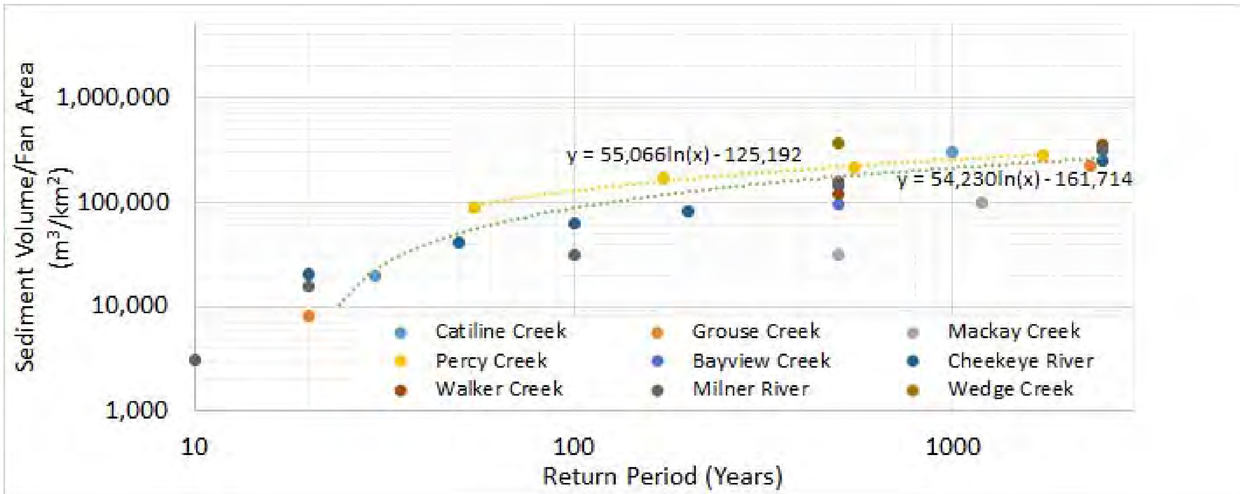

Figure D-6. **Regional F-M relationship for debris flows in southwestern BC from Jakob et al. (2016). The green dotted line symbolizes the best fit of all creeks considered, while the yellow line shows the upper credible limit.**

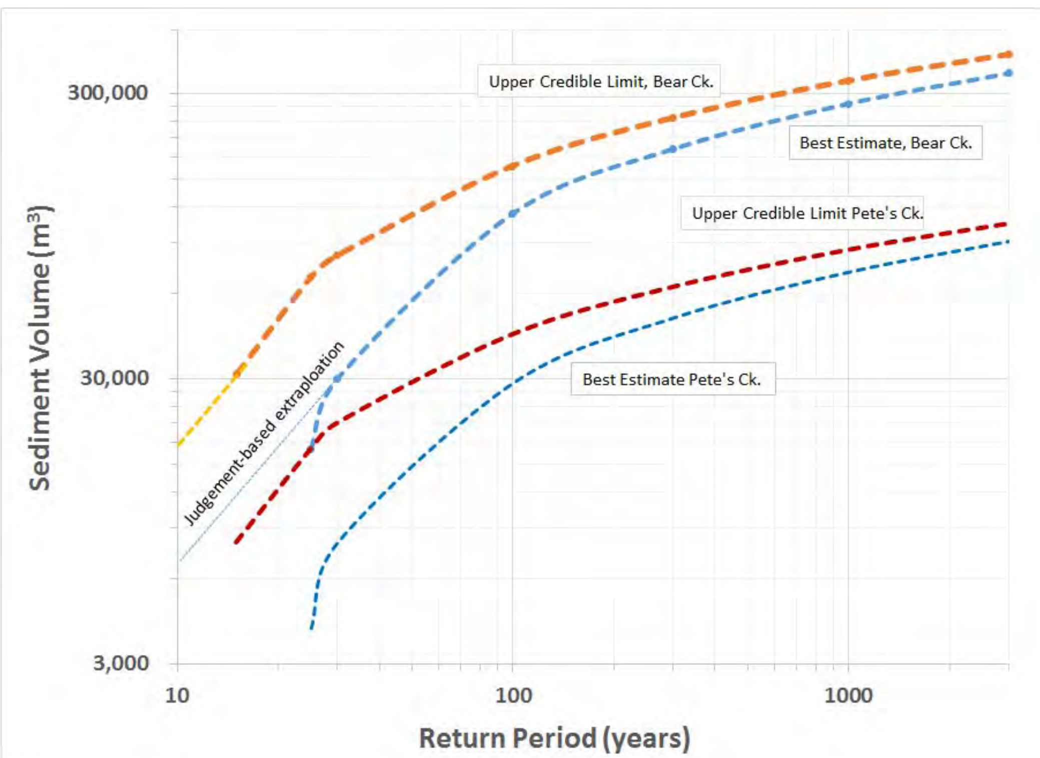

Figure D-7. **Preliminary debris flow frequency-volume relationship for Bear Creek and Pete's Creek with the Best Estimate and Upper Credible Limit delineated by different colours. The lower portion of the Bear Creek curve is extrapolated based on judgment.**

Return Period of Recent Debris Flows

Given the above F-M analysis, BGC attempted to determine the return period of the 1991 and 2016 debris flows. The results are shown in Figure D-8.

Thurber (2004) note that they collaborated with Dr. Oldrich Hungr, who used an F-M relationship to project a 10% annual probability in 50 years (approximately 500-year return period) of 60,000 m^3 at Bear Creek. However, no details on that work are available. According to BGC's analysis presented in this report, a 60,000 m^3 volume would correspond to approximately a 50-year debris flow. A 500-year return period debris-flow would correspond to a >200,000 m^3 sediment volume according to BGC's preliminary F-M analysis.

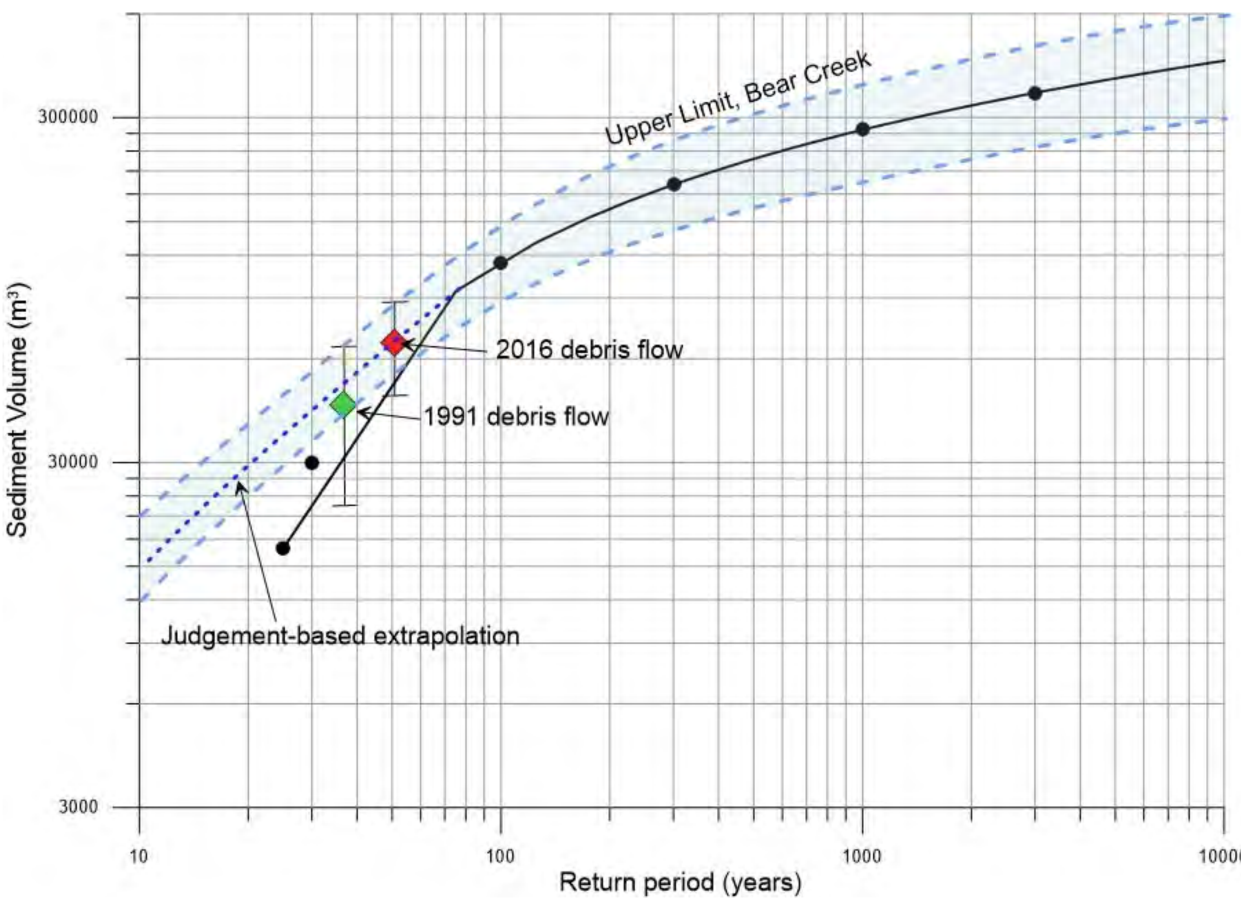

Figure D-8. Frequency-magnitude curve for Bear Creek with the reconstructed 1991 and 2016 debris flows. Uncertainty bounds are shown in light blue.

Validity Check

The test trenching and radiocarbon dating program allowed testing of the Bear Creek debris-flow F-M relationship.

First, Pete's Creek and Bear Creek watershed areas were summed. Then, BGC calculated the volume of debris on the Bear Creek fan complex above the lowest dated paleo-horizons. This was accomplished by assuming that the dated deposits extend fan-upwards at the same slope and thus the same deposit thickness, an assumption which cannot be substantiated with the available information. Table D-7 provides a summary of the three fan segments considered. The central fan section is based on three logged vertical sections for which the radiocarbon sample depths and average calendar (CAL in Table D-7) years were averaged and the areas affected summed.

Table D-7. Extrapolated fan volumes for various fan sectors for Bear Creek.

Fan Segment	^{14}C Sample Depth (m)	Average CAL age (yrs BP)	Area (m^2)	Volume (m^3)
1 (east)	10	4300	216,000	2,160,000
2 (central)	3.1	3600	630,000	1,933,000
3 (west)	2.9	3100	419,000	1,299,000
Total			**1,300,000**	**5,400,000**

If the F-M curve shown in Figure D-8 is correct, then the sum of all debris flows that occurred over approximately 3600 years (average of the 3100 to 4300-year range from the three fan segments) should equal the volume as reported in Table D-7. For this purpose, for each return period class, the total number of debris flows for the time period considered were summed and then added to arrive at a total volume of debris transported onto the fan of Bear Creek (Table D-8). The total number of events had to be adjusted to avoid double counting. This was accomplished by subtracting the number of events of the next higher return period class from the number of events in the return period class in question. For example, the true number of debris flows of the 300 to 1000-year return period class (mean 650 years) are calculated as 6 minus 2 with 2 being the number of expected debris flows in the 1000 to 3000-year event class.

Table D-8. Extrapolated fan volumes for various fan sectors for Bear Creek.

Mean Return Period (years)	No. of Events	Min. Debris-Flow Volume (m^3)	Mean Debris-Flow Volume (m^3)	True Debris Flow Number	Total Volume (min) (m^3)	Total Volume (mean) (m^3)
20	180	9,000	10,500	125	1,120,000	1,890,000
65	55	30,000	70,000	37	1,120,000	3,880,000
200	18	110,000	150,000	12	1,370,000	2,700,000
650	6	190,000	235,000	4	710,000	1,300,000
2000	2	280,000	315,000	2	560,000	570,000
				Total	**4,900,000**	**10,300,000**

The total figure of 4,900,000 m^3 is close to the approximated fan volume over the averaged 3600-year horizon, which indicates that the F-M relationship appears reasonable. However, if the mean (rather than minimum) volumes are being applied for each return period class, the total volume equates to approximately 10 million m^3.

As there is no consistent upward thinning of debris flow layers observed in the test trenches (Figure D-9), there is no reason to believe that debris flows have diminished in size over the past 4000 years or so and no adjustment of the F-M relationship appears necessary for this time period.

However, it would not be prudent to extrapolate the same method to a 10,000-year return period, as demonstrated below. First, BGC estimated the total volume of the Bear Creek fan complex. For the calculation of the approximate volume, two surfaces were compared:

1. For the fan top, the bare earth LiDAR surface was used based on a Digital Elevation Model created from LiDAR data using Global Mapper 18.1.
2. For the fan bottom, a sloped plane was created that started from Anderson Lake (at the current lake elevation) and projected downwards towards Seton Lake, matching the approximate slope between the two lakes. The plane was created using the ArcGIS 3d Analyst tool: 'create TIN'.
3. The ArcGIS 3d Analyst 'Cut-Fill' tool was then run to determine the volume of material between the two surfaces.

Using this methodology, the total fan volume was estimated to 74 Mm^3. In comparison, BGC's F-M analysis, if extended to a 10,000-year event time frame, results in a total fan volume of only 13 to 29 Mm^3 minimum debris-flow volumes, and mean debris flow volumes, respectively. The discrepancy between these two volumes could have two reasons: One is that the early Holocene witnessed much more frequent and larger events that have been observed over the past 4000 years because of a much higher availability of sediments once the glaciers had receded and before vegetation covered glacial sediments. The other is that one or more large landslide deposits may be underlying the dated deposits. Without further investigations, neither hypothesis can be confirmed, but is consequential to the present assessment.

Given that the largest event volume considered (1000 to 3000-year return period) has substantial bearing on the outcome of the risk assessment and thus mitigation, an additional check was conducted. The railroad cut parallel to Portage River (Section 8 in Figure D-1) displays an excellent cross-section of debris flows that can be traced to the west and east. The thickest unit in Section 8 is approximately 2.2 m thick in the centre and tapers over a distance of over 150 m on either side, with an average thickness estimated to approximately 1.2 m ± 0.25. Given that this debris flow must have originated from the fan apex, an area can be delineated to reconstruct the debris flow (Figure D-9). The assumption is that the debris flow had the approximate thickness throughout its longitudinal profile. Using an area of 290,000 m^2, the total volume of the debris flow is approximated to 360,000 m^3 which is very close to the estimated 1000 to 3000-year return period debris flow volume of (Figure D-8).

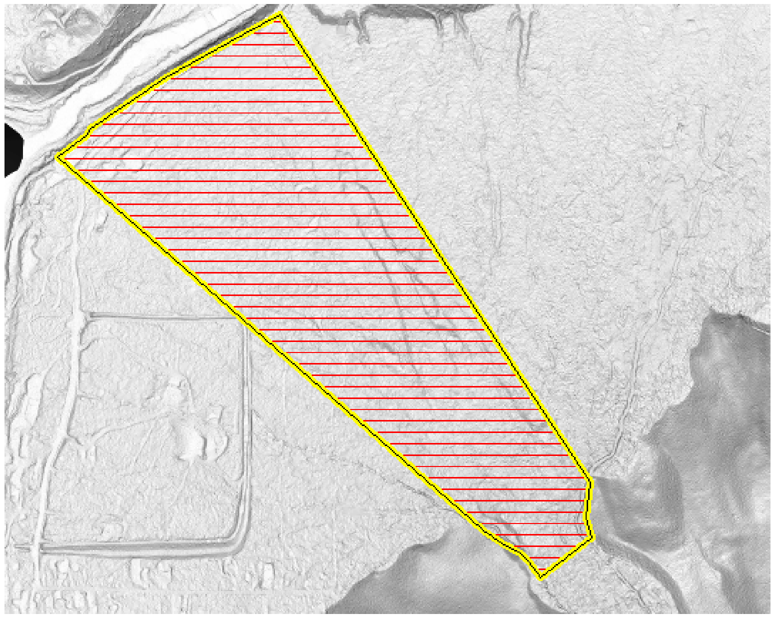

Figure D-9. Assumed "large" debris flow exposed in the Railroad Cut with an area of 290,000 m^2 and an average thickness of 1.2 m.

Channel Sediment Entrainment Volumes

The largest modeled event has substantial bearing on the risk results and, by extension, the scale of mitigation measures. Therefore, BGC conducted one more test for the validity of the largest event modeled. This involves a determination of the volume of sediment that would need to be entrained in the channel downstream of a credible source zone to achieve, in addition to the source zone volume, the total volume assumed by the time the debris flow reaches the fan apex.

Sediment entrainment was not calculated directly as it is unknown which of the many tributary channels would produce a debris flow. Instead, BGC back calculated the debris-flow volumes from the assumption that the regional F-M analysis is correct. The channel length between the unstable rock slope described above and the fan apex is approximately 3200 m. For the 1000 to 3000-year return period scenario, a total sediment volume of approximately 320,000 m^3 is estimated from Figure D-8. Using the range reported above for the source area volume, the material that would need to be entrained by debris flows between the rock slide source and the fan apex would thus be 170,000 to 270,000 m^3. Dividing this volume by the channel length, provides a yield rate estimate of 53 to 84 m^3/m. Channel width is variable ranging from around 10 m to 50 m in the lowermost sections. These figures are relatively high compared to other creeks in BC, with a notable exception at Neff Creek, located some 50 km west of Seton Portage. Here, BGC estimated a yield rate of 50 to 90 m^3/m^2, for the same September 2015 storm that also triggered debris flows on Pete's and Bear creeks. The high values are also within globally observed yield rates (Table D-9). Given the very high sediment load of the feeder channels in the

[2] This was determined by a fairly accurate estimate of the deposit volume from pre-and post-event LiDAR comparison, knowing the fan scour volume and knowing the length of channel in the upper watershed.

upper Bear Creek watershed, and particularly the very thick debris flow deposits in the sections immediately upstream of the fan apex, these yield rates appear reasonable.

Table D-9. Debris entrainment rates from literature

Reference	Location	No. of events	Yield rate (m^3/m)
Hungr et al. (1984)	BC Coast	5	6-18
Jakob et al. (1997)	BC Coast	2	23
Fannin and Rollerson (1993)	Haida Gwaii	253 196	13 24
Cenderelli and Kite (1998)	Appalachians, USA	4	up to 42
Franks (1999)	Hong Kong	40	0.2 to 5
King (1996)	Hong Kong	1	up to 50
Jakob et al. (2000)	BC Interior	1	28
Rickenmann and Weber (2003)	Kazakhstan	1	8 to 300
Lau (unpublished)	Neff Creek (near Pemberton)	1	50 to 90
Donovan and Santi (2017)	Western US	33	Up to 40
This study	Southwestern BC	1	53 to 84

It is of course conceivable that other source areas contribute to debris flows, or that multiple source areas produce debris flows in a single event. However, not all of those scenarios can reasonably be analysed, nor their return period be estimated.

Peak Discharge

To determine peak discharges for a range of return periods an empirical relationship was applied that relates debris flow volumes to peak flows for muddy debris flows in BC (Jakob 1996):

$$V = 338Q^{0.99} \quad \text{[D-3]}$$

Using Equation D-3 it is then possible to determine the peak discharges for all return period classes considered as summarized in Table D-10.

Table D-10. Debris-flow magnitude for different return periods for Bear Creek.

Return Period (T) (years)	Annual Probability (1/T)	Max. Sediment Volume Estimate (m^3)	Debris Flow Peak Discharge (m^3/s)
10 to 30	0.1 to 0.03	11,000	30
30 to 100	0.03 to 0.01	70,000	220
100 to 300	0.01 to 0.003	150,000	480
300 to 1000	0.003 to 0.001	240,000	760
1000 to 3000	0.001 to 0.0003	320,000	1000

To test the range of peak discharges estimated, the peak flow of the 2016 debris flow on Bear Creek was estimated. Based on field observations, the cross-sectional area of this event above the fan apex ranged between 12 and 24 m^2. Flow velocity was back-calculated using an empirical relationship between channel slope and flow depth presented by Prochaska et al. (2008):

$$v = 0.35 h_o S + 5.36 \quad \text{[D-2]}$$

where h_o is the flow depth and S is the sine of the channel slope. Using a flow depth of 1.5 to 2.0 m and a channel slope of 0.2 to 0.3 m/m the resulting flow velocities range between 5 and 6 m/s. The resulting peak discharge range is 60 to 144 m^3/s, with a mean of approximately 100 m^3/s. Note that Equation D-2 is insensitive to h_o and can be simplified to $v = 0.35S + 5.36$.

Accordingly, an estimated average discharge of 100 m^3/s would correspond to a return period of 34 years, while the maximum estimate discharge of 144 m^3/s would correspond to a return period of approximately 44 years. According to the debris-flow volume F-M analysis, the 2016 event on Bear Creek (estimated volume = 58,000 m^3) had an approximate return period of 45 years, which is very close to the upper estimate for the peak discharge.

Effects of Wildfires

A large wildfire burned on the eastern portions of the Bear Creek watershed during 2009. Wildfires are known to increase the frequency and magnitude of debris flows following the fire and numerous studies have been carried out throughout the western United States where stand-replacing wildfires frequently burn steep, mountainous terrain (e.g., Moody et al. 2013). Post-fire debris flows have also been examined in the Okanagan and Kootenay regions of British Columbia (Jordan and Covert 2009). The key question is if the 2009 wildfires affected the 2015 and 2016 debris flows, and if forestry recovery will lead to a change in the frequency-magnitude relationship.

Wildfires affect sediment input to debris-flow prone watersheds by decreasing tree canopy intercept of rainfall and absorption of moisture in the duff layer on the forest floor which increases runoff and erosion. The development of water repellent soils can also decrease infiltration of water into the soil and contribute to runoff (Doerr et al. 2000, Shakesby and Doerr 2006). Exposure of bare soils combined with higher runoff leads to an increased sediment delivery into the stream system and mobilization by debris flows.

The effects of the 2009 fires on the frequency and magnitude of debris flows in the Bear Creek watershed are difficult to quantify. However, given the extensive debris sources prevailing in the watershed that are unrelated to forest fires, BGC believes that the effects of the 2009 fire were minor and may not have contributed substantially to the 2015, 2016 debris flows. This belief is further supported by the occurrence of debris flows in 2015 and 2016 in Pete's creek watershed, which was not affected by fires. However, future stand-replacing fires in the western portions of the watershed could certainly lead to a temporary increase in debris flow frequency in Pete's Creek given that it is largely forested. In terms of the overall frequency-magnitude curve, given the long debris-flow history that was considered in developing the frequency-magnitude curve, major wildfires are likely incorporated. Therefore, the validity of the F-M curve should not be cast in doubt due to future wildfires.

With respect to the effects of wildfires on the fan of Bear Creek, little can be said without detailed field studies. The high (100%) mortality of trees on the affected fan portion implies that roots have died and the cohesive force of roots in stabilizing the fan surface will have been lost. This may result in more sediment entrainment on the fan from channel bank failures during future debris flows, though this will depend more on the moisture conditions in the fan sediment at the time of the debris flow and the ratio of water to sediment of the debris flow. Over time, shrubs and trees will regrowth on the fan and eventually cohesion provided by vegetative roots will be regained.

In summary, the frequency of post-wildfire debris flows in the Bear and Pete's Creek watersheds are unknown. Given the recent fire in the Bear watershed, it is likely that fires and associated increases in erosion have occurred in the past (charcoal was found in test pits). The effect of past post-wildfire debris flows is likely included in the frequency-magnitude relationship that was established based, in part, on the field evidence of past flows. An adjustment of the F-M relationship thus does not appear to be warranted. Irrespective, short-term increases in debris flow frequency can be expected following major stand-replacing wildfires if storms of sufficiently large magnitude were to coincide with the critical few years following the wildfires.

D.3.4. Summary

The above sections focused on deciphering the relationship between debris flow frequency and magnitude of debris flows on Bear Creek. Substantial effort was required as the F-M relationship forms the core of a quantitative risk assessment. Having an erroneous F-M relationship implies erroneous risk results and mitigation that is either over- or under designed.

Using several different techniques, BGC established that debris flows occur with return periods as little as 10 years. Such debris flows are likely to be associated with volumes of several thousand cubic metres. Debris-flow volumes were estimated up to a 1000 to 3000-year return period class as stipulated by APEGBC (2012). The class mean for this return period yields an estimated volume of approximately 320,000 m^3. Larger debris flows are possible, but would likely be associated with a major rock slope failure or large debris avalanche on one of the extensive talus slopes flanking the north face of the Bear Creek watershed.

Substantial uncertainty persists with respect to climate change on Bear Creek. Current projections call for a substantial warming trend in the next century (Appendix J) which could lead to the eventual disappearance of assumed permafrost. In addition, an increase of the frequency of extreme precipitation events is expected in conjunction with an increase of 20-40% in precipitation intensity (Appendix J). All of these factors will likely lead to more (high confidence), and possibly larger (low confidence) debris flows.

D.4. WHITECAP CREEK

D.4.1. Frequency Analysis

Recorded Debris Floods

Table D-11 lists recorded debris flood events that have occurred on Whitecap Creek. This record implies at least seven events since approximately 1920. This results in a minimum return period of debris floods of approximately 14 years. Little is known about the magnitude of the respective events. However, given that most of them apparently impounded Portage River, they appear to have transported considerable volumes of debris.

Table D-11. Previous events on Whitecap Creek.

Date	Description	Reference
1920-1940s (specific dates unknown)	People of Lillooet noted a drop in Seton Lake water levels like due to a debris flood event on Whitecap Creek that blocked Portage River.	R. James, Tsal'alh, email September 28, 2017
1973-1974	Debris flood that temporarily blocked Portage River.	R. James, Tsal'alh, email September 28, 2017
1977	Debris flood that temporarily blocked Portage River.	R. James, Tsal'alh, email September 28, 2017
1980s (specific dates unknown)	Two separate debris flood events.	Pers. Comm. N. Adrian, Seton Portage resident, September 12, 2017
September 20, 2015	Debris flood/channel avulsion that isolated and/or damaged an access road, four residences and an office building. Debris blocked Portage River over a length of approximately 170 m.	MFLNRO (2015)
November 8, 2016	Debris flood/channel avulsion that isolated and/or damaged an access road, four residences and an office building. Debris partially blocked Portage River.	MFLNRO (2016)

Air Photograph Interpretation

Air photograph interpretation was also completed for Whitecap Creek, as summarized in Table D-12.

Table D-12. Air photo record of Whitecap Creek.

Air Photo Year	Observations
1948	Fresh sediment in channel. Downstream of the hydro right of way, the channel is slightly wider than across the right of way.
1951	Observations are generally consistent with the 1948 air photo, but the air photo is coarser and more difficult to interpret.
1964	The channel has avulsed approximately 300 m upstream of the outlet of the river (approximately mid fan). The channel runs along the base of the cliff adjacent to the channel. The road bridge has been constructed over Portage River. The hydro right of way across the upper fan has been constructed.
1965	The channel has avulsed back to its approximate 1951 location on the mid-fan.
1972	The resolution of this air photo is too coarse to interpret on Whitecap Creek.
1975	A debris flood event has occurred between the 1965 and 1975 air photos. The channel is wider than previous photos, particularly on the mid to lower fan. The channel has avulsed at the outlet at Portage River (approximately 60 m west).
1987	The channel has avulsed at the outlet at Portage River to its approximate 1965 location 60 m east of the road bridge. A small road has been constructed across Whitecap Creek approximately 130 m upstream of the outlet at Portage River.
1997	Observations are generally consistent with the 1987 photo.
2005	Observations are generally consistent with the 1997 photo. The road across Whitecap Creek is wider.
2012 (Digital Globe satellite image)	Observations are generally consistent with the 2005 photo.

The avulsions locations and their occurrences are shown in Figure D-10.

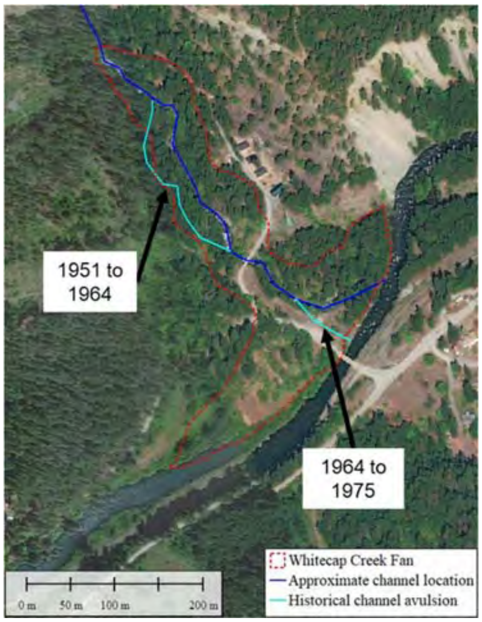

Figure D-10. Whitecap Creek historical avulsion locations. The historical and present channel location is shown in dark blue and the historical avulsion locations are in light blue.

In summary, Whitecap Creek has avulsed on the mid and lower fan within the air photo record, including the following events:

- A large flood may have occurred between 1951 and 1964, causing the avulsion that was observed on mid fan. This event does not appear to have been documented by historical accounts.
- A large flood event appears to have occurred between the 1965 and 1975 air photos that cause the avulsion on the lower fan. This is probably the 1973 or 1974 event that was reported by R. James.

This analysis suggests that the return period of debris floods on Whitecap Creek is about 12 years.

Dendrogeomorphology

Fourteen trees were sampled during the field program from coniferous trees on Whitecap Creek. The analysis methods are presented in Section D.3.1, and the results of the analysis for Whitecap Creek are summarized in Table D-13.

Table D-13. Debris-flood event dates inferred from dendrochronology on Whitecap Creek.

Inferred Date	Affected Samples	Corresponding Data
1894	1 tree strongly affected	
1910	1 tree strongly affected	
1936	2 trees affected	At some point in the 1920-1940s, the level of Seton Lake dropped; Lillooet residents attributed it to a creek-blocking debris flood from Whitecap Creek
1945	2 scars, 1 tree affected	
1959	1 scar, 3 trees affected	May correspond to the mid-fan avulsion observed between the 1951 and 1964 air photos
1964	1 scar, 2 trees affected	May correspond to the mid-fan avulsion observed between the 1951 and 1964 air photos
1973	5 trees affected, 1 tree strongly affected	Whitecap Creek blocked Portage River, also observed in the air photographs
1977	6 trees affected, 2 trees strongly affected	Whitecap Creek blocked Portage River
1984	6 trees affected, 4 trees strongly affected	
2015	1 scar	Known event
2016	2 trees strongly affected	Known event

The data summarized in Table D-13 suggest an average return period of 11 years, or an annual probability of debris-flood occurrence of approximately 10%.

D.4.2. Magnitude Analysis

Given Whitecap Creek's susceptibility to debris floods, the analytical methods differ from those for Bear Creek. Also, compared to debris-flow magnitude analysis, debris-flood magnitude analysis focuses more on peak discharge quantification than on sediment volume quantification.

The following steps were undertaken to estimate peak discharge (Q_{max}) at Whitecap Creek:

1. Estimate of the peak discharge during the November 9, 2016 debris flood.
2. A regional flood frequency analysis (FFA).
3. Rainfall-runoff modelling.
4. Comparison of the FFA and the runoff modelling; the higher of the two was chosen for analysis (base Q_{max}).
5. Landslide dam outbreak flood (LDOF) assessment.
6. Scaling of the base Q_{max} to reflect the potential for debris floods and LDOFs.

November 8, 2016 Debris-Flood Magnitude Reconstruction

The November 8, 2016 debris flood magnitude was approximated via a number of methods, as described below.

At the fan apex, approximately 50 m downstream of the bedrock canyon, two channel cross-sections with high water marks were surveyed. These cross-sections have wetted areas of 18 and 24 m^2 (Figure D-11). From the FLO 2D modeling that was carried out on Whitecap Creek (Appendix G), a flow velocity of 4.5 to 6.5 m/s was extracted. The peak flow for the November 2016 event is thus estimated to range between approximately 80 and 160 m^3/s (Figure D-12).

The corresponding sediment volume was estimating by delineating the areas that appeared to have been inundated with debris during the 2016 event. These areas were delineated in Global Mapper based on review of still photographs (Figure D-13), resulting in an estimated deposition area of approximately 36,000 m^2.

The approximate depth of the deposit is estimated between 1.0 and 1.5 m: the resultant sediment volume was between 36,000 m^3 and 54,000 m^3, with an estimated average of 45,000 m^3. The 2015 event covered a very similar area compared to the 2016 event, but the magnitude of this event cannot be reconstructed. However, the area delineation was complicated by the presence of fresh debris from the 2015 event (which may have been mistakenly included in the 2016 area), and the fact that sediment was cleared from the area after both events.

Figure D-11. Estimated cross-section of the November 2016 debris flood on Whitecap Creek. Photo: BGC November 9, 2017 looking upstream.

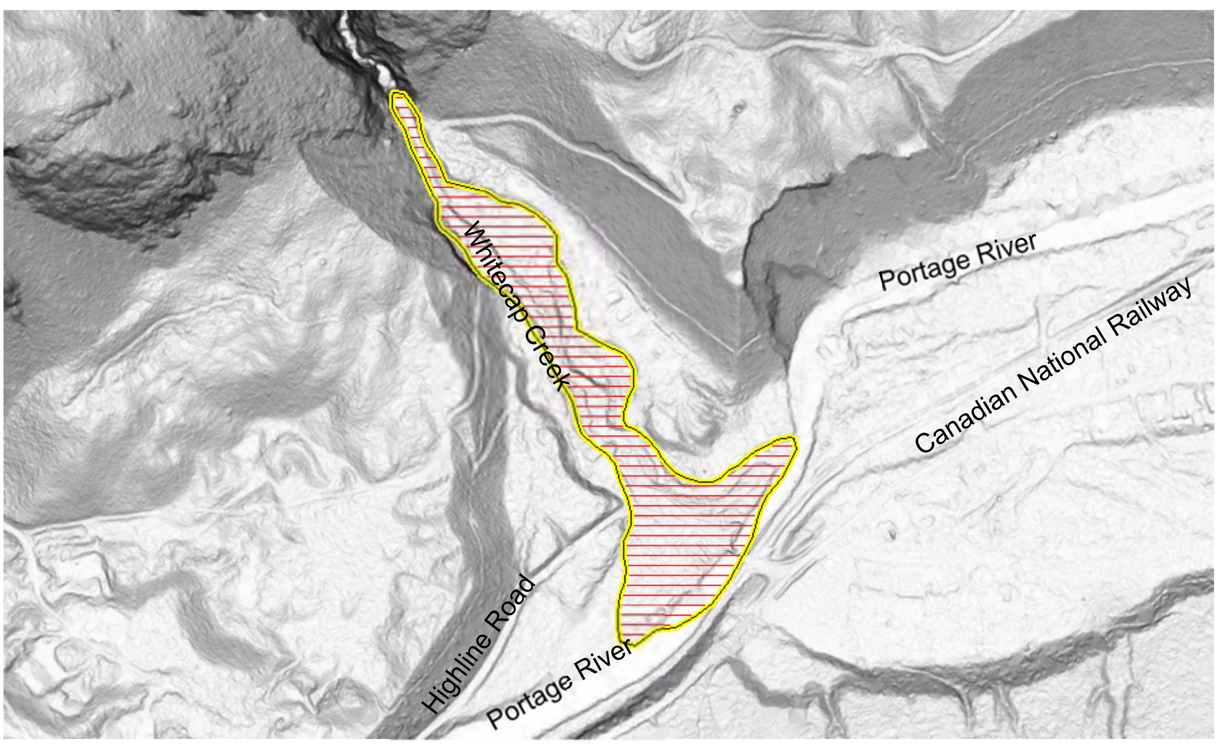

Figure D-12. Approximate area inundated by the 2016 debris flood on Whitecap Creek.

Flood Frequency Analysis and Rainfall-Runoff Modelling

The FFA depends on regional streamflow gauges maintained by the Water Survey of Canada (WSC). The gauge data were used to develop regressions between drainage area and peak flow for individual return period floods. Regional FFA relationships should be used with caution, especially for high return periods that exceed the record length and for small watersheds.

Rainfall-runoff modelling provides a more watershed-specific peak flow estimate, which depends on the watershed topography, rainfall distribution, runoff rate and time of concentration. Choosing the appropriate runoff curve number (CN) is particularly uncertain without the benefit of peak flow calibration data; hence rainfall-runoff modeling was conducted for a range of CN values.

The FFA and rainfall-runoff assessment methods are presented in more detail in Appendix C, and the results are summarized in Table D-14.

Table D-14. Whitecap Creek (drainage area: 74 km^2) flood frequency results.

Method	Scenario (m^3/s)	Return Period (Years)					
		3	10	30	100	300	1000
Regional Analysis	Q_{IMAX}	37	50	64	84	108	143
Rainfall-Runoff Model	CN_{60}	**14**	**37**	67	112	167	244
	CN_{65}	20	49	**85**	138	202	290
	CN_{70}	28	63	107	**169**	242	340
	CN_{75}	38	81	132	204	**286**	**395**

There is no rule of which CN value is the most "correct", especially in the absence of calibration data. However, experience has shown that peak flows in steep small creeks are often much higher than those determined by regional analyses for higher return periods (Jakob and Jordan 2001). For lower return periods, a CN value of 60 was adopted, with increasing CN values for higher return periods (all adopted values in bold). Higher CN values for longer return periods are intended to reflect higher antecedent moisture conditions in the watershed.

Landslide Dam Outbreak Flood (LDOF) Assessment

The impoundment of Whitecap Creek by landslides could result in a peak flow that substantially exceeds the base Q_{max} estimates from the FFA and rainfall-runoff modelling. The LDOF assessment involved the following steps:

1. Determine whether there is evidence of past landslide dams in the Whitecap Creek watershed.
2. Identify locations where landslide dams could occur in the future.
3. Estimate the size of the landslide dam(s) that could occur, and the volume of water that would be impounded.
4. Estimate the peak discharge that would result from breaching of the landslide dam(s).

BGC used the LiDAR hillshade imagery to identify tributaries or other areas within the Whitecap Creek watershed that could result in landslide dams. We looked for signs of deep-seated landslides (scarps and amphitheatre-shaped land missing from the hillside) as well as tributary debris-flow fans. Figure D-13 shows one of these locations extracted from the LiDAR shaded relief image.

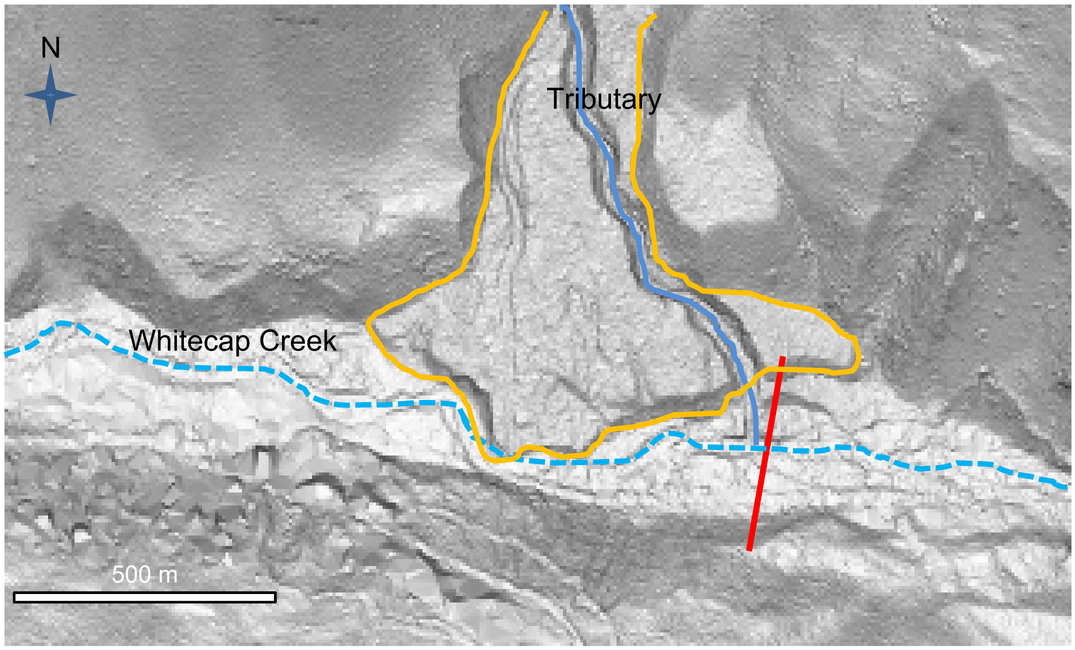

Figure D-13. Location on Whitecap Creek where a tributary debris flow could impound the creek. The possible dam alignment is shown in red. The tributary fan (Dam 1) is outlined in orange.

Two additional locations were identified where landslide dams of varying sizes could occur and impound the creek. The dam volume and impounded water volume were estimated using Muck3D software, and are summarized in Table D-15. The dam volumes were chosen to be conservative.

Table D-15. Possible landslide dam geometries in the Whitecap Creek watershed.

Dam	Location	Dam Height (m)	Dam Volume (m^3)	Dam base width (m)	Impounded water volume (m^3)
1	Upper watershed	25	269,000	150	385,000
2	Upper watershed	35	563,000	220	1,300,000
3	Lower watershed	40	660,000	250	2,365,000

The risk posed by a landslide dam depends on the rate at which it breaches. If the dam breaches slowly, the impounded water is released gradually and no or little flood surge is created. LDOFs occur when the dam breaches quickly, releasing a substantial volume of water.

Estimation of breach rate is complicated because it depends on a range of factors that are difficult to predict. However, empirical relationships have been developed that can be used to estimate or predict breach rate based on the behaviour of previous landslide dams. Two models (O'Connor and Beebee (2009) and Peng and Zhang (2012)) were compared for this project; equations and calculations are on file at BGC. Input parameters include dam height, impounded water volume and breach rates. The results of the assessment are presented in Table D-16.

Table D-16. Whitecap LDOF peak discharge estimates from empirical relationships.

Dam	Peak discharge (m^3/s) for various breach models		
	O'Connor and Beebee (2009) (median)	O'Connor and Beebee (2009) (upper bound)	Peng and Zhang (2012) (low erodibility coefficient)[1]
1	70	670	120
2	170	1620	210
3	270	2560	270

Note:
1. The high erodibility coefficient of Peng and Zhang (2012) was not used as it results in unreasonably high peak flows.

Without measurements from known LDOFs, BGC cannot rule out the upper bound O'Connor and Beebee peak discharges. However, Dams 2 and 3 are considered improbably large. Therefore, BGC proposes that the maximum likely peak discharge from Whitecap Creek is around 600 or 700 m^3/s, as per the Dam 1 location.

While this method is appropriate to estimate possible peak flows due to landslide dam outbreak floods, it does not inform on their return period. Return period was estimated by BGC by interpreting geomorphological evidence such as paired terraces upstream or downstream of potential landslide dam heights.

Table D-17 presents the adjustments that were made to the rainfall-runout modelling, based on the results of the LDOF assessment. Clearwater peak discharges for each return period class reflect the average of the lower and upper ends of the class.

Table D-17. Peak flow adjustments for full suite of return periods on Whitecap Creek.

Return Period (T) (years)	Clear Water Flood Peak Discharge (m^3/s)	Factor Adjustment	Debris-Flood Peak Discharge (m^3/s)	Process
3 to 10	25	-	-	Flood
10 to 30	60	1.0	60	Debris Flood
30 to 100	130	1.0	130	Debris Flood
100 to 300	230	1.2	275	Small LDOF
300 to 1000	340	1.2	410	Small LDOF
1000 to 3000	395	1.5	600	Large LDOF

LDOF peak flow estimates are associated with uncertainty due to the following assumptions:

- The landslide dam geometry has been inferred based on digital elevation models. The actual landslide geometry as well as upstream and downstream channel geometries at the time of the landslide failure may have been different, thus resulting in different outflow hydrographs.
- The peak flow estimates assume that the landslide will be breached to the bottom of the current thalweg, which may not be the case.
- The peak flow estimates also assume that the entire landslide mass fails in one event, rather than by partial failure. The latter would lead to smaller landslides, lesser upstream impoundment and lower LDOF peak flows.

D.4.3. Frequency-Magnitude Analysis

The above analyses provide estimates of debris flood peak flows, but not sediment volumes. Sediment volumes were not considered in the numerical modeling, but are important for any future design of mitigation measures aimed to contain debris and to understand the potential of Whitecap Creek debris floods impounding Portage River. To estimate debris-flood sediment volumes, an empirical rainfall-sediment volume relationship was applied.

Rainfall-Sediment Relationship

Debris-flood volumes can be predicted from the volume of rains that falls over a watershed when the rainfall is of sufficient magnitude to trigger flooding that entrains large volumes of debris. The method below describes how this was applied to Whitecap Creek.

During August 21-23, 2005 severe flooding occurred in a large area of northern Switzerland with significant morphological changes in stream channels (Jäggi 2007). This event was associated with more than 200 mm of rain within three days with corresponding return periods exceeding 100 years. As many mountain creek hazards in Switzerland have been mitigated by catchment basins and LiDAR data collection is prevalent, the sediment volumes could be determined with relatively good precision.

A database was subsequently created with 33 debris flows and 39 fluvial sediment transport events, details of which are reported in Rickenmann and Koschni (2010). These authors used a variety of transport movement equations to compare modeled and predicted sediment transport volumes including those by Rickenmann (2001), Rickenmann and McArdell (2007), Hunziker and Jäggi (1992), Recking *et al.* (2008), and D'Agostino *et al.* (1996). Rickenmann and Koschni (2010) found reasonable agreements between modelled and measured sediment volumes for channels with less than 5% gradient using the Meyer-Peter and Mueller equations. In contrast, for steeper channels, the observed sediment volumes transported by fluvial processes are over-predicted by bedload equations developed for steep channels.

Given the value of the Rickenmann and Koschni (2010) database, BGC analyzed the data further. First, BGC separated the debris flow events from the mostly fluvial transport data. Watersheds with very large areas and correspondingly low gradients (< 1%) were also deleted from the dataset. These deletions provided a final dataset of 36 cases. Multivariate regression analysis was then applied to the log-transformed dataset to determine sediment volumes based on catchment area, rainfall volume, runoff coefficient, surface runoff and channel gradient. This analysis yielded the two following formulae:

$$logV_S = 0.753logV_R - 0.553,\ R^2 = 0.79 \quad \text{[Eq. D-1]}$$

$$logV_S = -1.55 + 0.877logV_R + 0.019S,\ R^2 = 0.81 \quad \text{[Eq. D-2]}$$

where V_S is the total sediment volume displaced and V_R is the total rainfall over a 3-day period. The difference between the two formulae is the inclusion of channel slope S in Equation D-2. However, since the increase in variance explained is very small (2%), the effect of slope appears small which is likely due to the observation that channel slopes differ only slightly in the watersheds analysed. Moreover, channel slope is closely related to watershed area and watershed area directly correlates with runoff. Therefore, some co-linearity (predictor variables correlating with each other) exists which is undesirable in multiple regression analysis and which can lead to incorrect results. Equation D-1 presented above is appropriate only for debris floods with channel gradients from approximately 5 to 24%.

In addition to the Swiss dataset, BGC created a dataset with 13 creeks in the Bow Valley that experienced debris floods during a significant 3-day storm in June 2013. Sediment volumes deposited on each fan were estimated by comparing 2008 or 2009 LiDAR to 2013 LiDAR. Rainfall volumes were calculated using the June 19-22, 2013 precipitation isohyet along with estimated snowmelt contributions for each watershed.

Both the Swiss and Bow Valley data were log transformed to achieve statistical normality and a regression analysis was conducted for the combined Bow Valley and Swiss data which resulted in Equation D-3, which shows very little difference from the Swiss dataset regression. The combined regression was used in further analyses.

$$logV_S = 0.70logV_R - 0.18,\ R^2 = 0.79 \quad \text{[Eq. D-3]}$$

where V_S is the total sediment volume displaced and V_R is the total 3-day rainfall volume. The regression analysis of the combined data is shown in Figure D-14.

The correspondence of the Swiss and Bow-Valley rainfall-sediment correlations suggests that a relationship between rainfall and sediment mobilized may be due to similar geological conditions, with the Bow Valley (purely sedimentary rocks) results plotting slightly higher than those in the Swiss dataset. While this relation appears to be reasonably robust, it has not been verified for temporal independence. In other words, it is still unknown if this relation still holds for different storms of different intensities and durations for individual creeks.

The rainfall volumes as determined from hydrological analyses (Appendix C) were then used in conjunction with a judgement based estimate of 20% snowmelt contribution to determine the total equivalent rainfall volume V_R that was entered into Equation D-3. Table D-18 summarizes the results for a hypothetical three-day storm.

Table D-18. Summary of results from rainfall sediment relationship modeling.

Return Period (T) (years)	10	30	100	300	1000
72-hr rainfall (mm)	75	94	114	133	154
+snowmelt contribution (mm)	90	113	134	160	185
Storm Volume (m^3)	6,660,000	8,347,000	10,123,000	11,810,000	13,675,000
Sediment Volume (m^3)	38,000	46,000	53,000	59,000	66,000

Table D-19 summarizes the F-M relationship that was developed based on the combination of the above analyses.

Table D-19. Whitecap Creek frequency-magnitude relationship.

Return Period (T) (years)	Annual Probability (%)	Sediment Volume Best Estimate (m^3)	Clear Water Flood Peak Discharge (m^3/s)	Debris-Flood Peak Discharge (m^3/s)	Process
3 to 10	10 to 33	unknown	25	-	Flood
10 to 30	3 to 10	30,000	60	60	Debris Flood
30 to 100	1 to 3	38,000	130	130	Debris Flood
100 to 300	0.3 to 1	46,000	230	275	Small LDOF
300 to 1000	0.1 to 0.03	59,000	340	410	Small LDOF
1000 to 3000	0.03 to 0.01	66,000	395	600	Large LDOF

Based on Table D-19, the November 2016 debris flood event (Q_{max} ~ 120 m^3/s, sediment volume ~ 45,000 m^3) has a return period of 30 to 100 years.

D.4.4. Summary

Whitecap Creek is subject to producing episodic debris floods. These hydrogeomorphic events are being transported from the upper watershed through the bedrock canyon onto the alluvial fan where additional sediment can be entrained through bank collapse of the paleo-delta deposits on the western fan edge. The analyses presented herein suggest that the largest considered debris flood is likely a LDOF with a peak discharge of up to 600 m^3/s and a corresponding debris volume of approximately 66,000 m^3. Compared to Bear Creek, Whitecap Creek debris flood sediment volumes are much lower, despite the fact that the Whitecap Creek watershed is approximately 20 times larger than Bear Creek's. The lower volumes are attributable to the fact that sediment is being mobilized through exceedance of a critical shear stress threshold along the alluvial channel bed. This threshold is dependent on channel slope and flow depth. The volume of debris is thus dependent on the severity and duration of a rainstorm as only a portion of the bed surface material is being transported. In contrast, Bear Creek debris flows increase in volume from the watershed onto the fan by entraining more and more sediment. During this process, the steep bedrock channels in the upper watershed can be completely depleted of sediment.

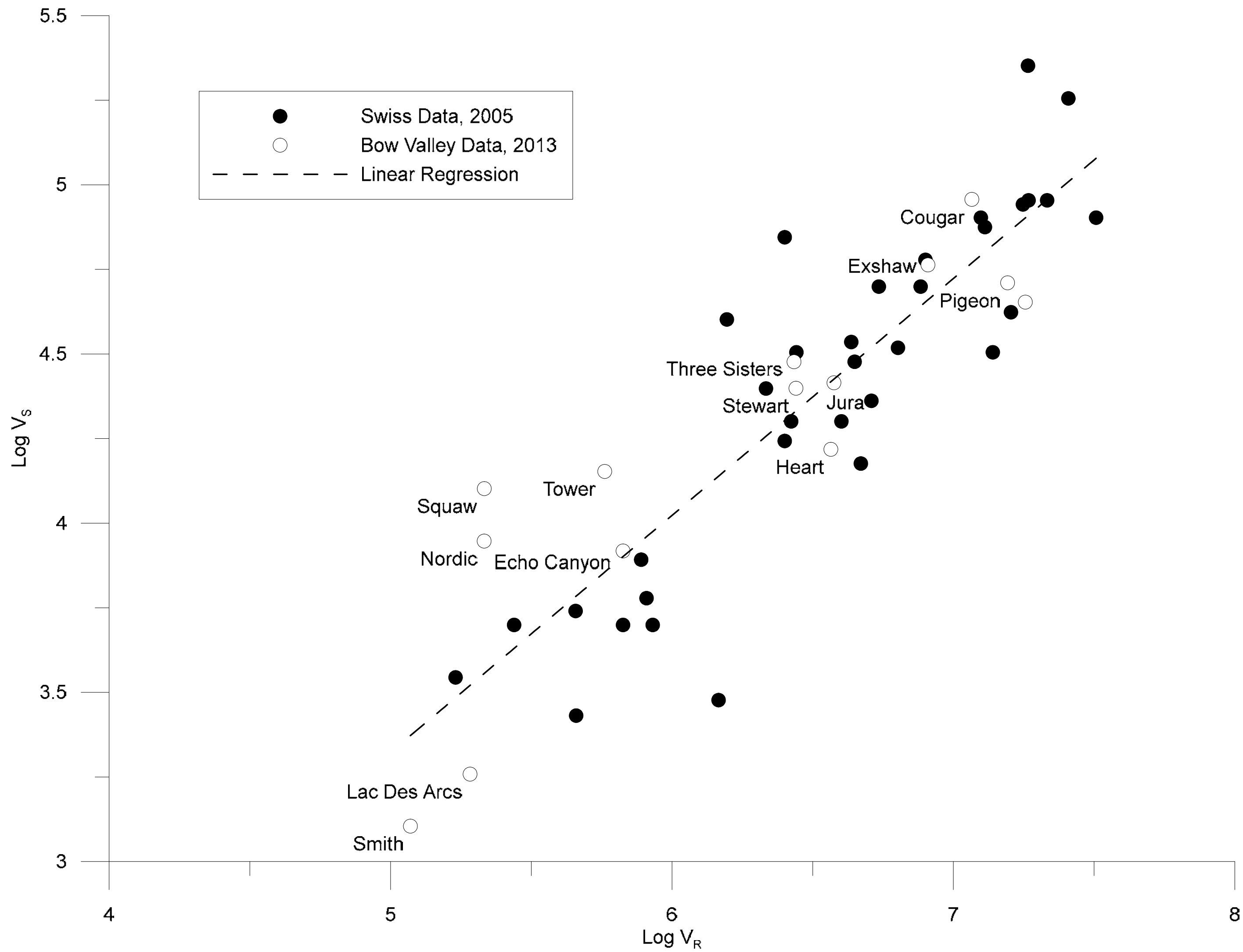

Figure D-14. Datasets complied by Rickenmann and Koschni (2010) and BGC.

D.5. SPIDER CREEK

D.5.1. Frequency Analysis

Recorded Debris Floods

Recorded debris floods on Spider Creek are summarized in Table D-20.

Table D-20. Previous events on Spider Creek.

Date	Description	Reference
1961-1963 (specific date unknown)	A sudden and high flood occurred when a landslide above the Spider Creek waterfall blocked the creek for a few hours (LDOF). When the landslide dam broke, a high wave breached the channel and traveled northeast towards 400 Spider Creek Road.	Pers. comm. W. Alexander, Tsal'alh, September 12, 2017
1982-1983 (specific date unknown)	Event on Spider Creek at 100 Spider Creek Road. No further information provided.	Pers. comm. W. Alexander, Tsal'alh, September 12, 2017

These data would suggest a frequency of approximately 30 years for debris floods on Spider Creek.

Air Photograph Interpretation

Air photograph interpretation was completed for Spider Creek, as summarized in Table D-21.

Table D-21. Spider Creek air photograph interpretation.

Air Photo Year	Observations
1948	The stream channel is difficult to see through the trees.
1951	The resolution of this air photo is too coarse to interpret on Spider Creek.
1964	The stream channel is more distinct than the 1948 air photo, but it is still difficult to see the channel through the trees.
1965	The stream channel is difficult to see through the trees but there appears to be erosion along the margins of the active floodplain.
1972	The resolution of this air photo is too coarse to interpret on Spider Creek.
1975	The stream channel is difficult to see through the trees but there may be sediment deposited on the lower portions of the channel.
1987	The stream channel is difficult to see through the trees.
1997	No change to the 1987 photo.
2005	No change to the 1997 photo.
2012 (Digital Globe satellite image)	Portions of the fan have been burnt by a wildfire and there are dead trees above the floodplain on the terraces.

Due to the thick vegetation along the stream channel, it was difficult to determine if debris floods had occurred in the channel, and channel changes could not be mapped. This implies that there were no extreme events that would have destroyed the riparian vegetation belt. Neither the 1961 to 1963, nor the 1982/83 events appear to have been of sufficient magnitude to kill trees and leave a discernible swath along the creek corridor. Therefore, the return period of damaging events is likely greater than 50 years.

Dendrogeomorphology

Five trees were sampled from coniferous trees on Spider Creek during the field program. The analysis methods are presented in Section D.3.1, and the results of the analysis are summarized in Table D-22.

Table D-22. Debris-flood event dates inferred from dendrochronology on Spider Creek.

Inferred Date	Affected Samples	Corresponding Data
1907	2 trees strongly affected	1907 event on Whitecap Creek
Early 1960s	1 scar, 3 trees affected	Reports of high discharge and a possible LDOF
Early 1970s	4 trees affected	
1991	1 scar, 3 trees affected	Debris flows on Bear and Pete's creeks
2016	2 trees affected	2015 and 2016 events on Bear, Pete's and Whitecap creeks

Due to the small sample size, it was only possible to identify larger and more recent events on Spider Creek, those, however, are more important for hazard assessments.

D.5.2. Magnitude Analysis

Like Whitecap Creek, Spider Creek is prone to debris floods, and the magnitude of debris floods could be increased by LODFs. The same methods were used to evaluate debris floods and LDOFs on Spider Creek as on Whitecap Creek.

Flood Frequency Analysis and Rainfall-Runoff Modelling

FFA and rainfall-runoff modelling results for Spider Creek are summarized in Table D-23.

Table D-23. Spider Creek (drainage area: 25 km²) flood frequency results.

Method	Scenario (m^3/s)	Return Period (Years)					
		3	10	30	100	300	1000
Regional Analysis	Q_{IMAX}	26	34	45	60	78	107
Rainfall-Runoff Model	CN_{60}	**6**	**16**	28	47	70	102
	CN_{65}	8	21	**36**	58	84	121
	CN_{70}	11	27	45	**71**	101	142
	CN_{75}	16	34	56	86	**120**	**164**

Like Whitecap Creek, BGC decided to adopt the peak discharge values corresponding to variable CN values with higher CN values for longer return periods (bold).

Landslide Dam Outbreak Flood (LDOF) Assessment

The LDOF assessment methods are outlined in Section D.4.2. Figure D-15 shows a particularly sizable landslide that occurred sometime in the past 1000 to 10,000 years according to BGC's estimates.

In addition to the location shown in Figure D-15, two other possible landslide locations were identified. Estimated dam geometries and impounded water volumes are summarized in Table D-24. The dam volumes are purposefully near the upper limit of credibility, to get a sense of the largest peak discharge that the Spider Creek watershed could produce.

Table D-24. Possible landslide dam geometries in the Whitecap Creek watershed.

Dam	Location	Dam Height (m)	Dam Volume (m^3)	Dam base width (m)	Impounded water volume (m^3)
1	Lower watershed	10	51,000	200	10,000
2	Lower watershed	50	842,000	275	366,000
3a	Figure D-15	15	93,000	155	31,000
3b	Figure D-15	35	302,000	250	110,200
3c	Figure D-15	80	5,240,000	700	5,080,000

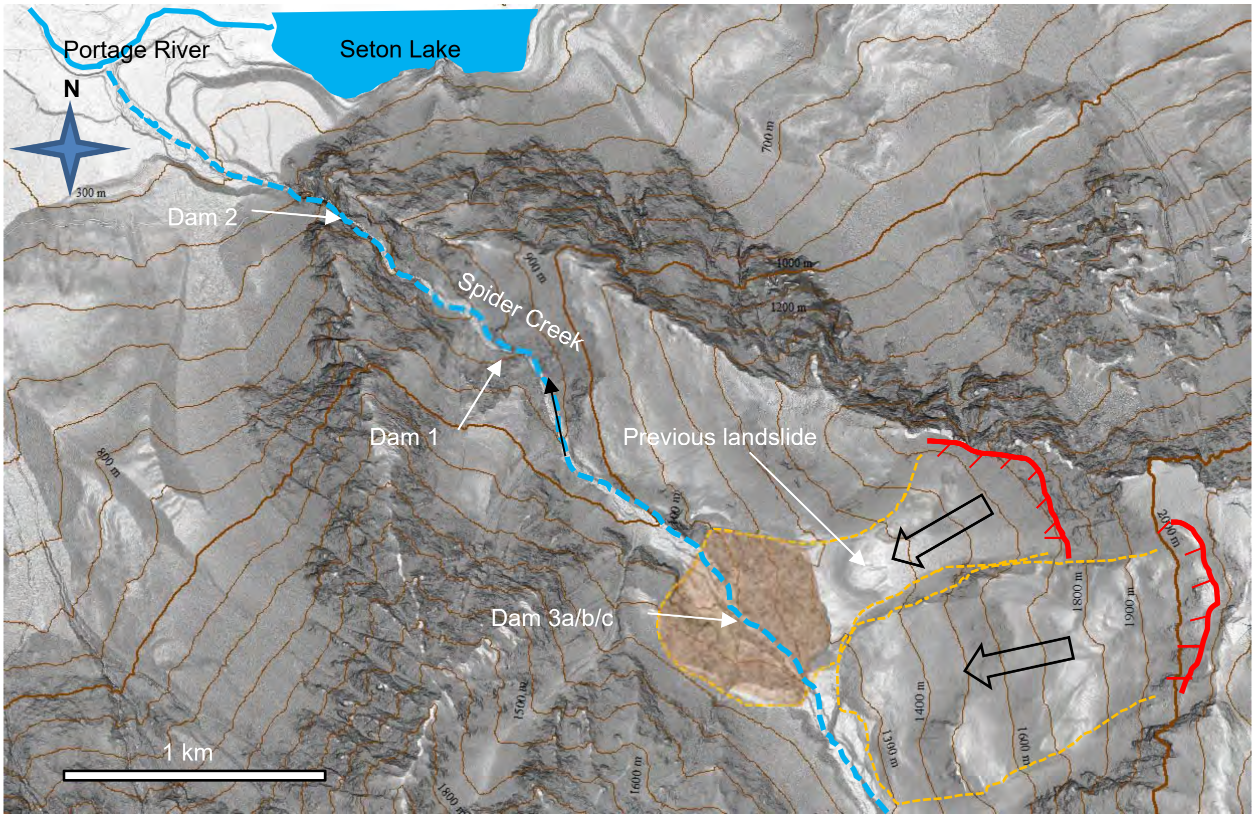

Figure D-15. Upper Spider Creek watershed with locations for previous and potential landslide dams. Note that the southern landslide did not appear to have reached Spider Creek. Imagery: LiDAR 2017.

The results of the breach rate and LDOF discharge assessment are presented in Table D-25.

Table D-25. Whitecap LDOF peak discharge estimates from empirical relationships.

Dam	Peak discharge (m^3/s) for various breach models		
	O'Connor and Beebee (2009) (median)	O'Connor and Beebee (2009) (upper bound)	Peng and Zhang (2012) (low erodibility coefficient)
1	5	50	30
2	40	370	100
3a	10	90	40
3b	20	160	60
3c	320	3000	320

Based on this analysis, BGC proposes that the maximum likely peak discharge from Spider Creek is around 1000 m^3/s. Table D-26 presents the adjustments that were made to the rainfall-runout modelling, based on the results of the LDOF assessment.

Table D-26. Peak flow adjustments for full suite of return periods on Spider Creek.

Return Period (T) (years)	Clear Water Flood Peak Discharge (m³/s)	Factor Adjustment	Debris-Flood Peak Discharge (m³/s)	Process
3 to 10	10	-	-	Flood
10 to 30	25	-	-	Flood
30 to 100	55	-	-	Flood
100 to 300	95	1.5	140	Small LDOF
300 to 1000	140	2	280	Large LDOF
1000 to 3000	165	3	500-1000	Very large LDOF

D.5.3. Frequency-Magnitude Analysis

Rainfall-Sediment Relationship

To estimate flood and debris flood sediment volumes, an empirical rainfall-sediment volume relationship was applied, as summarized in Section D.5.4. Results are presented in Table D-27.

Table D-27. Spider Creek frequency-magnitude relationship.

Return Period (years)	Annual Probability (1/T)	Sediment Volume Best Estimate (m³)	Clear Water Flood Peak Discharge (m³/s)	Debris-flood Peak Discharge (m³/s)	Process
10 to 30	3 to 10	13,000	25	-	Flood
30 to 100	1 to 3	17,000	55	-	Flood
100 to 300	0.3 to 1	20,000	95	140	LDOF
300 to 1000	0.1 to 0.03	24,000	140	280	LDOF
1000 to 10,000	0.03 to 0.01	28,000	165	500 to 1000	LDOF

D.5.4. Summary

Spider Creek is subject to producing episodic debris floods. These events are transported from the upper watershed through the bedrock canyon and through the steep channel leading to Portage River. The analyses presented herein suggest that the largest considered debris flood is likely a LDOF with a peak discharge of up to 1000 m^3/s and a corresponding debris volume of approximately 30,000 m^3. The volume and peak flow estimates are very approximate.

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APPENDIX E
TEST PIT LOGS

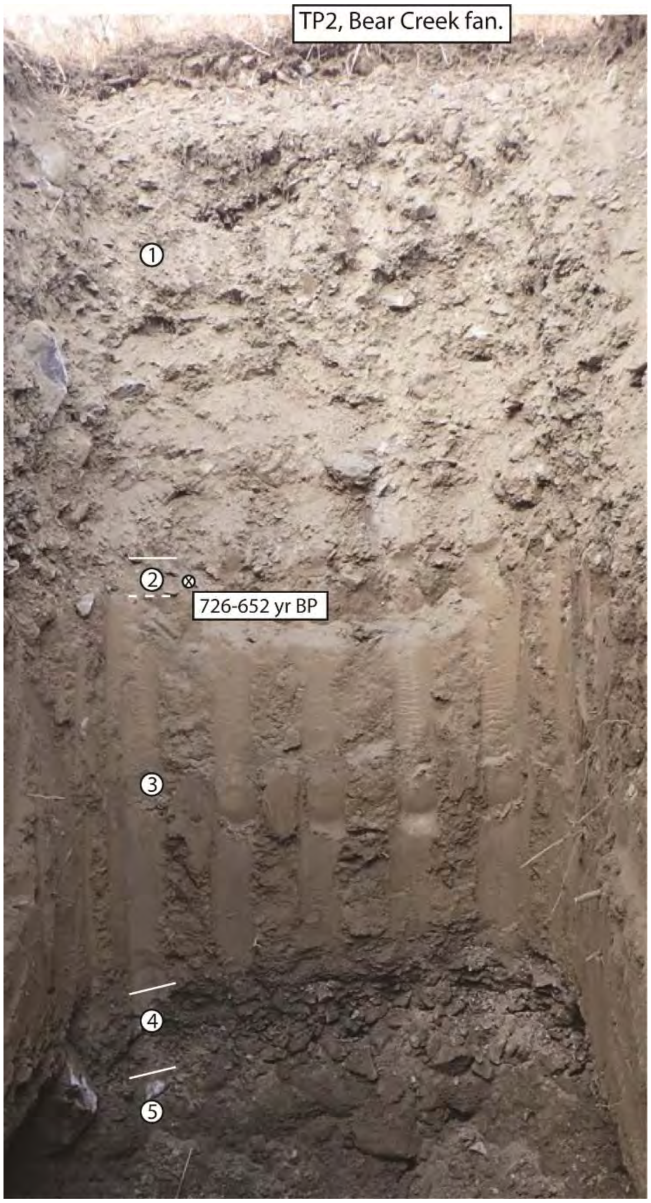
Note: TP9 and TP14 were not completed.

TP1 – Bear Creek fan

Unit	Depth (cm)	Observations
Unit 1	0-30	Muddy rubble, 2016 debris flow
Unit 2	30-105	Litter, Folic, Humic (LFH[1]) with rooted stump on muddy rubble
Unit 3	105-120	Silty sand with reddening from fire, charcoal sample from reddened zone at 120 cm gave 922-766 cal yr BP (Beta-474067)
Unit 4	120-300	Muddy rubble, single thick event, but lower 60 cm is darker and more washed, not as muddy
Unit 5	300-310	Muddy rubble
Base	-	Not seen

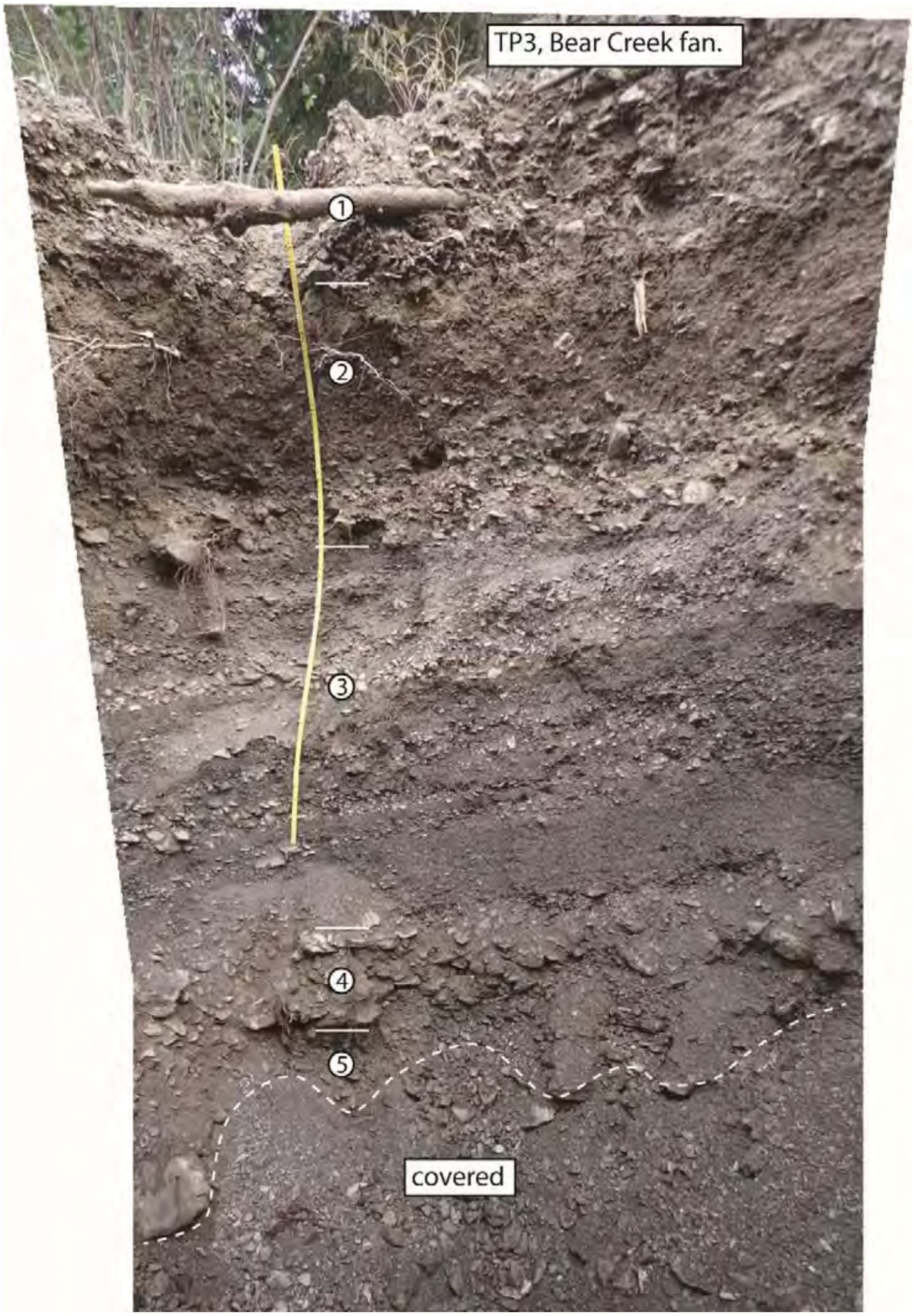
[1] Litter, Folic, Humic - describes the composition of the surface organic horizon in a typical forest soil pedon.

TP2 – Bear Creek fan



Unit	Depth (cm)	Observations
Surface	0-5	LFH
Unit 1	5-135	Muddy rubble
Unit 2	135-145	Silty fine sand with brunisolic soil and charcoal fragments, dated as 726-652 cal yr BP (Beta-474068)
Unit 3	145-220	Overbank silty sand
Unit 4	220-285	Stratified granule gravel, occasional angular fine boulder
Unit 5	285-310	Pebble cobble gravel, mixed lithology, rounded to subround clasts
Base	-	Not seen

TP3 – Bear Creek fan

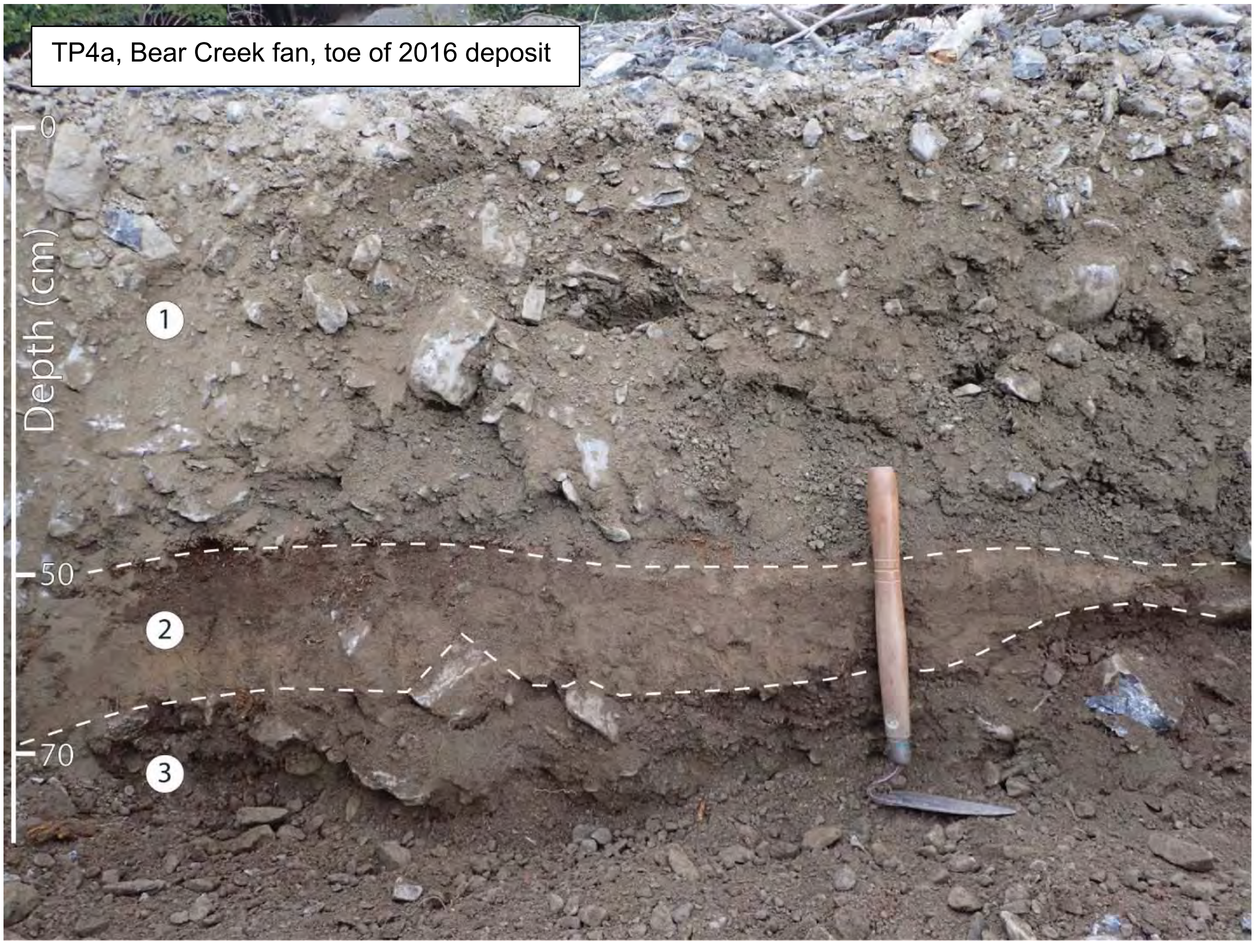


Unit	Depth (cm)	Observations
Unit 1	0-30	2016 event
Unit 2	30-90	Rubble diamict
Unit 3	90-200	Cross stratified coarse sand and pebble gravel
Unit 4	200-220	Lag cobble gravel
Unit 5	220-250	Pebble cobble gravel
Base	-	Not seen

TP4 – Bear Creek fan

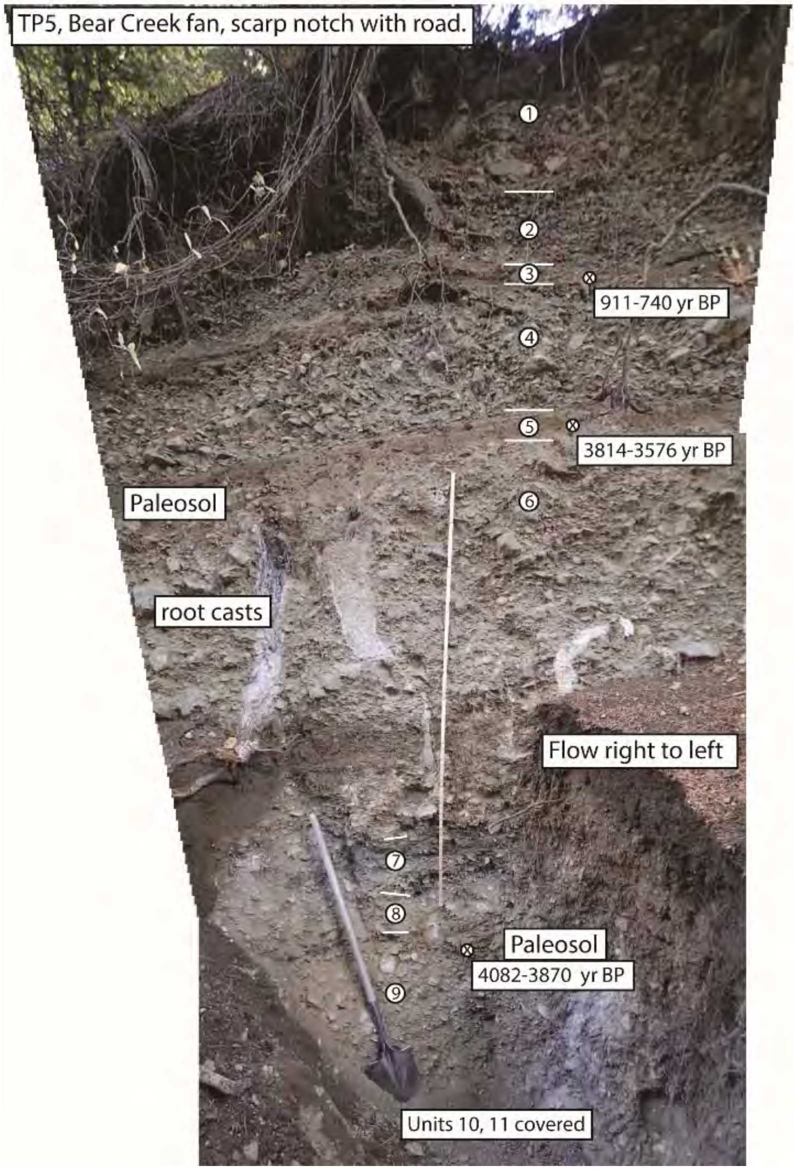
Unit	Depth (cm)	Observations
Unit 1	0-45	Cobble pebble gravel, clast supported, lower 10 cm openwork, upper 25 cm silty sand matrix
Unit 2	45-75	As above
Unit 3	75-130	Cobble pebble gravel, matrix to clast supported, occasional boulders to 50 cm, basal 15 cm like hyperconcentrated flow granular, fine pebble
Unit 4	130-145	Openwork, pebble
Unit 5	145-170	Horizontally bedded/stratified fine pebble
Unit 6	170-200	Cobble pebble gravel matrix to clast supported, occasional boulders to 50 cm
Unit 7	200-220	Bedded sand
Unit 8	220-240	Washed pebble gravel
Unit 9	240-260	Similar to Unit 6
Base	-	Not seen

TP4a – Bear Creek fan



Unit	Depth (cm)	Observations
Unit 1	0-50	Rubble diamict, 2016 deposit
Unit 2	50 – 70	Fine sand and silt with brunisolic soil in the upper 10 cm
Unit 3	70 – 80	Rubble diamict, brunisolic.

TP5 – Bear Creek fan



Unit	Depth (cm)	Observations
Unit 1	0-155 cm	Silty rubble diamict with clasts to fine boulder, 3-5 cm LFH, no soil development
Unit 2	155-165 cm	Washed sandy pebble gravel
Unit 3	165-175 cm	Silty afterflow deposit, weak soil development, residues yielded age of 911-740 BP (Beta-478121)
Unit 4	175-275 cm	Silty rubble diamict
Unit 5	275-285 cm	Silty afterflow, upper 3-5 cm Bf[2] soil development, exploited by modern live roots, paleosol dated at 3814-3576 cal yr BP (Beta-474071)

[2] Implies a paleosol with radiometric dating potential. "B" is the enriched soil horizon in a soil pedon. "A" is the leached horizon and "C" is the parent material. The suffix "f" refers to ferric enrichment through oxidation in a forest soil.

Unit	Depth (cm)	Observations
Unit 6	285-460 cm	Silty rubble diamict with root casts accentuated by carbonate precipitate; Unit 7. 460-500 cm, bedded granular sand and open work pebble gravel
Unit 7	450-500 cm	Bedded granular sand and open work pebble gravel
Unit 8	500-520	Rubble diamict
Unit 9	520-640 cm	Rubble diamict, upper 10 cm reddened with charcoal flecks, sample at 525 cm yielded age of 4082-3870 BP (Beta-478122);
Unit 10	640-665 cm	Granule gravel and open work pebble
Unit 11	665-750 cm	Rubble diamict
Base	-	Not seen

TP6 – no photo

Unit	Depth (cm)	Observations
Unit 1	0-25	Rubble diamict
Unit 2	25-65	Wavy lower contact, silty matrix to clast supported pebble gravel, outsize clasts cobble to fine boulder, subround clasts, looks like water worked diamict
Unit 3	65-95	Stratified sandy gravel, fluvial
Unit 4	95-130	Silty pebble gravel, weak horizontal stat, looks like hyperconcentrated, outsize clasts to cobble size
Unit 5	200-300	Stratified river gravel
Unit 6	300-350	Rubble diamict, hard
Base	-	Not seen

TP7 – no photo

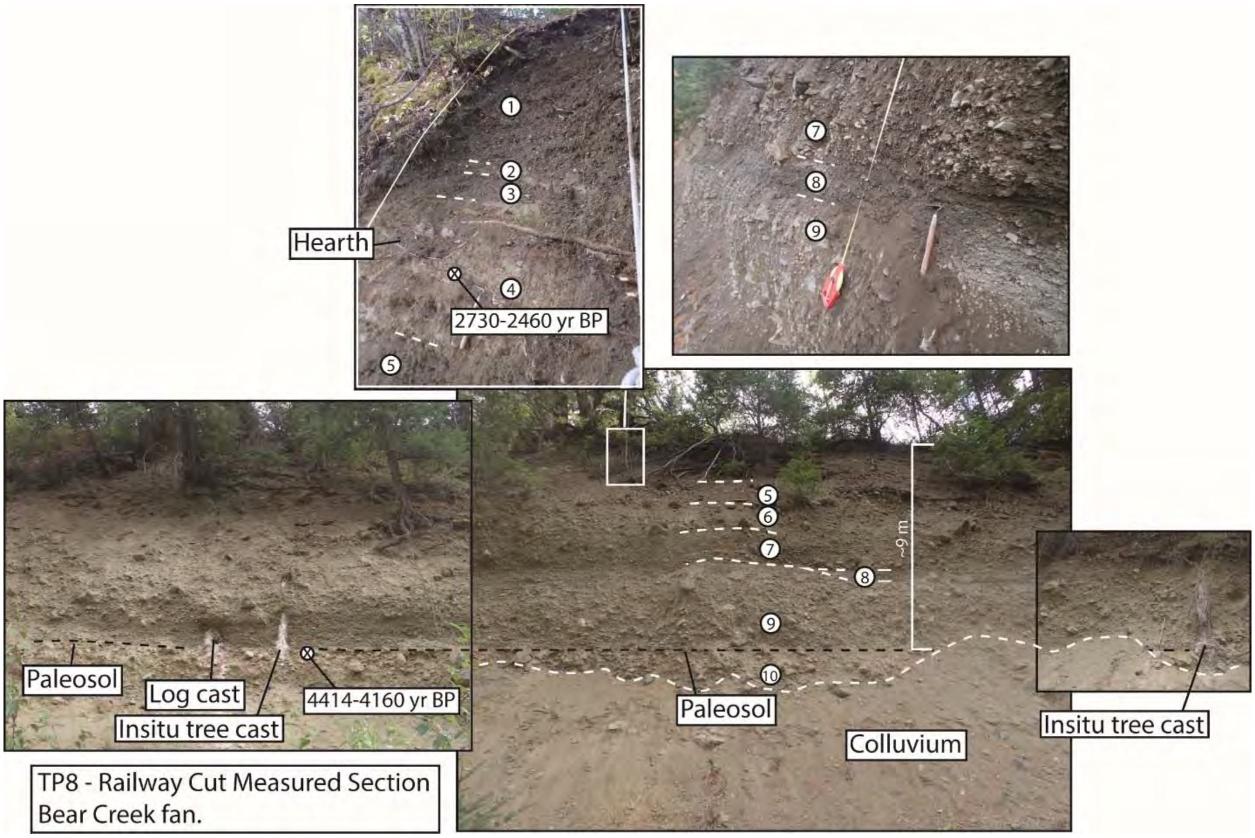
Unit	Depth (cm)	Observations
Unit 1	0-70	Silty rubble diamict
Unit 2	70-200	Stratified sandy cobble pebble gravel, occasional clasts to fine boulder, subround; charcoal sample at 70 cm upper contact dated at 500-315 cal yr BP (Beta-474073)
Base	-	Not seen

410 Spider Creek Road exposure and TP3 notch

410 Spider Creek Road (white house) exposure (left) and TP3 Notch (right) Log

Unit	Depth (cm)	Observations
Unit 1	0-60	Recent event
Unit 2	60-105	Rubble diamict with Bf soil developed
Unit 3	105-180	Rubble diamict with lenses of afterflow
Unit 4	180-260	Rubble diamict, 2 cm afterflow on surface
Unit 5	260-285	Rubble diamict, reddened on surface; 285-295 cm, silty granular afterflow with charcoal flecks, dated as 3449-3260 cal yr BP (Beta-474070)
Unit 6	295-345	Rubble diamict
Unit 7	345-475	Rubble diamict
Unit 8	475-485	Silty sandy afterflow
Unit 9	485-600	Rubble diamict
Base	-	Not seen

TP8 – Pete's Creek fan



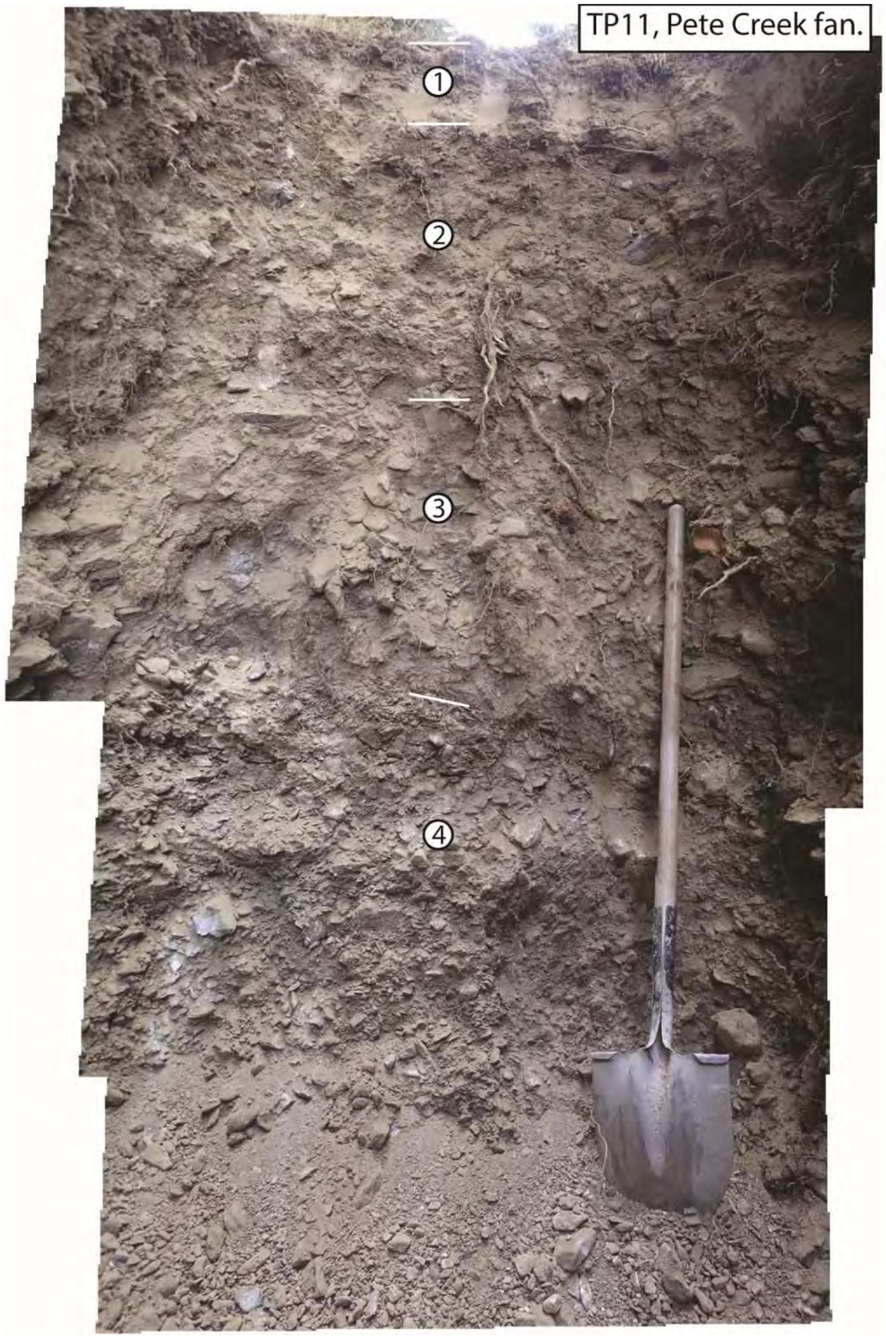
Measurements VD, corrected for slope

Unit	Depth (cm)	Observations
Unit 1	0-230	Rubble diamict, poorly exposed
Unit 2	230-240	Silty sand
Unit 3	240-260	Muddy pebble gravel
Unit 4	260-330	Wavy bedded silty sand with reddened lenses and charcoal streaks, looks like hearth features, several angular cobbles in "hearth" depression, charcoal sample at 296 cm yielded age of 2730-2460 BP (Beta-478130);
Unit 5	330-430	Rubble diamict, base unconformable
Unit 6	430-500	Rubble diamict, upper 10-15 cm muddy granular, partly eroded;
Unit 7	500-720	Rubble diamict, D90 = 500 mm
Unit 8	720-750	Weakly stratified pebble diamict, sharp upper contact, gradual lower contact
Unit 9	750-930	Rubble diamict, D90 = 700-800 mm, diamict envelops trees rooted on diamict below, this unit extends at least 100 m in width along the exposed portion of the railway cut
Unit 10	930-1115	Rubble diamict, from 930-945 cm is a paleosol developed on surface with in-situ tree casts and logs, yields age of 4414-4160 cal yr BP (Beta-474075);
Unit 11	1115-1150	Rubble diamict
Unit 12	1150-1420	Covered; 1420 cm is level of tracks.
Base	-	Not seen

TP10 – Pete's Creek fan

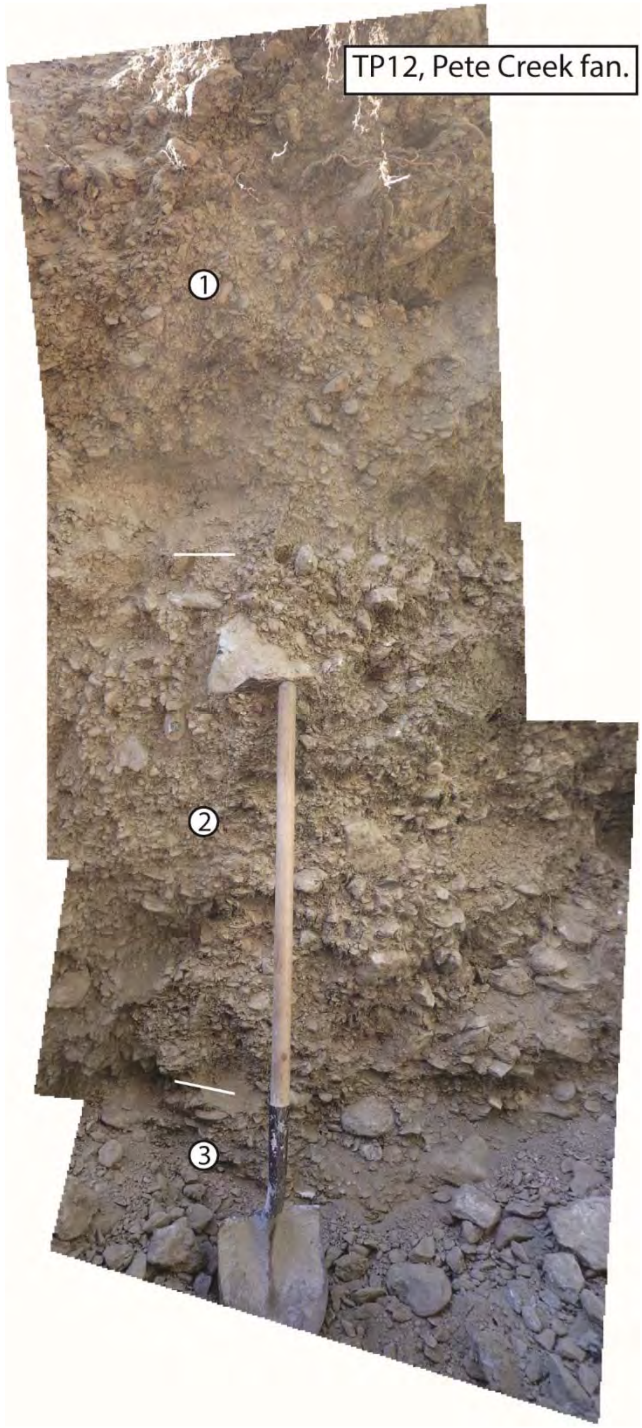
Unit	Depth (cm)	Observations
Unit 1	0-200	Rubble diamict, cobble pebble, occasional fine boulder, angular to subangular
Unit 2	200-210	Silty fine sand with charcoal, gave age of 1286-1180 cal yr BP (Beta-474078)
Unit 3	210-300	Rubble diamict
Base	-	Not seen

TP11 – Pete's Creek fan



Unit	Depth (cm)	Observations
Unit 1	0-25	Road fill
Unit 2	25-120	Matrix to clast supported rubble diamict, muddy matrix;
Unit 3	120-205	Rubble diamict
Unit 4	205-285	Rubble diamict, mostly pebble size, less cobble, rare fine boulder
Base	-	Not seen

TP12 – Pete's Creek fan



Unit	Depth (cm)	Observations
Unit 1	0-280	Rubble diamict
Unit 2	280-480	Rubble diamict
Unit 3	480-580	Rubble diamict
Base	-	Not seen

TP13 – Bear Creek fan

Unit	Depth (cm)	Observations
Unit 1	0-220	Rubble diamict, brunisol on surface
Unit 2	220-290	Coarsening up rubble diamict
Unit 3	290-300	Pinching out lense, rubble diamict, grey
Unit 4	300-400	Rubble diamict
Base	-	Not seen

TP15 – Bear Creek fan

Unit	Depth (cm)	Observations
Unit 1	0-105	Rubble diamict, lower contact marked by root horizon
Unit 2	105-300	Rubble diamict
Unit 3	300-325	Rubble diamict, upper contact marked by discontinuous sandy layer, unconformable
Base	-	Not seen

TP16 – Bear Creek fan

Unit	Depth (cm)	Observations
Unit 1	0-149	Rubble diamict
Unit 2	140-255	Rubble diamict
Unit 3	255-285	Rubble diamict, upper 10 cm, silt/sand, slightly oxidized, sample at 260 cm yielded age of 1692-1528 BP (Beta-478123);
Base	-	Not seen

TP17 – Bear Creek fan

Unit	Depth (cm)	Observations
Unit 1	0-35	Rubble diamict
Unit 2	35-40	Sandy granule gravel
Unit 3	40-90	Rubble diamict
Unit 4	90-125	Sandy pebble gravel, erosional lower contact
Unit 5	125-260	Rubble diamict
Unit 6	260-290	Rubble diamict, upper 10 cm silt/sand with charcoal laminae, sample at 265 cm yielded age of 2309-2065 BP (Beta-478124)
Unit 7	290-315	Yellow silt with charcoal lenses, sample at 305 cm yielded age of 2677-2346 BP (Beta-478125);
Unit 8	315-330	Rubble diamict with upper 10 cm, reddened paleosol, upper 1 cm white carbonate, red soil sampled at 325 cm yielded age of 2485-2477 BP (Beta-478126);
Base	-	Not seen

TP18 – Bear Creek fan

Unit	Depth (cm)	Observations
Unit 1	0-80	Fill
Unit 2	80-118	Silty sand, 80-85 cm Bf zone
Unit 3	118-157	Muddy pebble gravel, subangular to subround, clast supported
Unit 4	157-170	Bedded silty sand and med to fine sand, at 165 cm charcoal sample yielded age of 2333-2153 BP (Beta-478127);
Unit 5	170-180	Erosion all lower contact, muddy pebble gravel, like previous gravel
Unit 6	180-200	Silty sand
Unit 7	200-215	Pebble gravel
Unit 8	215-215	Silty sand
Unit 9	225-350	Rubble diamict, upper 5-7 cm show reddening and charcoal lenses, sampled at 230 cm yielded age of 2730-2460 BP (Beta-478128)
Base	-	Not seen

TP19 – Anderson Lake

TP19, Anderson Lake, 5 m Strandline

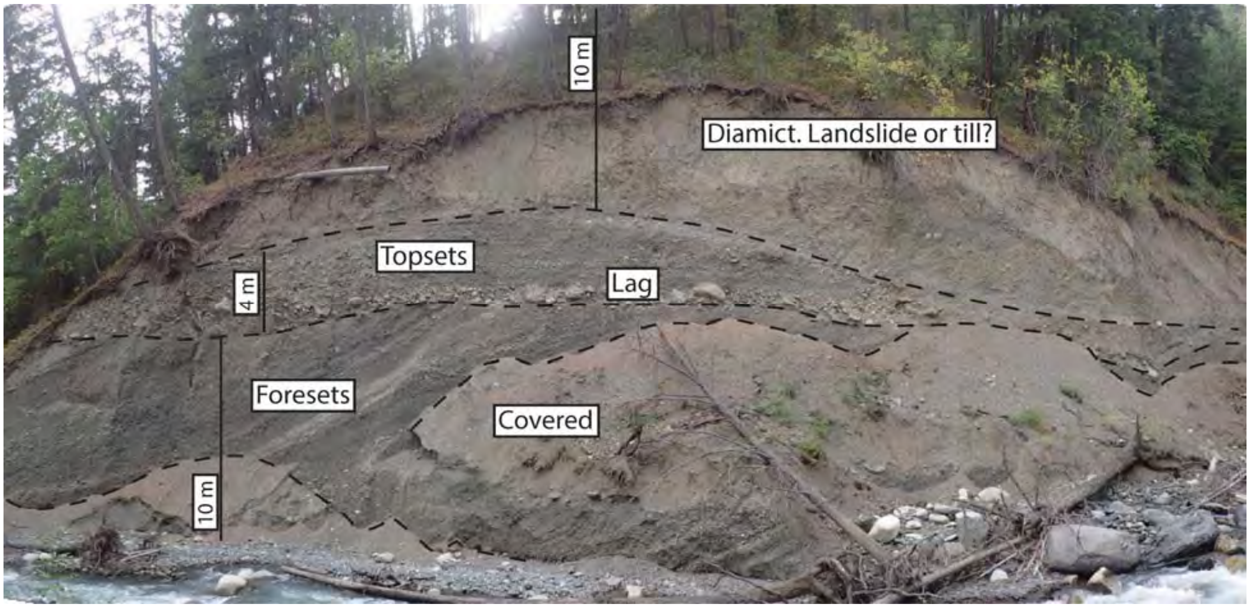
Unit	Depth (cm)	Observations
Unit 1	0-20	LFH on, humic pea gravel
Unit 2	20-45	Pea gravel
Unit 3	45-55	humic silt with reddened lenses dipping into cut, Carbon sediments from reddened lens yields age of 420-0 BP (Beta-478129)
Unit 4	55-90	Pebbly pea gravel
Unit 5	90-100	Diamict, bns

TP19a – Anderson Lake

Modern back scarp below pit house. High water mark is 5.3 m below surface.

Unit	Depth (cm)	Observations
Unit 1	0 – 220	Pit house rim spoil over diamicton, boulders to 750 mm
Unit 2	220 – 255	Interbedded pea gravel and mixed angular and rounded pebble gravel, beach strand
Unit 3	255 – 280	Pea gravel, beach strand
Unit 4	280 – 360	Rubble diamict, bns

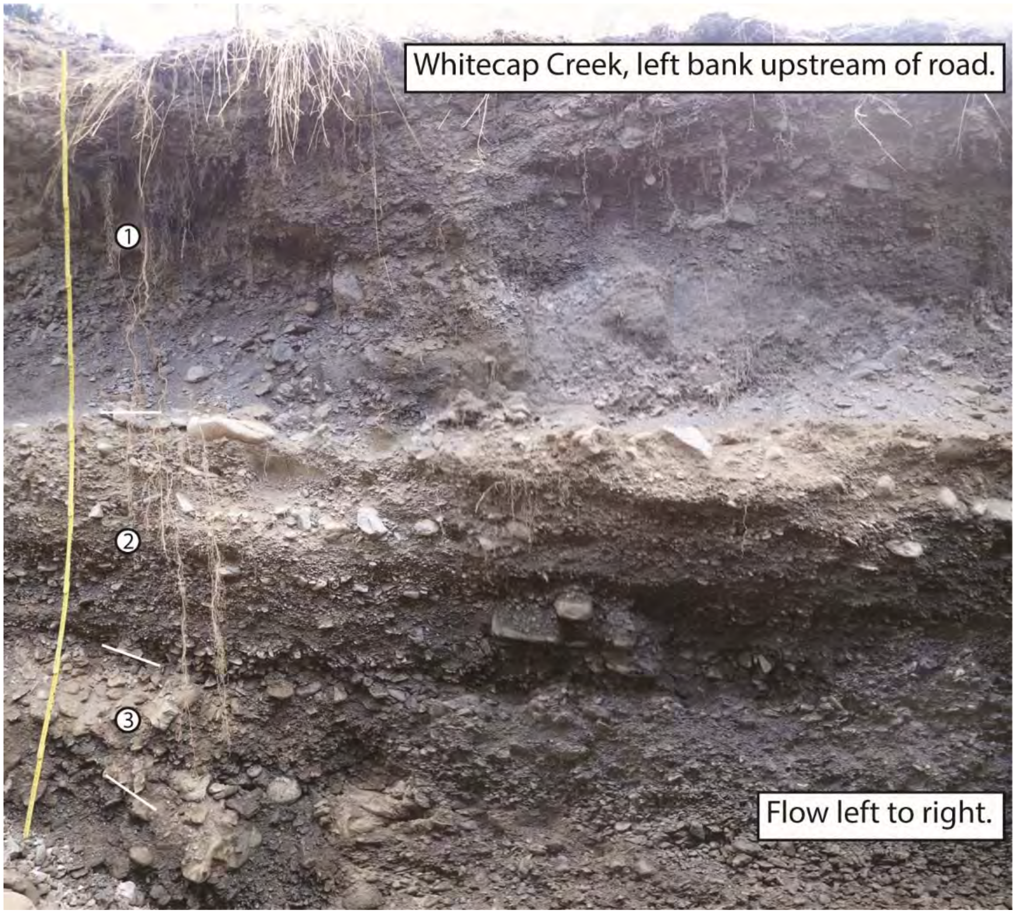
Whitecap Glacial Section



Measured from base:

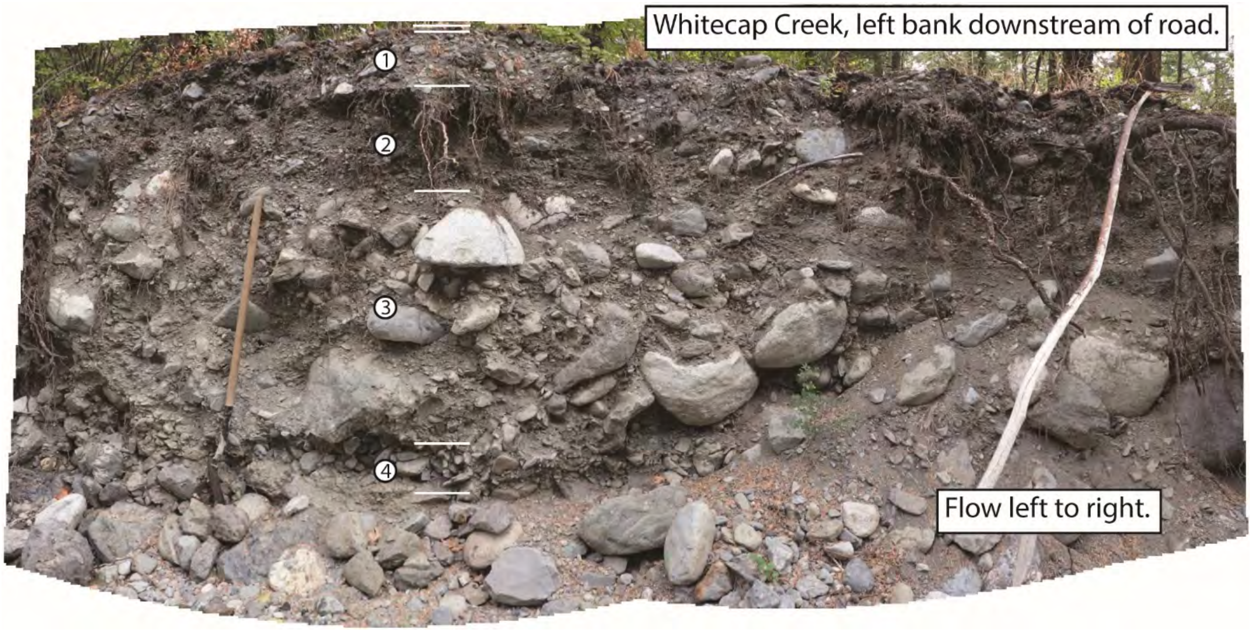
- 10 m sandy gravel foreset delta gravels, overlain by
- 4 m topset gravel with boulder lag on lower contact, upper contact erosional, wavy over 50 m distance, overlain by
- 10 m+ diamict, either till or perhaps landslide, genesis not confirmed.

Whitecap Upstream Section



Unit	Depth (cm)	Observations
Unit 1 & 2		Bouldery cobble/pebble, matrix supported diamict, largest clasts fine to med boulder, surround to round, mixed lithology
Unit 3		Muddy matrix to clast supported, granular to pebble rubble, angular to subangular, weakly stratified; interpreted hyperconcentrated

Whitecap Downstream Section



Unit	Depth (cm)	Observations
Surface	0-3	LFH
Unit 1	3-25	Sandy cobble pebble gravel
Unit 2	25-75	Sandy granular matrix, supporting cobbles, weak trough cross beds over 3 m distance
Unit 3	75-170	Matrix supported silty boulder cobble diamict, angular to subround clasts, mixed lithologies
Unit 4	170-200	Openwork pebble cobble
Base	-	Not seen

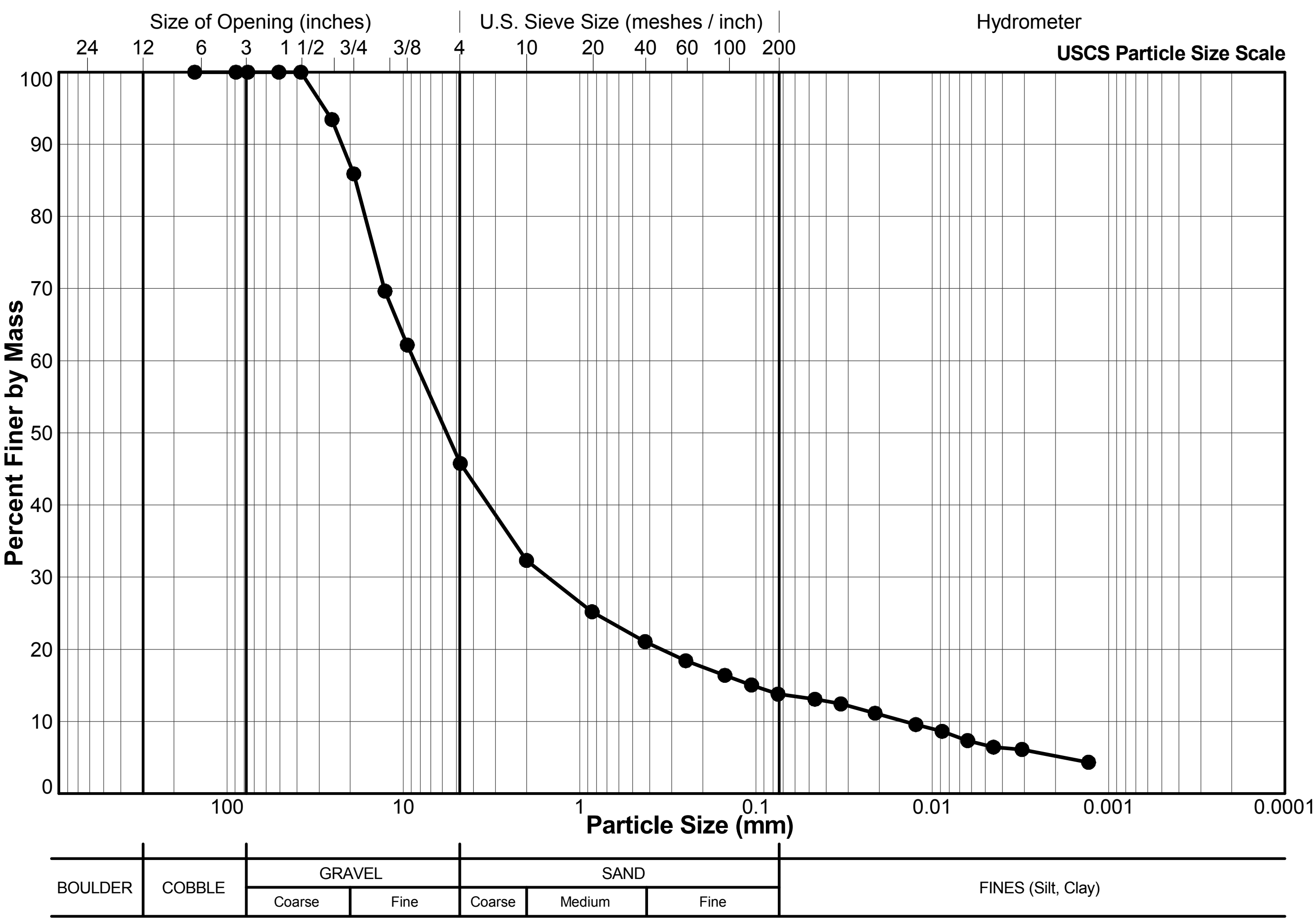
APPENDIX F
LAB RESULTS: GRAIN SIZE ANALYSIS & RADIOCARBON ANALYSIS

SUMMARY OF PARTICLE SIZE DISTRIBUTION

ASTM D 422

Client: BGC Engineering Inc.
Project: Seton Portage Debris Flow, Ref # 1358003-001
Location: Not Given
Project No.: 1547053 **Phase:** 8000

Sample Location: 1358003
Sample No.: 1
Depth (m): N/A
Lab Schedule No.: 455



Legend

Sieve Size (USS)	(mm)	Particle Size (mm)	Percent Passing
6"	152.4		100.0
3.5"	88.9		100.0
3"	76.2		100.0
2"	50.8		100.0
1 1/2"	38.1		100.0
1"	25.4		93.4
3/4"	19.1		85.9
1/2"	12.7		69.6
3/8"	9.5		62.2
#4 US MESH	4.75		45.8
#10 US MESH	2		32.3
#20 US MESH	0.85		25.2
#40 US MESH	0.425		21.1
#60 US MESH	0.25		18.4
#100 US MESH	0.15		16.4
#140 US MESH	0.106		15.0
#200 US MESH	0.075		13.8
		0.0463	13.1
		0.0330	12.4
		0.0211	11.1
		0.0124	9.6
		0.0088	8.6
		0.0063	7.3
		0.0045	6.4
		0.0031	6.1
		0.0013	4.3

SJ/DC	11/29/2016	LH	12/6/2016
Tech	Date	Checked	Date

National IM Server:GINT_GAL_NATIONALIM Unique Project ID:1491 Output Form: LAB_PARTICLE SIZE (W/ GRADATIONS) 2015_lhu_6/12/16

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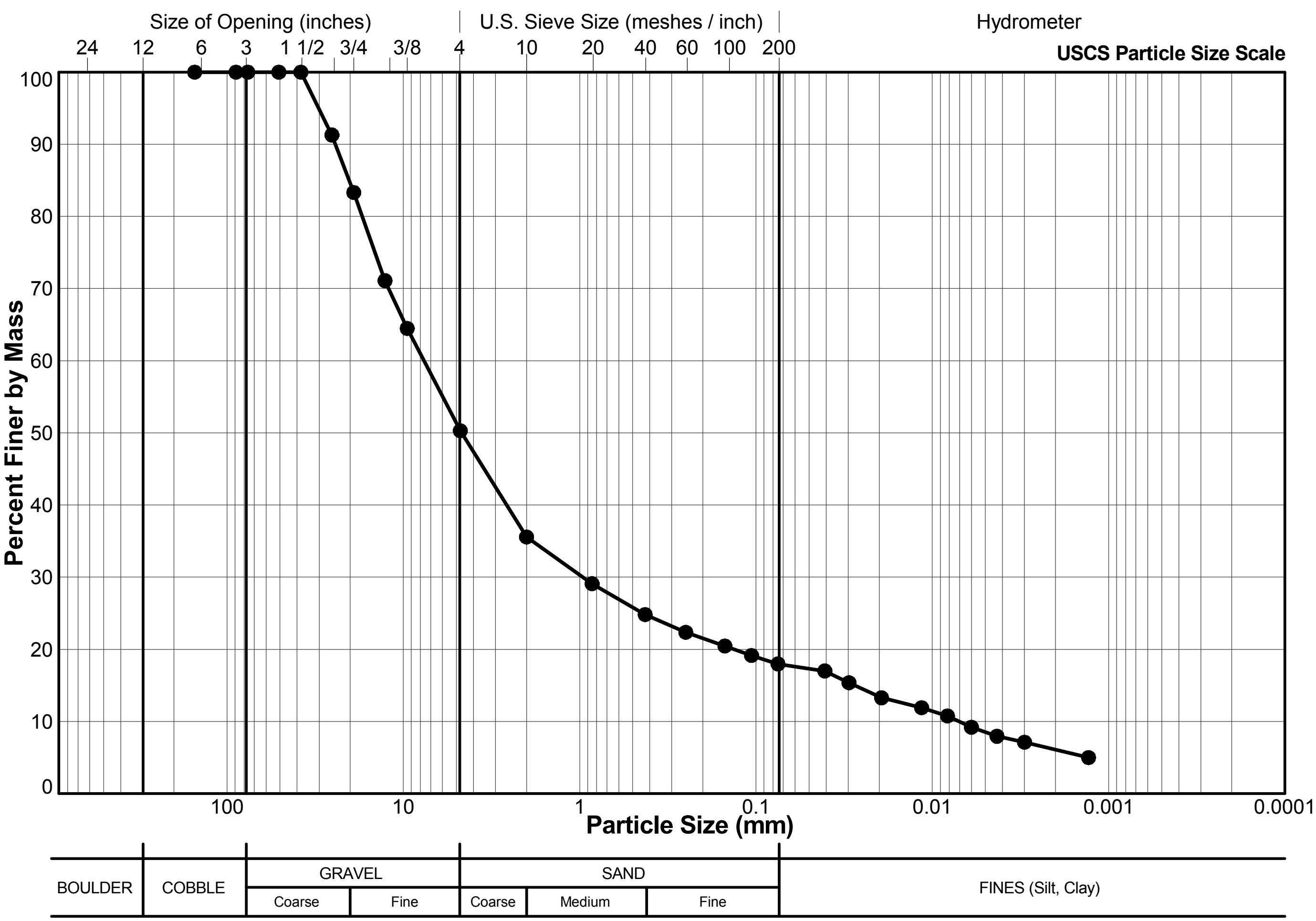
SUMMARY OF PARTICLE SIZE DISTRIBUTION

ASTM D 422

Client: BGC Engineering Inc.
Project: SLRD Seton Portage; Ref #1358-005-03
Location: Not Given
Project No.: 1774305 **Phase:** 4000

Sample Location: Bear Creek
Sample No.: G1
Depth (m): N/A
Lab Schedule No.:



Legend

Sieve Size (USS)	(mm)	Particle Size (mm)	Percent Passing
6"	152.4		100.0
3.5"	88.9		100.0
3"	76.2		100.0
2"	50.8		100.0
1 1/2"	38.1		100.0
1"	25.4		91.3
3/4"	19.1		83.3
1/2"	12.7		71.1
3/8"	9.5		64.5
#4 US MESH	4.75		50.3
#10 US MESH	2		35.6
#20 US MESH	0.85		29.1
#40 US MESH	0.425		24.8
#60 US MESH	0.25		22.4
#100 US MESH	0.15		20.5
#140 US MESH	0.106		19.1
#200 US MESH	0.075		18.0
		0.0407	17.0
		0.0297	15.4
		0.0194	13.3
		0.0115	11.9
		0.0082	10.8
		0.0060	9.2
		0.0043	7.9
		0.0030	7.1
		0.0013	5.0

Tech	Date	Checked	Date
SJ/FF	9/22/2017	LH	9/27/2017

National IM Server:GINT_GAL_NATIONALIM Unique Project ID:1753 Output Form: LAB_PARTICLE SIZE (W/ GRADATIONS) 2015 lhu 28/9/17

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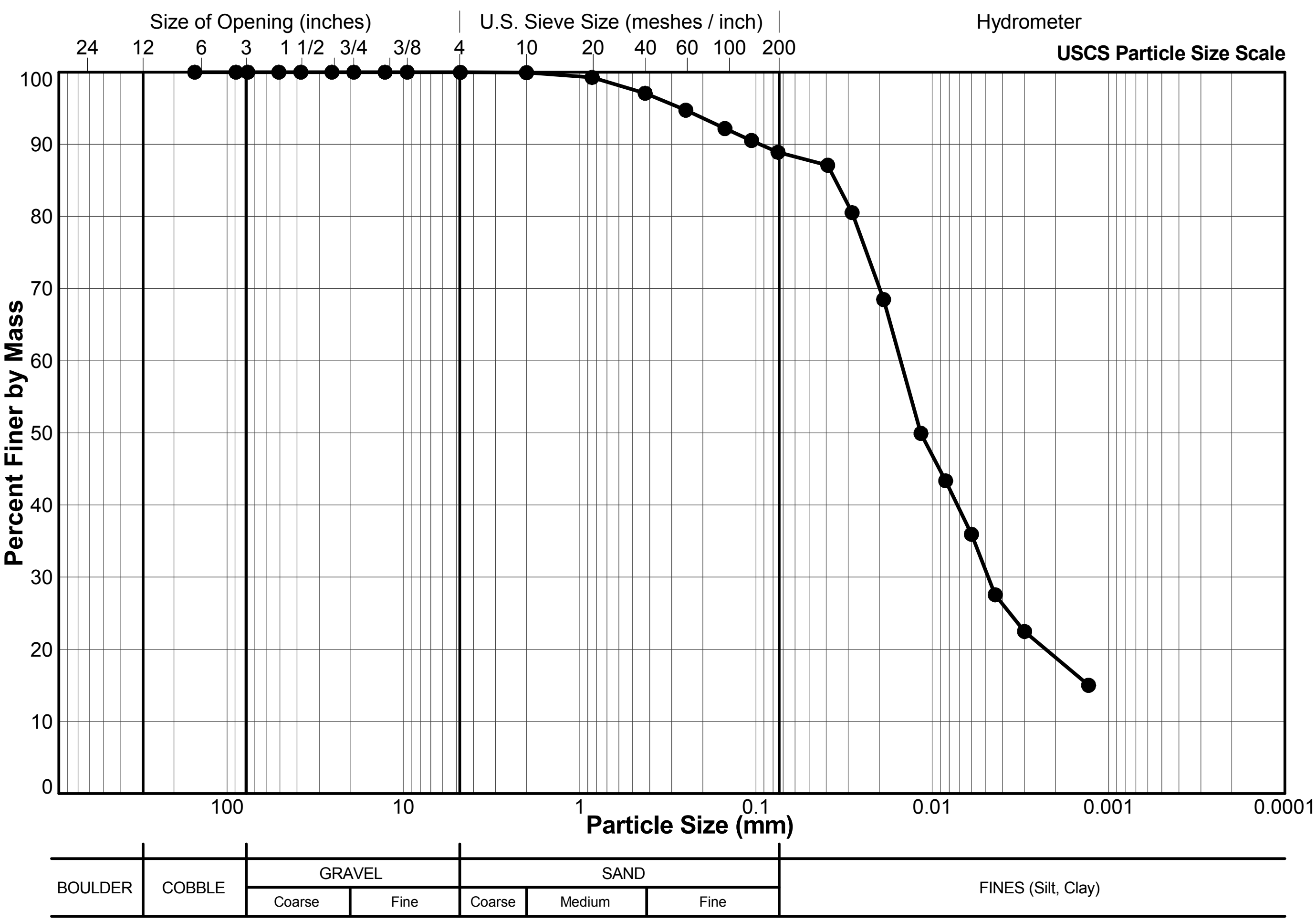
SUMMARY OF PARTICLE SIZE DISTRIBUTION

ASTM D 422

Client: BGC Engineering Inc.
Project: SLRD Seton Portage; Ref #1358-005-03
Location: Not Given
Project No.: 1774305 **Phase:** 4000

Sample Location: Bear Creek
Sample No.: G2
Depth (m): N/A
Lab Schedule No.:



Legend

Sieve Size (USS)	(mm)	Particle Size (mm)	Percent Passing
6"	152.4		100.0
3.5"	88.9		100.0
3"	76.2		100.0
2"	50.8		100.0
1 1/2"	38.1		100.0
1"	25.4		100.0
3/4"	19.1		100.0
1/2"	12.7		100.0
3/8"	9.5		100.0
#4 US MESH	4.75		100.0
#10 US MESH	2		99.9
#20 US MESH	0.85		99.3
#40 US MESH	0.425		97.1
#60 US MESH	0.25		94.7
#100 US MESH	0.15		92.2
#140 US MESH	0.106		90.5
#200 US MESH	0.075		88.9
		0.0392	87.1
		0.0285	80.5
		0.0189	68.5
		0.0116	49.9
		0.0084	43.4
		0.0060	35.9
		0.0044	27.6
		0.0030	22.5
		0.0013	15.0

SJ/FF	9/22/2017	LH	9/27/2017
Tech	Date	Checked	Date

National IM Server:GINT_GAL_NATIONALIM Unique Project ID:1753 Output Form: LAB_PARTICLE SIZE (W/ GRADATIONS) 2015 lhu 28/9/17

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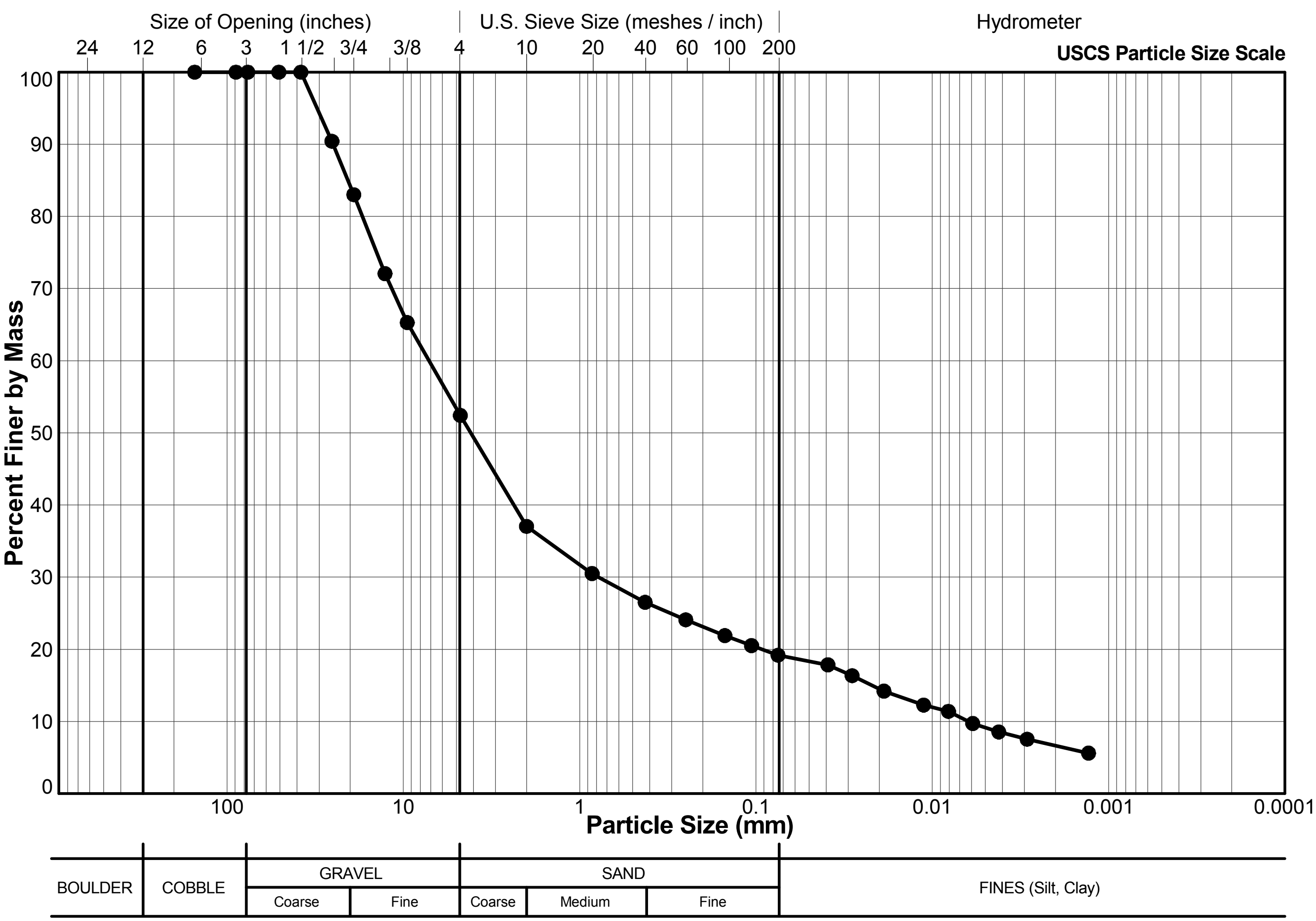
SUMMARY OF PARTICLE SIZE DISTRIBUTION

ASTM D 422

Client: BGC Engineering Inc.
Project: SLRD Seton Portage; Ref #1358-005-03
Location: Not Given
Project No.: 1774305 **Phase:** 4000

Sample Location: Bear Creek
Sample No.: G3
Depth (m): N/A
Lab Schedule No.:



Legend

Sieve Size (USS)	(mm)	Particle Size (mm)	Percent Passing
6"	152.4		100.0
3.5"	88.9		100.0
3"	76.2		100.0
2"	50.8		100.0
1 1/2"	38.1		100.0
1"	25.4		90.4
3/4"	19.1		83.0
1/2"	12.7		72.1
3/8"	9.5		65.3
#4 US MESH	4.75		52.4
#10 US MESH	2		37.0
#20 US MESH	0.85		30.5
#40 US MESH	0.425		26.5
#60 US MESH	0.25		24.1
#100 US MESH	0.15		21.9
#140 US MESH	0.106		20.5
#200 US MESH	0.075		19.2
		0.0391	17.8
		0.0285	16.3
		0.0188	14.2
		0.0112	12.3
		0.0081	11.4
		0.0059	9.7
		0.0042	8.5
		0.0029	7.5
		0.0013	5.6

SJ/FF	9/22/2017	LH	9/27/2017
Tech	Date	Checked	Date

National IM Server:GINT_GAL_NATIONALIM Unique Project ID:1753 Output Form: LAB_PARTICLE SIZE (W/ GRADATIONS) 2015 lhu 28/9/17

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Consistent accuracy delivered on time

Darden Hood
President

Ronald Hatfield
Christopher Patrick
Deputy Directors

October 02, 2017

Emily Moase
BGC Engineering
500-980 Howe Street
Vancouver, BC V6Z 0C8
Canada

RE: Radiocarbon Dating Results

Ms. Moase,

Enclosed are the radiocarbon dating results for 12 samples recently sent to us. As usual, the method of analysis is listed on the report with the results and calibration data is provided where applicable. The Conventional Radiocarbon Ages have all been corrected for total fractionation effects and where applicable, calibration was performed using 2013 calibration databases (cited on the graph pages).

You will notice that Beta-474072 is reported with the units “pMC” rather than BP. “pMC” stands for "percent modern carbon". Results are reported in the pMC format when the analyzed material had more 14C than did the modern (AD 1950) reference standard. The source of this "extra" 14C in the atmosphere is thermo-nuclear bomb testing which on-set in the 1950s. Its presence generally indicates the material analyzed was part of a system that was respiring carbon after the on-set of the testing (AD 1950s). On occasion, the two sigma lower limit will extend into the time region before this "bomb-carbon" onset (i.e. less than 100 pMC). In those cases, there is some probability for 18th, 19th, or 20th century antiquity.

Reported results are accredited to ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 standards and all chemistry was performed here in our laboratory and counted in our own accelerators here. Since Beta is not a teaching laboratory, only graduates trained to strict protocols of the ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 program participated in the analyses.

As always Conventional Radiocarbon Ages and sigmas are rounded to the nearest 10 years per the conventions of the 1977 International Radiocarbon Conference. When counting statistics produce sigmas lower than +/- 30 years, a conservative +/- 30 BP is cited for the result. The reported d13C values were measured separately in an IRMS (isotope ratio mass spectrometer). They are NOT the AMS d13C which would include fractionation effects from natural, chemistry and AMS induced sources.

When interpreting the results, please consider any communications you may have had with us regarding the samples.

Thank you for prepaying the analyses. As always, if you have any questions or would like to discuss the results, don’t hesitate to contact us.

Sincerely ,

Darden Hood
Digital signature on file

BETA Beta Analytic RADIOCARBON DATING Consistent accuracy delivered on time

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 474067	**BGC-1**	**920 +/- 30 BP** IRMS δ13C: -23.4 o/oo
Submitter Material: Organic material		**(95.4%) 1028 - 1184 cal AD (922 - 766 cal BP)**

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 89.18 +/- 0.33 pMC
Fraction Modern Carbon: 0.8918 +/- 0.0033
D14C: -108.21 +/- 3.33 o/oo
Δ14C: -115.41 +/- 3.33 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 890 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), “present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 474068	**BGC-2**	**730 +/- 30 BP** IRMS δ13C: -26.9 o/oo

Submitter Material: Organic material — **(95.4%) 1224 - 1298 cal AD (726 - 652 cal BP)**

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 91.31 +/- 0.34 pMC
Fraction Modern Carbon: 0.9131 +/- 0.0034
D14C: -86.87 +/- 3.41 o/oo
Δ14C: -94.24 +/- 3.41 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 760 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), “present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 474069	**BGC-3**	**180 +/- 30 BP** IRMS δ13C: -23.7 o/oo

Submitter Material: Organic material

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

(53.6%)	**1726 - 1814 cal AD**	**(224 - 136 cal BP)**
(19.7%)	**1652 - 1696 cal AD**	**(298 - 254 cal BP)**
(17.9%)	**1916 - Post AD 1950**	**(34 - Post BP 0)**
(4.2%)	**1836 - 1877 cal AD**	**(114 - 73 cal BP)**

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 97.78 +/- 0.37 pMC
Fraction Modern Carbon: 0.9778 +/- 0.0037
D14C: -22.16 +/- 3.65 o/oo
Δ14C: -30.05 +/- 3.65 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 160 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 474070	**BGC-4**	**3150 +/- 30 BP**	IRMS δ13C: -24.5 o/oo

Submitter Material: Organic material

(87.6%)	**1500 - 1383 cal BC**	**(3449 - 3332 cal BP)**
(7.8%)	**1340 - 1311 cal BC**	**(3289 - 3260 cal BP)**

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 67.56 +/- 0.25 pMC
Fraction Modern Carbon: 0.6756 +/- 0.0025
D14C: -324.39 +/- 2.52 o/oo
Δ14C: -329.84 +/- 2.52 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 3140 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase | Rerport Date: October 02, 2017

BGC Engineering | Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 474071	**BGC-5**	**3410 +/- 30 BP** IRMS δ13C: -22.4 o/oo

Submitter Material: Paleosol

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 65.41 +/- 0.24 pMC
Fraction Modern Carbon: 0.6541 +/- 0.0024
D14C: -345.91 +/- 2.44 o/oo
Δ14C: -351.18 +/- 2.44 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 3370 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

(93.1%)	**1773 - 1627 cal BC**	**(3722 - 3576 cal BP)**
(2.3%)	**1865 - 1849 cal BC**	**(3814 - 3798 cal BP)**

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 474072	**BGC-6**	**102.14 +/- 0.38 pMC**	IRMS δ13C: -23.9 o/oo

Submitter Material: Log fragment — **(95.4%) post AD 1950**

Analyzed Material: Plant material
Pretreatment: (plant material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Conventional Radiocarbon Age: -170 +/- 30 BP
Fraction Modern Carbon: 1.0214 +/- 0.0038
D14C: 21.39 +/- 3.81 o/oo
Δ14C: 13.14 +/- 3.81 o/oo(1950:2017)
Raw pMC: (without d13C correction): 102.37 +/- 0.38 pMC
Calibration: BetaCal3.21: HPD method: (none)

COMMENTS: The reported result indicates an age of post 0 BP and has been reported as a % of the modern reference standard, indicating the material was living about the last 60 years or so (“pMC” = percent modern carbon).

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), “present” = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 474073	**BGC-7**	**360 +/- 30 BP** IRMS δ13C: -25.3 o/oo

Submitter Material: Organic material

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 95.62 +/- 0.36 pMC
Fraction Modern Carbon: 0.9562 +/- 0.0036
D14C: -43.83 +/- 3.57 o/oo
Δ14C: -51.54 +/- 3.57 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 360 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

(47.7%)	**1450 - 1530 cal AD**	**(500 - 420 cal BP)**
(47.7%)	**1540 - 1635 cal AD**	**(410 - 315 cal BP)**

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 474075	**BGC-10**	**3870 +/- 30 BP** IRMS δ13C: -24.7 o/oo

Submitter Material: Paleosol

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 61.77 +/- 0.23 pMC
Fraction Modern Carbon: 0.6177 +/- 0.0023
D14C: -382.31 +/- 2.31 o/oo
Δ14C: -387.29 +/- 2.31 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 3870 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

(89.7%)	**2465 - 2278 cal BC**	**(4414 - 4227 cal BP)**
(4.3%)	**2251 - 2229 cal BC**	**(4200 - 4178 cal BP)**
(1.4%)	**2220 - 2211 cal BC**	**(4169 - 4160 cal BP)**

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 474076	**BGC-11**	**2900 +/- 30 BP**	IRMS δ13C: -25.0 o/oo

Submitter Material: Charcoal

(78.8%)	**1134 - 1004 cal BC**	**(3083 - 2953 cal BP)**
(16.6%)	**1207 - 1141 cal BC**	**(3156 - 3090 cal BP)**

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 69.70 +/- 0.26 pMC
Fraction Modern Carbon: 0.6970 +/- 0.0026
D14C: -303.03 +/- 2.60 o/oo
Δ14C: -308.66 +/- 2.60 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 2900 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 474078	**BGC-13**	**1290 +/- 30 BP**	IRMS δ13C: -23.9 o/oo
Submitter Material: Organic material		**(95.4%) 664 - 770 cal AD**	**(1286 - 1180 cal BP)**

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 85.16 +/- 0.32 pMC
Fraction Modern Carbon: 0.8516 +/- 0.0032
D14C: -148.36 +/- 3.18 o/oo
Δ14C: -155.23 +/- 3.18 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 1270 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase | Rerport Date: October 02, 2017

BGC Engineering | Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 474079	**BGC-15**	**210 +/- 30 BP** IRMS δ13C: -26.1 o/oo

Submitter Material: Organic material

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 97.42 +/- 0.36 pMC
Fraction Modern Carbon: 0.9742 +/- 0.0036
D14C: -25.80 +/- 3.64 o/oo
Δ14C: -33.67 +/- 3.64 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 230 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

(50.5%)	**1734 - 1806 cal AD**	**(216 - 144 cal BP)**
(30.9%)	**1646 - 1684 cal AD**	**(304 - 266 cal BP)**
(14.0%)	**1930 - Post AD 1950**	**(20 - Post BP 0)**

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), “present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Rerport Date: October 02, 2017

BGC Engineering — Material Received: September 20, 2017

Sample Information and Data	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 474080	**BGC-16**	**520 +/- 30 BP** — IRMS δ13C: -25.4 o/oo

Submitter Material: Potential ash layer

Analyzed Material: Charred material
Pretreatment: (charred material) acid/alkali/acid

Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 93.73 +/- 0.35 pMC
Fraction Modern Carbon: 0.9373 +/- 0.0035
D14C: -62.68 +/- 3.50 o/oo
Δ14C: -70.25 +/- 3.50 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 530 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

(84.9%)	**1392 - 1443 cal AD**	**(558 - 507 cal BP)**
(10.5%)	**1324 - 1345 cal AD**	**(626 - 605 cal BP)**

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.4 o/oo)

Laboratory number **Beta-474067**

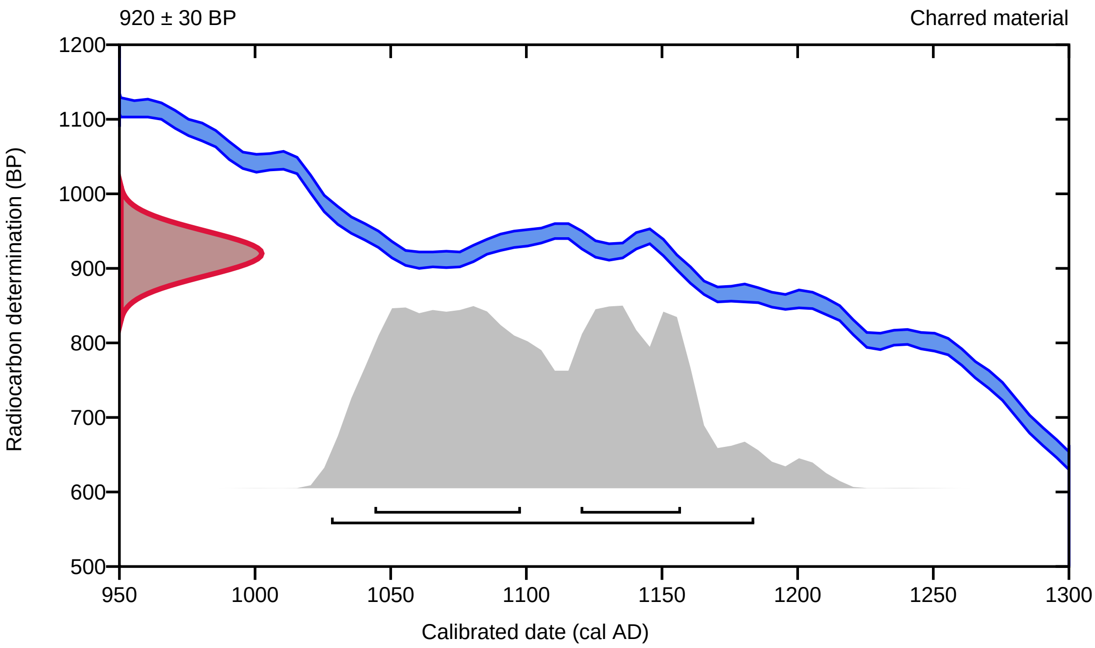
Conventional radiocarbon age **920 ± 30 BP**

95.4% probability

(95.4%) 1028 - 1184 cal AD (922 - 766 cal BP)

68.2% probability

(41.9%) 1044 - 1098 cal AD (906 - 852 cal BP)
(26.3%) 1120 - 1157 cal AD (830 - 793 cal BP)



Database used
INTCAL13

References
References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -26.9 o/oo)

Laboratory number **Beta-474068**

Conventional radiocarbon age **730 ± 30 BP**

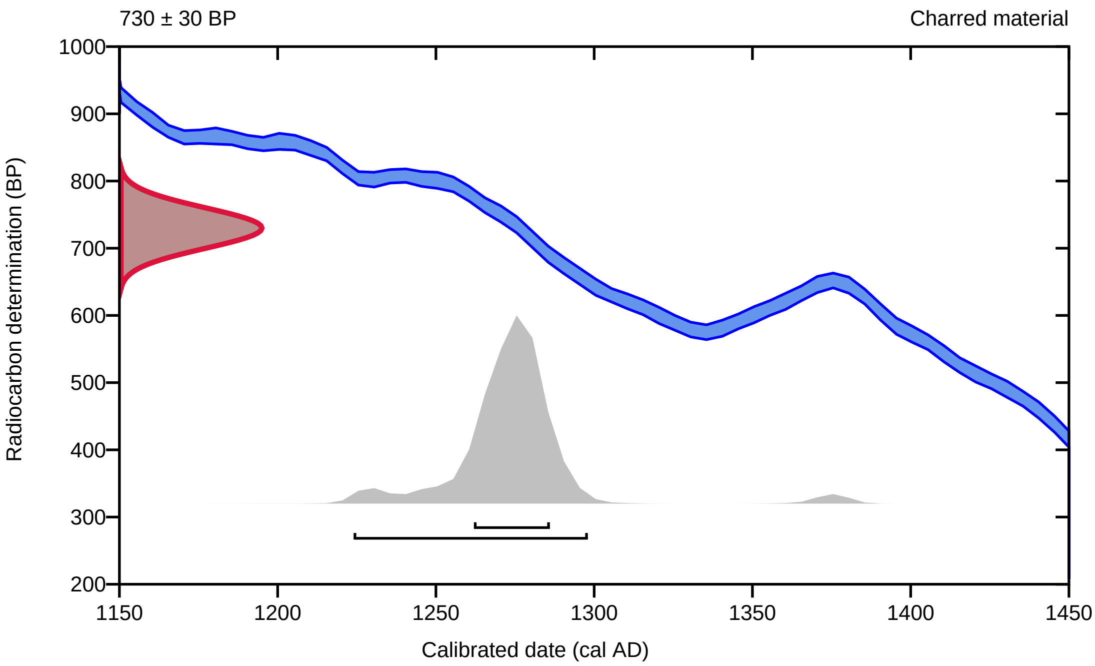
95.4% probability

(95.4%) 1224 - 1298 cal AD (726 - 652 cal BP)

68.2% probability

(68.2%) 1262 - 1286 cal AD (688 - 664 cal BP)

BGC-2



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.7 o/oo)

Laboratory number **Beta-474069**

Conventional radiocarbon age **180 ± 30 BP**

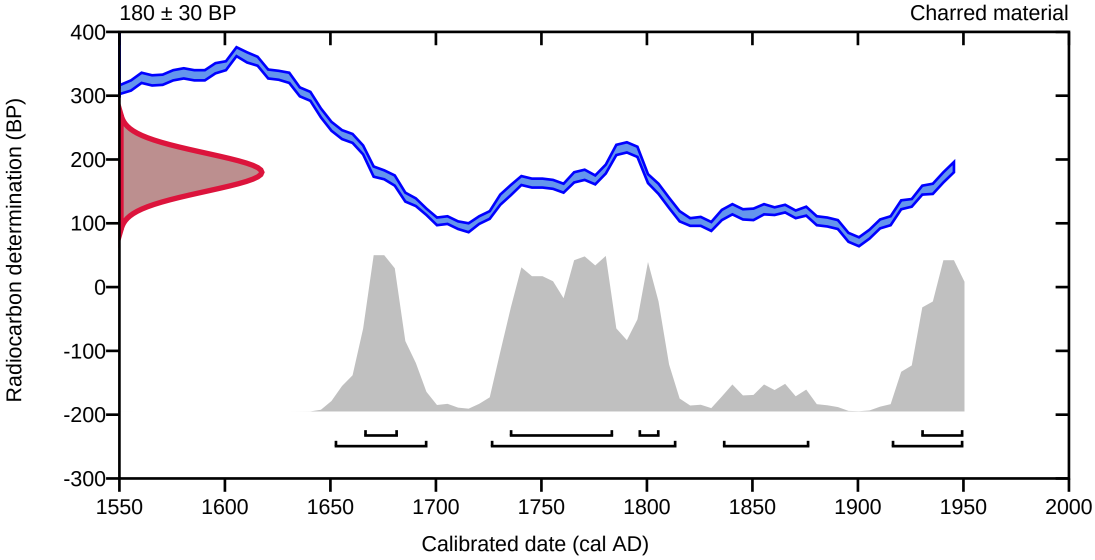
95.4% probability

(53.6%)	1726 - 1814 cal AD	(224 - 136 cal BP)
(19.7%)	1652 - 1696 cal AD	(298 - 254 cal BP)
(17.9%)	1916 - Post cal AD 1950	(34 - Post cal BP 0)
(4.2%)	1836 - 1877 cal AD	(114 - 73 cal BP)

68.2% probability

(35.4%)	1735 - 1784 cal AD	(215 - 166 cal BP)
(14.1%)	1930 - Post cal AD 1950	(20 - Post cal BP 0)
(12.2%)	1666 - 1682 cal AD	(284 - 268 cal BP)
(6.4%)	1796 - 1806 cal AD	(154 - 144 cal BP)

BGC-3



Database used
INTCAL13

References
References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.5 o/oo)

Laboratory number **Beta-474070**

Conventional radiocarbon age **3150 ± 30 BP**

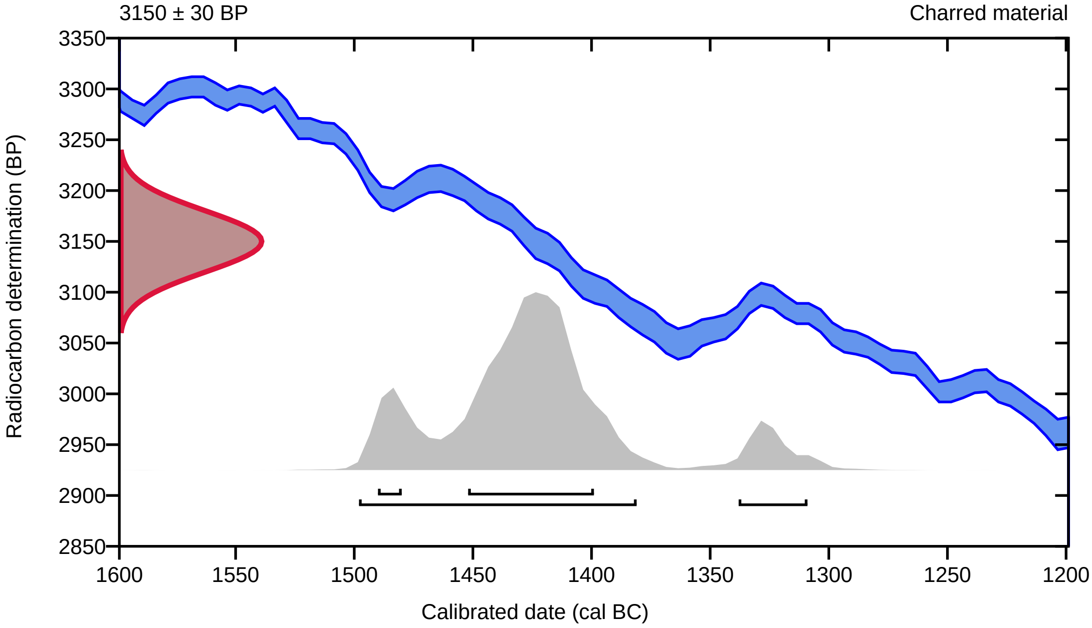
95.4% probability

(87.6%)	1500 - 1383 cal BC	(3449 - 3332 cal BP)
(7.8%)	1340 - 1311 cal BC	(3289 - 3260 cal BP)

68.2% probability

(61.2%)	1454 - 1401 cal BC	(3403 - 3350 cal BP)
(7%)	1492 - 1482 cal BC	(3441 - 3431 cal BP)

BGC-4



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -22.4 o/oo)

Laboratory number **Beta-474071**

Conventional radiocarbon age **3410 ± 30 BP**

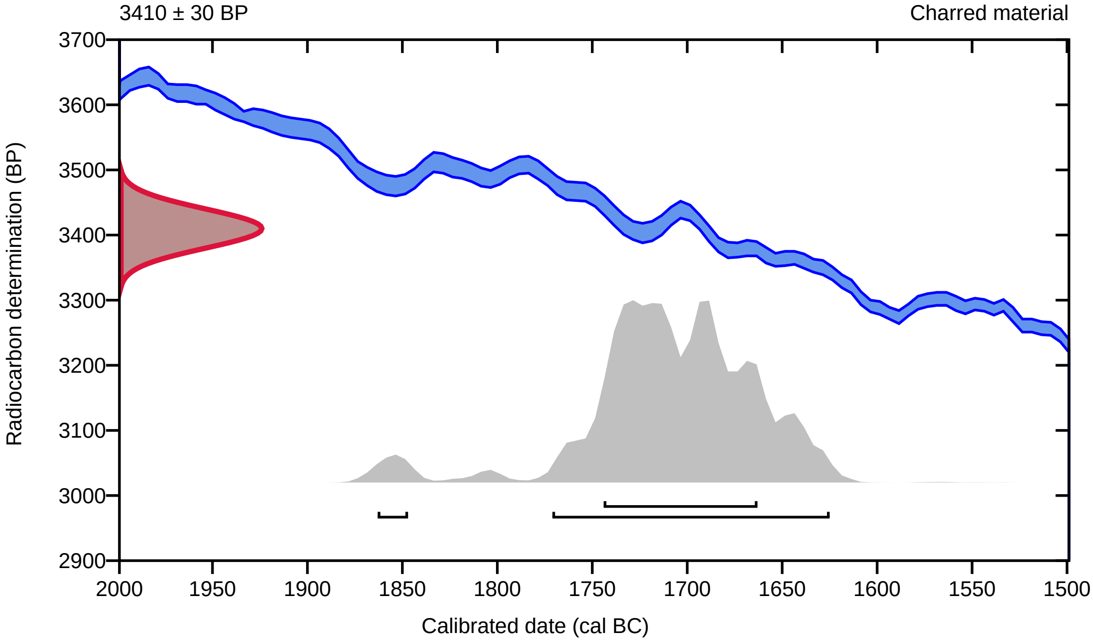
95.4% probability

(93.1%)	1773 - 1627 cal BC	(3722 - 3576 cal BP)
(2.3%)	1865 - 1849 cal BC	(3814 - 3798 cal BP)

68.2% probability

(68.2%)	1746 - 1665 cal BC	(3695 - 3614 cal BP)

BGC-5



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -25.3 o/oo)

Laboratory number **Beta-474073**

Conventional radiocarbon age **360 ± 30 BP**

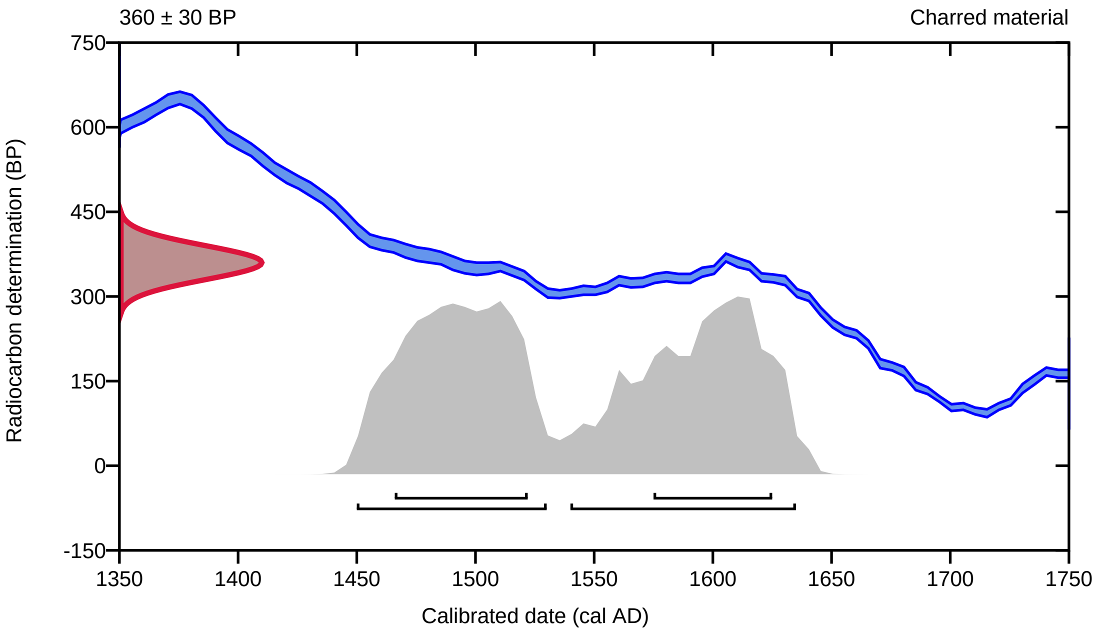
95.4% probability

(47.7%)	1450 - 1530 cal AD	(500 - 420 cal BP)
(47.7%)	1540 - 1635 cal AD	(410 - 315 cal BP)

68.2% probability

(37.4%)	1466 - 1522 cal AD	(484 - 428 cal BP)
(30.8%)	1575 - 1625 cal AD	(375 - 325 cal BP)

BGC-7



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.7 o/oo)

Laboratory number **Beta-474075**

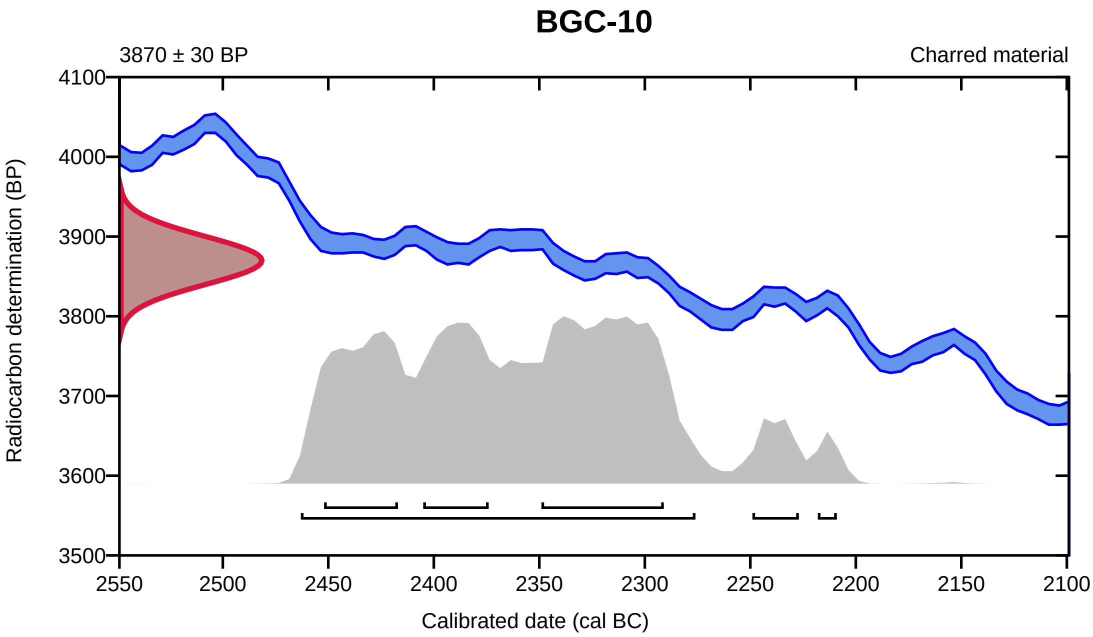
Conventional radiocarbon age **3870 ± 30 BP**

95.4% probability

(89.7%)	2465 - 2278 cal BC	(4414 - 4227 cal BP)
(4.3%)	2251 - 2229 cal BC	(4200 - 4178 cal BP)
(1.4%)	2220 - 2211 cal BC	(4169 - 4160 cal BP)

68.2% probability

(33.3%)	2351 - 2293 cal BC	(4300 - 4242 cal BP)
(18%)	2454 - 2419 cal BC	(4403 - 4368 cal BP)
(16.9%)	2407 - 2376 cal BC	(4356 - 4325 cal BP)



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -25.0 o/oo)

Laboratory number **Beta-474076**

Conventional radiocarbon age **2900 ± 30 BP**

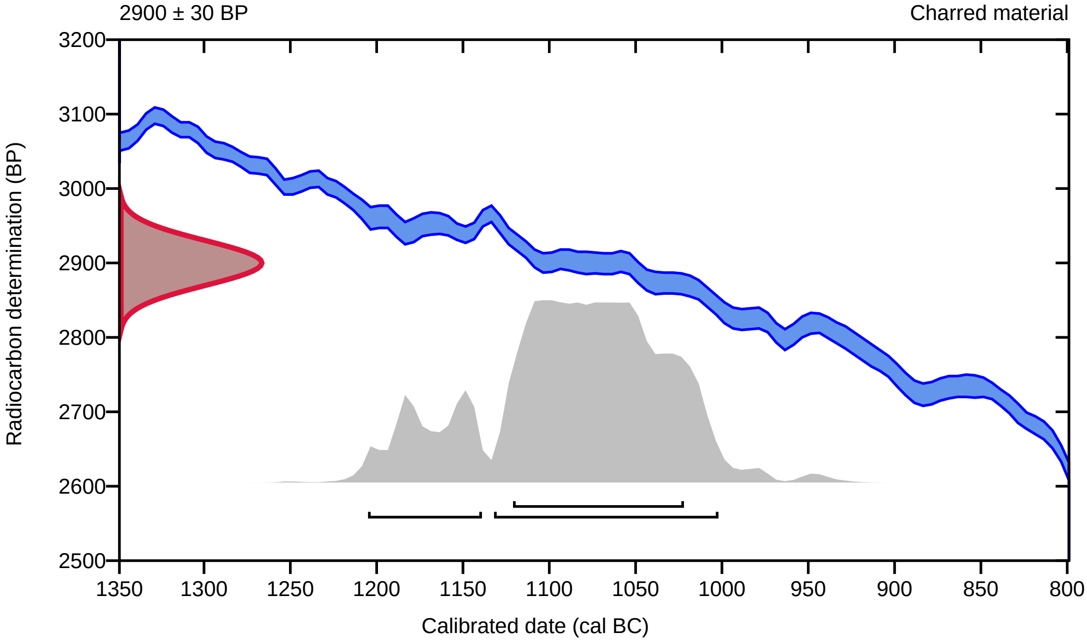
95.4% probability

(78.8%)	1134 - 1004 cal BC	(3083 - 2953 cal BP)
(16.6%)	1207 - 1141 cal BC	(3156 - 3090 cal BP)

68.2% probability

(68.2%)	1123 - 1024 cal BC	(3072 - 2973 cal BP)

BGC-11



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

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BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.9 o/oo)

Laboratory number **Beta-474078**

Conventional radiocarbon age **1290 ± 30 BP**

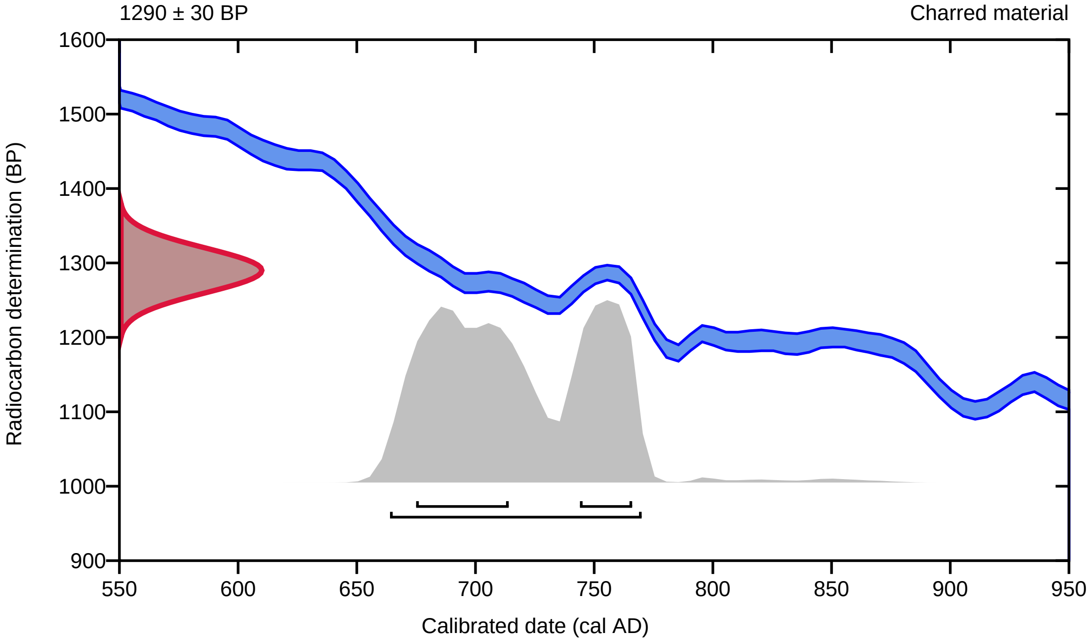
95.4% probability

(95.4%)	664 - 770 cal AD	(1286 - 1180 cal BP)

68.2% probability

(42.8%)	675 - 714 cal AD	(1275 - 1236 cal BP)
(25.4%)	744 - 766 cal AD	(1206 - 1184 cal BP)

BGC-13



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -26.1 o/oo)

Laboratory number **Beta-474079**

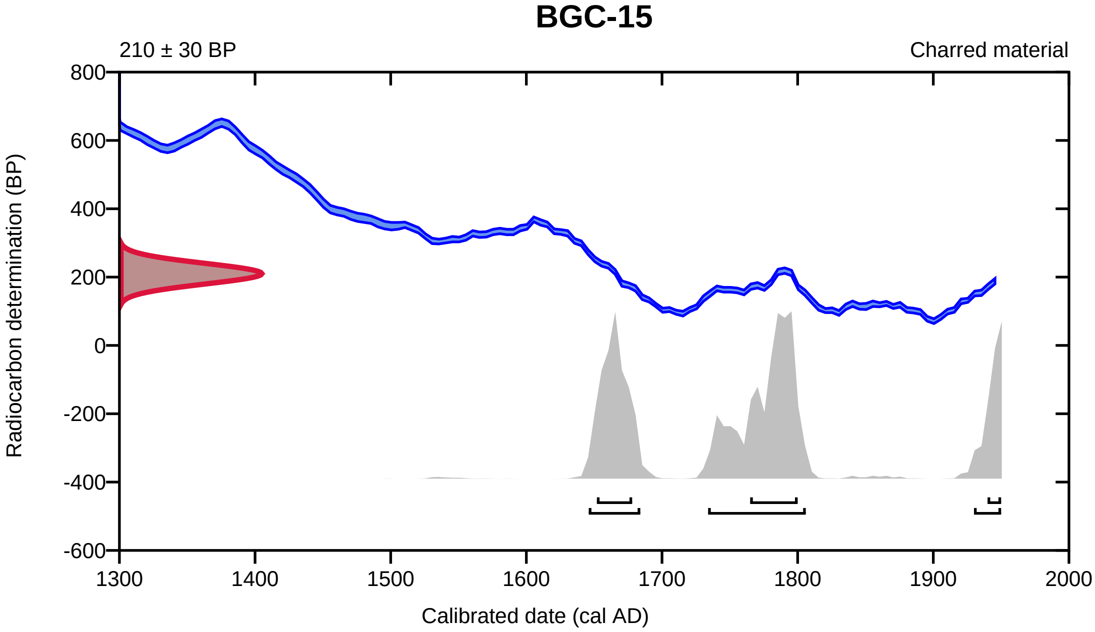
Conventional radiocarbon age **210 ± 30 BP**

95.4% probability

(50.5%)	1734 - 1806 cal AD	(216 - 144 cal BP)
(30.9%)	1646 - 1684 cal AD	(304 - 266 cal BP)
(14%)	1930 - Post cal AD 1950	(20 - Post cal BP 0)

68.2% probability

(32.8%)	1765 - 1800 cal AD	(185 - 150 cal BP)
(25.1%)	1652 - 1678 cal AD	(298 - 272 cal BP)
(10.2%)	1940 - Post cal AD 1950	(10 - Post cal BP 0)



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -25.4 o/oo)

Laboratory number **Beta-474080**

Conventional radiocarbon age **520 ± 30 BP**

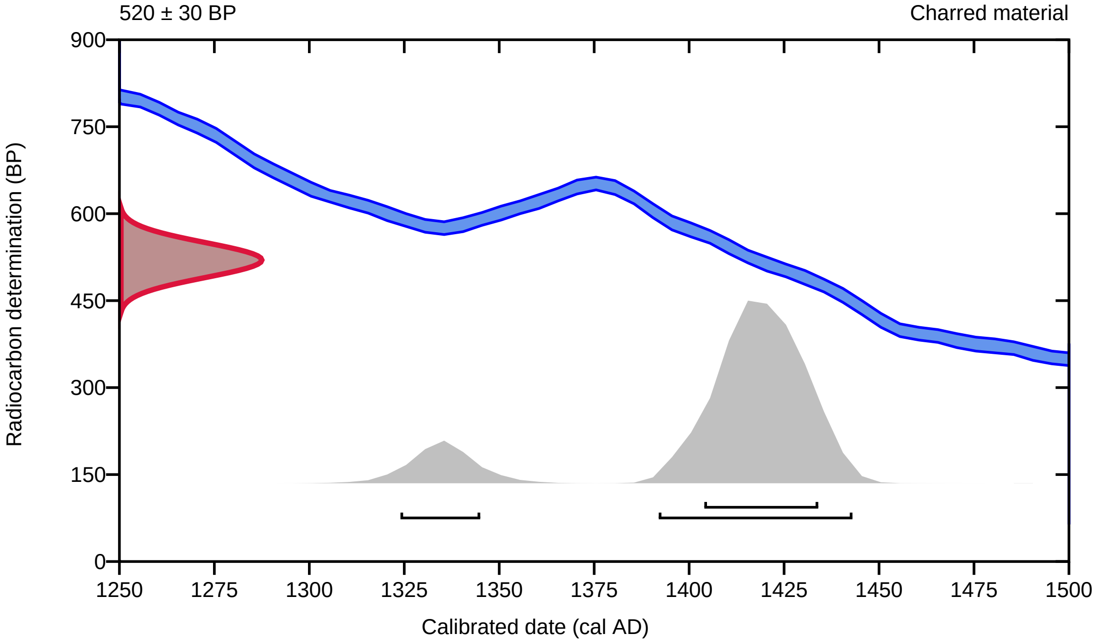
95.4% probability

(84.9%)	1392 - 1443 cal AD	(558 - 507 cal BP)
(10.5%)	1324 - 1345 cal AD	(626 - 605 cal BP)

68.2% probability

(68.2%)	1404 - 1434 cal AD	(546 - 516 cal BP)

BGC-16



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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President

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ISO/IEC 2005:17025-Accredited Testing Laboratory

November 20, 2017

Ms. Emily Moase
BGC Engineering
500-980 Howe Street
Vancouver, BC V6Z 0C8
Canada

RE: Radiocarbon Dating Results

Ms. Moase,

Enclosed are the radiocarbon dating results for ten samples recently sent to us. As usual, the method of analysis is listed on the report with the results and calibration data is provided where applicable. The Conventional Radiocarbon Ages have all been corrected for total fractionation effects and where applicable, calibration was performed using 2013 calibration databases (cited on the graph pages).

The web directory containing the table of results and PDF download also contains pictures, a cvs spreadsheet download option and a quality assurance report containing expected vs. measured values for 3-5 working standards analyzed simultaneously with your samples.

Reported results are accredited to ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 standards and all chemistry was performed here in our laboratory and counted in our own accelerators here. Since Beta is not a teaching laboratory, only graduates trained to strict protocols of the ISO/IEC 17025:2005 Testing Accreditation PJLA #59423 program participated in the analyses.

As always Conventional Radiocarbon Ages and sigmas are rounded to the nearest 10 years per the conventions of the 1977 International Radiocarbon Conference. When counting statistics produce sigmas lower than +/- 30 years, a conservative +/- 30 BP is cited for the result. The reported d13C values were measured separately in an IRMS (isotope ratio mass spectrometer). They are NOT the AMS d13C which would include fractionation effects from natural, chemistry and AMS induced sources.

When interpreting the results, please consider any communications you may have had with us regarding the samples.

The cost of the analysis was charged to the VISA card provided. Thank you. As always, if you have any questions or would like to discuss the results, don't hesitate to contact us.

Sincerely,

Darden Hood
Digital signature on file

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase
BGC Engineering

Report Date: November 20, 2017
Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 478121	**BGC-17**	**900 +/- 30 BP** IRMS δ13C: -23.1 o/oo

Submitter Material: Organics
Pretreatment: (organic sediment) acid washes

(95.4%) 1039 - 1210 cal AD (911 - 740 cal BP)

Analyzed Material: Organic sediment
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 89.40 +/- 0.33 pMC
Fraction Modern Carbon: 0.8940 +/- 0.0033
D14C: -105.99 +/- 3.34 o/oo
Δ14C: -113.21 +/- 3.34 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 870 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase
BGC Engineering

Report Date: November 20, 2017
Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 478122	**BGC-18**	**3640 +/- 30 BP**	IRMS δ13C: -22.9 o/oo

Submitter Material: Organics
Pretreatment: (charred material) acid/alkali/acid

(79.6%)	**2056 - 1921 cal BC**	**(4005 - 3870 cal BP)**
(15.8%)	**2133 - 2084 cal BC**	**(4082 - 4033 cal BP)**

Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 63.56 +/- 0.24 pMC
Fraction Modern Carbon: 0.6356 +/- 0.0024
D14C: -364.37 +/- 2.37 o/oo
Δ14C: -369.50 +/- 2.37 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 3600 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase | Report Date: November 20, 2017

BGC Engineering | Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 478123	**BGC-19**	**1680 +/- 30 BP**	IRMS δ13C: -23.4 o/oo

Submitter Material: Organics

Pretreatment: (organic sediment) acid washes

(85.2%)	**321 - 422 cal AD**	**(1629 - 1528 cal BP)**
(10.2%)	**258 - 296 cal AD**	**(1692 - 1654 cal BP)**

Analyzed Material: Organic sediment
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 81.13 +/- 0.30 pMC
Fraction Modern Carbon: 0.8113 +/- 0.0030
D14C: -188.72 +/- 3.03 o/oo
Δ14C: -195.27 +/- 3.03 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 1650 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Report Date: November 20, 2017

BGC Engineering — Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 478124	**BGC-20**	**2170 +/- 30 BP**	IRMS δ13C: -25.9 o/oo

Submitter Material: Organics
Pretreatment: (charred material) acid/alkali/acid

(92.9%)	**360 - 156 cal BC**	**(2309 - 2105 cal BP)**
(2.5%)	**134 - 116 cal BC**	**(2083 - 2065 cal BP)**

Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 76.33 +/- 0.29 pMC
Fraction Modern Carbon: 0.7633 +/- 0.0029
D14C: -236.73 +/- 2.85 o/oo
Δ14C: -242.89 +/- 2.85 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 2180 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase | Report Date: November 20, 2017

BGC Engineering | Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 478125	**BGC-21**	**2390 +/- 30 BP**	IRMS δ13C: -24.8 o/oo

Submitter Material:	Organics	**(91.3%)**	**542 - 397 cal BC**	**(2491 - 2346 cal BP)**
Pretreatment:	(charred material) acid/alkali/acid	**(2.3%)**	**709 - 694 cal BC**	**(2658 - 2643 cal BP)**
		(1.9%)	**728 - 715 cal BC**	**(2677 - 2664 cal BP)**

Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 74.27 +/- 0.28 pMC
Fraction Modern Carbon: 0.7427 +/- 0.0028
D14C: -257.35 +/- 2.77 o/oo
Δ14C: -263.34 +/- 2.77 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 2390 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase
BGC Engineering

Report Date: November 20, 2017
Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 478126	**BGC-22**	**2360 +/- 30 BP**	IRMS δ13C: -23.2 o/oo

Submitter Material: Organics
Pretreatment: (organic sediment) acid washes

(94.2%)	**522 - 383 cal BC**	**(2471 - 2332 cal BP)**
(1.2%)	**536 - 528 cal BC**	**(2485 - 2477 cal BP)**

Analyzed Material: Organic sediment
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 74.54 +/- 0.28 pMC
Fraction Modern Carbon: 0.7454 +/- 0.0028
D14C: -254.57 +/- 2.78 o/oo
Δ14C: -260.58 +/- 2.78 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 2330 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), “present” = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Report Date: November 20, 2017

BGC Engineering — Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 478127	**BGC-23**	**2230 +/- 30 BP** IRMS δ13C: -22.6 o/oo

Submitter Material: Organics — **(74.6%) 328 - 204 cal BC (2277 - 2153 cal BP)**

Pretreatment: (charred material) acid/alkali/acid — **(20.8%) 384 - 339 cal BC (2333 - 2288 cal BP)**

Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 75.76 +/- 0.28 pMC
Fraction Modern Carbon: 0.7576 +/- 0.0028
D14C: -242.41 +/- 2.83 o/oo
Δ14C: -248.52 +/- 2.83 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 2190 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase | Report Date: November 20, 2017

BGC Engineering | Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)
Beta - 478128	**BGC-24**	**2490 +/- 30 BP** IRMS δ13C: -24.0 o/oo

Submitter Material: Organics

Pretreatment: (charred material) acid/alkali/acid

(95.4%) 781 - 511 cal BC (2730 - 2460 cal BP)

Analyzed Material: Charred material

Analysis Service: AMS-Standard delivery

Percent Modern Carbon: 73.35 +/- 0.27 pMC

Fraction Modern Carbon: 0.7335 +/- 0.0027

D14C: -266.53 +/- 2.74 o/oo

Δ14C: -272.45 +/- 2.74 o/oo(1950:2017)

Measured Radiocarbon Age: (without d13C correction): 2470 +/- 30 BP

Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase
BGC Engineering

Report Date: November 20, 2017
Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 478129	**BGC-25**	**230 +/- 30 BP**	IRMS δ13C: -23.1 o/oo

Submitter Material: Organics	**(45.8%)**	**1635 - 1684 cal AD**	**(315 - 266 cal BP)**
Pretreatment: (organic sediment) acid washes	**(40.1%)**	**1736 - 1805 cal AD**	**(214 - 145 cal BP)**
	(8.6%)	**1935 - Post AD 1950**	**(15 - Post BP 0)**
	(0.9%)	**1530 - 1538 cal AD**	**(420 - 412 cal BP)**

Analyzed Material: Organic sediment
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 97.18 +/- 0.36 pMC
Fraction Modern Carbon: 0.9718 +/- 0.0036
D14C: -28.23 +/- 3.63 o/oo
Δ14C: -36.07 +/- 3.63 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 200 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

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REPORT OF RADIOCARBON DATING ANALYSES

Emily Moase — Report Date: November 20, 2017

BGC Engineering — Material Received: November 03, 2017

Laboratory Number	Sample Code Number	Conventional Radiocarbon Age (BP) or Percent Modern Carbon (pMC) & Stable Isotopes Calendar Calibrated Results: 95.4 % Probability High Probability Density Range Method (HPD)	
Beta - 478130	**BGC-27**	**2490 +/- 30 BP**	IRMS δ13C: -24.5 o/oo

Submitter Material: Organics — **(95.4%) 781 - 511 cal BC (2730 - 2460 cal BP)**

Pretreatment: (charred material) acid/alkali/acid

Analyzed Material: Charred material
Analysis Service: AMS-Standard delivery
Percent Modern Carbon: 73.35 +/- 0.27 pMC
Fraction Modern Carbon: 0.7335 +/- 0.0027
D14C: -266.53 +/- 2.74 o/oo
Δ14C: -272.45 +/- 2.74 o/oo(1950:2017)
Measured Radiocarbon Age: (without d13C correction): 2480 +/- 30 BP
Calibration: BetaCal3.21: HPD method: INTCAL13

Results are ISO/IEC-17025:2005 accredited. No sub-contracting or student labor was used in the analyses. All work was done at Beta in 4 in-house NEC accelerator mass spectrometers and 4 Thermo IRMSs. The "Conventional Radiocarbon Age" was calculated using the Libby half-life (5568 years), is corrected for total isotopic fraction and was used for calendar calibration where applicable. The Age is rounded to the nearest 10 years and is reported as radiocarbon years before present (BP), "present" = AD 1950. Results greater than the modern reference are reported as percent modern carbon (pMC). The modern reference standard was 95% the 14C signature of NIST SRM-4990C (oxalic acid). Quoted errors are 1 sigma counting statistics. Calculated sigmas less than 30 BP on the Conventional Radiocarbon Age are conservatively rounded up to 30. d13C values are on the material itself (not the AMS d13C). d13C and d15N values are relative to VPDB-1. References for calendar calibrations are cited at the bottom of calibration graph pages.

BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.1 o/oo)

Laboratory number **Beta-478121**

Conventional radiocarbon age **900 ± 30 BP**

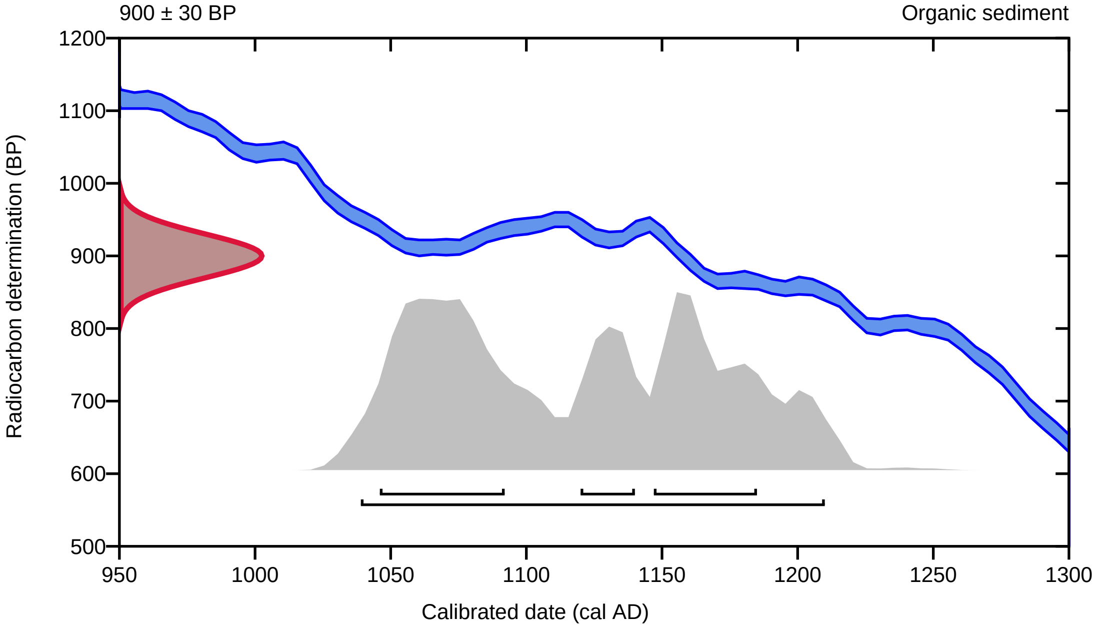
95.4% probability

(95.4%)	1039 - 1210 cal AD	(911 - 740 cal BP)

68.2% probability

(33%)	1046 - 1092 cal AD	(904 - 858 cal BP)
(23.5%)	1147 - 1185 cal AD	(803 - 765 cal BP)
(11.8%)	1120 - 1140 cal AD	(830 - 810 cal BP)

BGC-17



Database used
INTCAL13

References
References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -22.9 o/oo)

Laboratory number **Beta-478122**

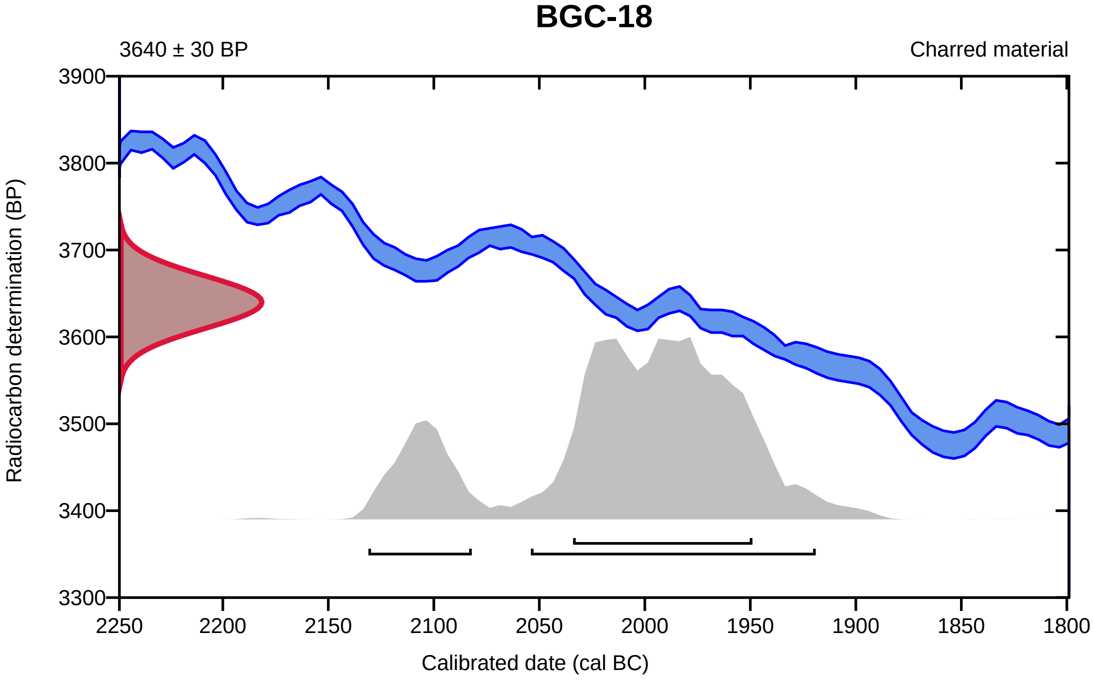
Conventional radiocarbon age **3640 ± 30 BP**

95.4% probability

(79.6%)	2056 - 1921 cal BC	(4005 - 3870 cal BP)
(15.8%)	2133 - 2084 cal BC	(4082 - 4033 cal BP)

68.2% probability

(68.2%)	2036 - 1951 cal BC	(3985 - 3900 cal BP)



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.4 o/oo)

Laboratory number **Beta-478123**

Conventional radiocarbon age **1680 ± 30 BP**

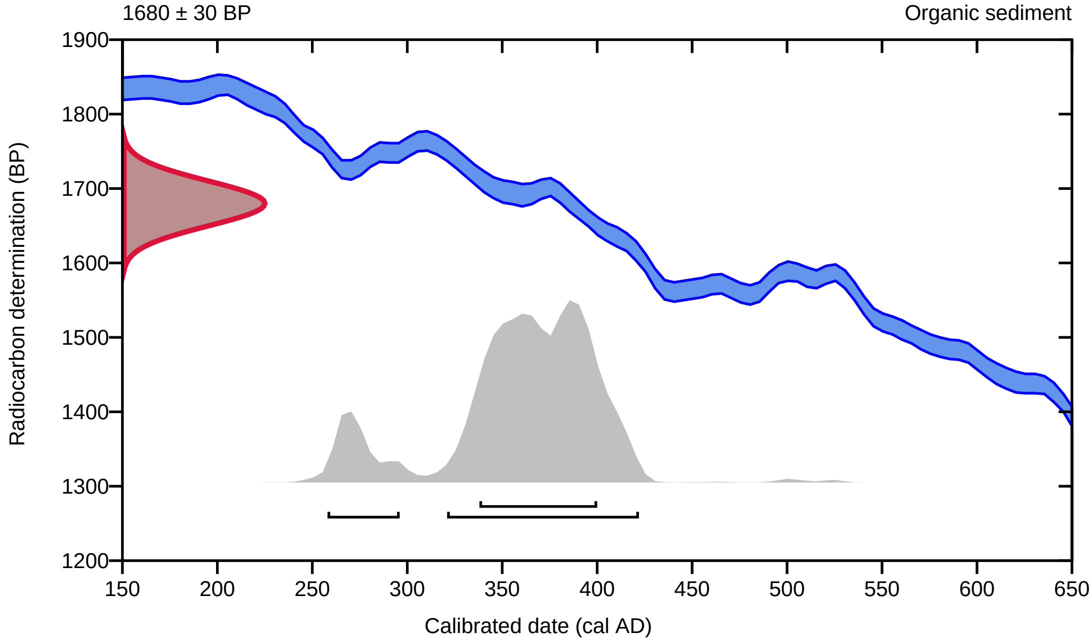
95.4% probability

(85.2%)	321 - 422 cal AD	(1629 - 1528 cal BP)
(10.2%)	258 - 296 cal AD	(1692 - 1654 cal BP)

68.2% probability

(68.2%)	338 - 400 cal AD	(1612 - 1550 cal BP)

BGC-19



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -25.9 o/oo)

Laboratory number **Beta-478124**

Conventional radiocarbon age **2170 ± 30 BP**

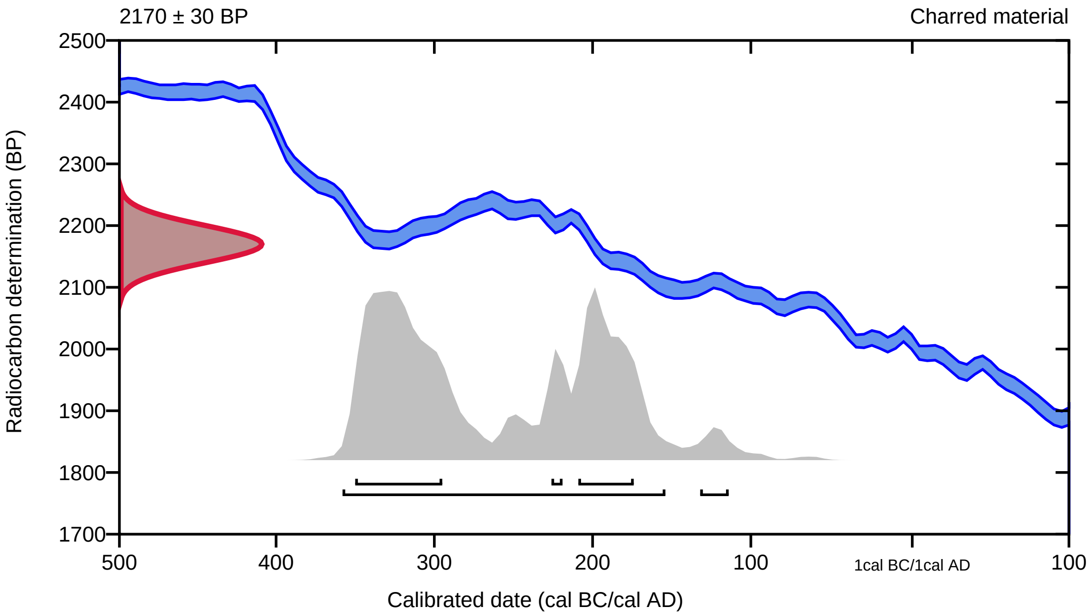
95.4% probability

(92.9%)	360 - 156 cal BC	(2309 - 2105 cal BP)
(2.5%)	134 - 116 cal BC	(2083 - 2065 cal BP)

68.2% probability

(40.2%)	352 - 297 cal BC	(2301 - 2246 cal BP)
(24.3%)	211 - 176 cal BC	(2160 - 2125 cal BP)
(3.7%)	228 - 221 cal BC	(2177 - 2170 cal BP)

BGC-20



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.8 o/oo)

Laboratory number **Beta-478125**

Conventional radiocarbon age **2390 ± 30 BP**

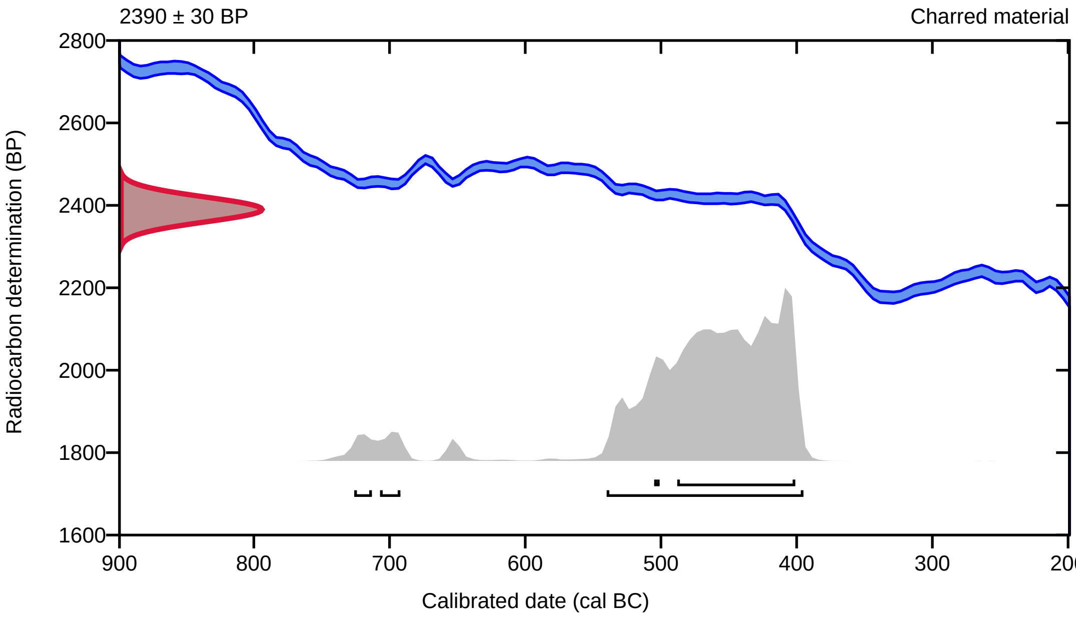
95.4% probability

(91.3%)	542 - 397 cal BC	(2491 - 2346 cal BP)
(2.3%)	709 - 694 cal BC	(2658 - 2643 cal BP)
(1.9%)	728 - 715 cal BC	(2677 - 2664 cal BP)

68.2% probability

(66.1%)	490 - 403 cal BC	(2439 - 2352 cal BP)
(2.1%)	507 - 503 cal BC	(2456 - 2452 cal BP)

BGC-21



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.2 o/oo)

Laboratory number **Beta-478126**

Conventional radiocarbon age **2360 ± 30 BP**

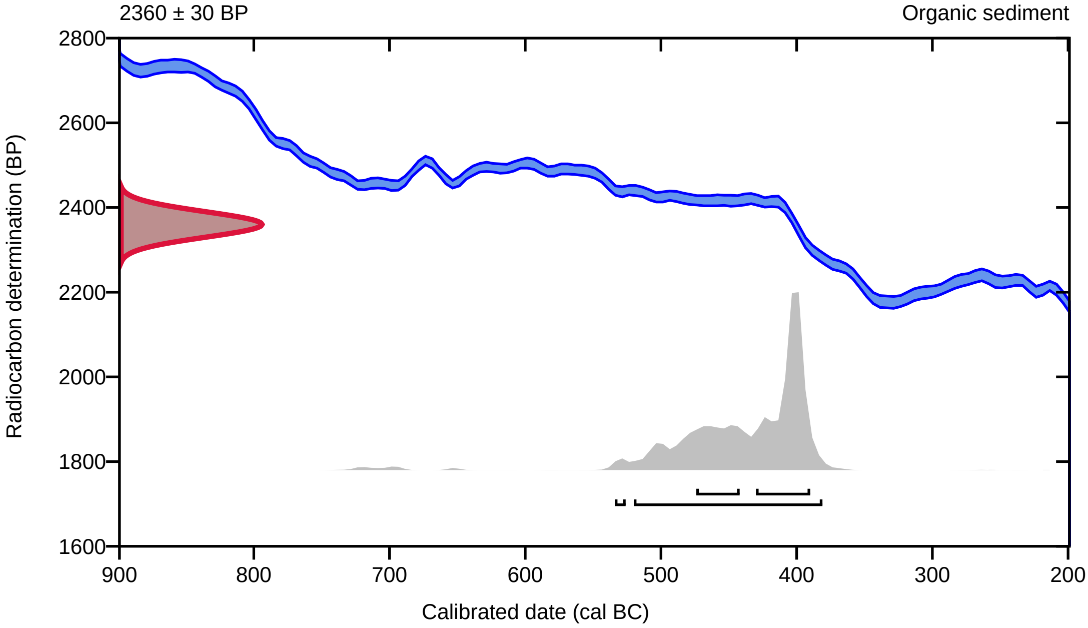
95.4% probability

(94.2%)	522 - 383 cal BC	(2471 - 2332 cal BP)
(1.2%)	536 - 528 cal BC	(2485 - 2477 cal BP)

68.2% probability

(49.1%)	432 - 392 cal BC	(2381 - 2341 cal BP)
(19.1%)	476 - 444 cal BC	(2425 - 2393 cal BP)

BGC-22



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -22.6 o/oo)

Laboratory number **Beta-478127**

Conventional radiocarbon age **2230 ± 30 BP**

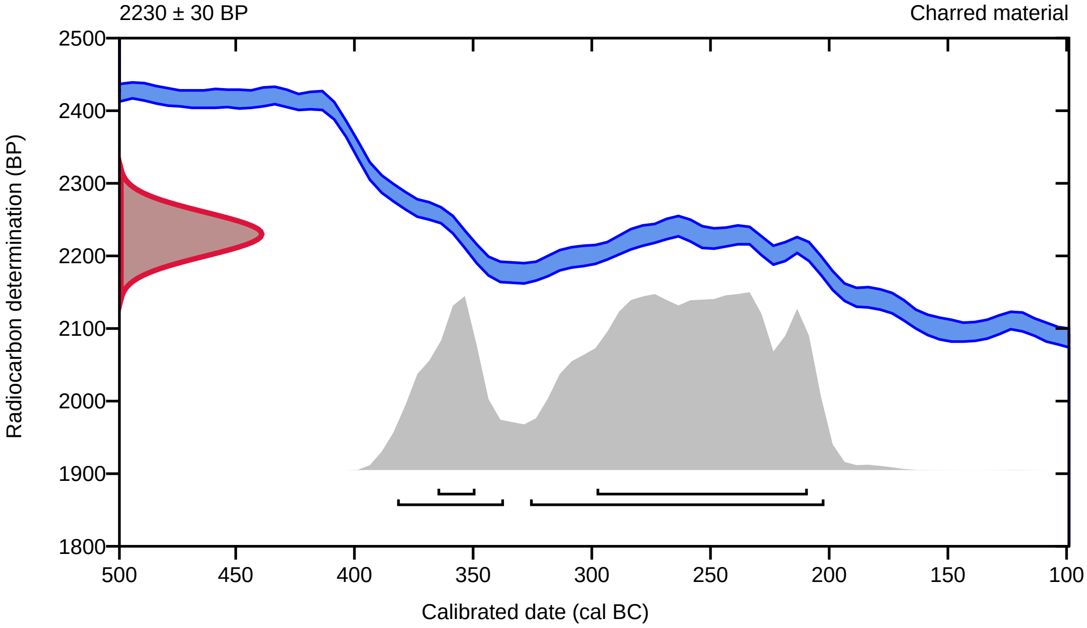
95.4% probability

(74.6%)	328 - 204 cal BC	(2277 - 2153 cal BP)
(20.8%)	384 - 339 cal BC	(2333 - 2288 cal BP)

68.2% probability

(58.1%)	300 - 211 cal BC	(2249 - 2160 cal BP)
(10.1%)	367 - 351 cal BC	(2316 - 2300 cal BP)

BGC-23



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.0 o/oo)

Laboratory number **Beta-478128**

Conventional radiocarbon age **2490 ± 30 BP**

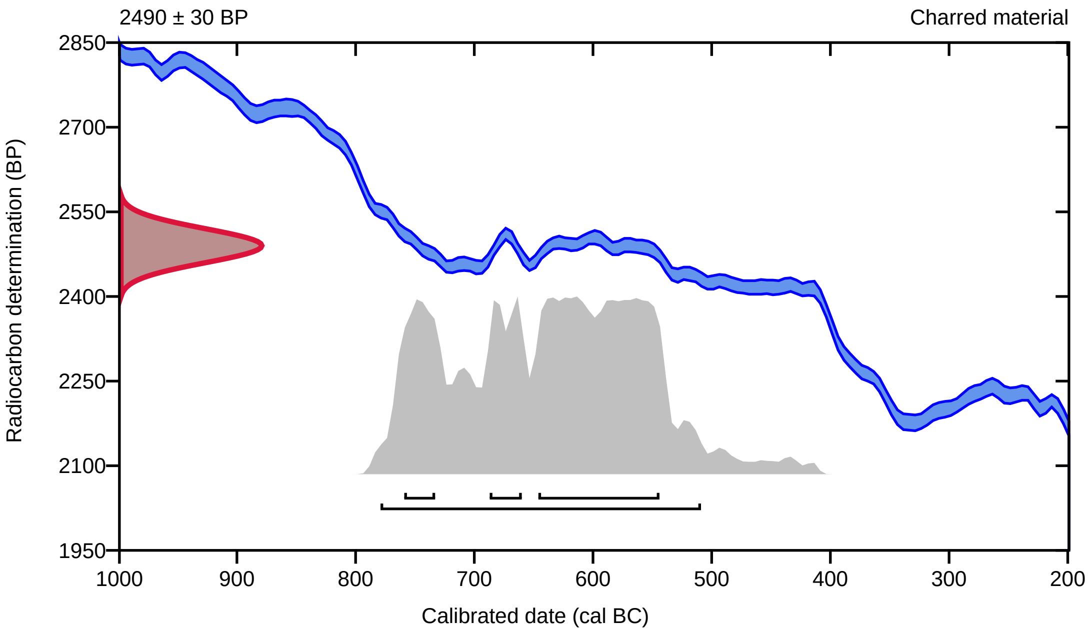
95.4% probability

(95.4%)	781 - 511 cal BC	(2730 - 2460 cal BP)

68.2% probability

(45.9%)	648 - 546 cal BC	(2597 - 2495 cal BP)
(11.4%)	761 - 735 cal BC	(2710 - 2684 cal BP)
(10.9%)	689 - 662 cal BC	(2638 - 2611 cal BP)

BGC-24



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

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BetaCal 3.21

Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -23.1 o/oo)

Laboratory number **Beta-478129**

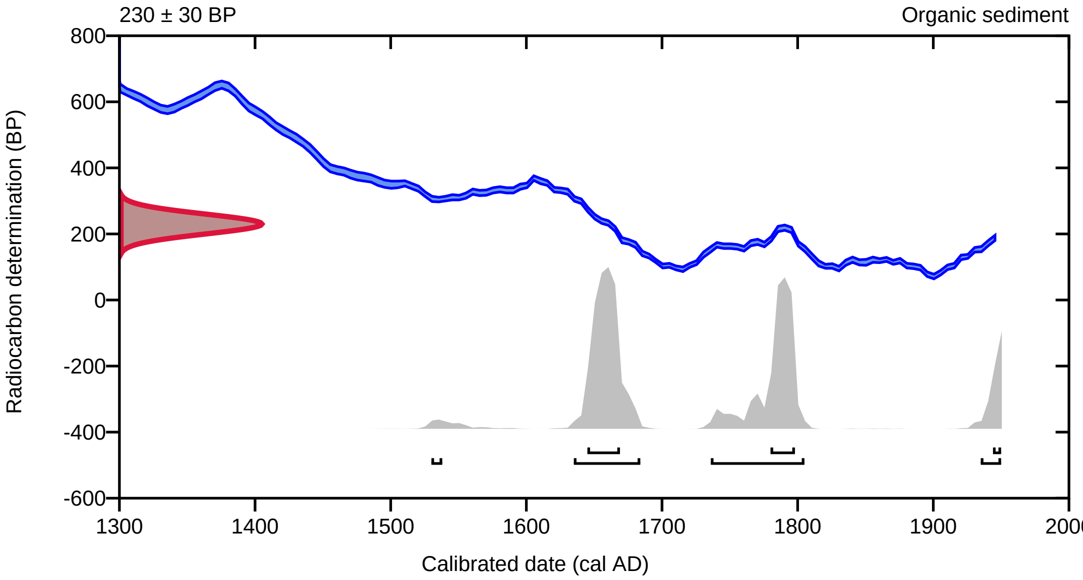
Conventional radiocarbon age **230 ± 30 BP**

95.4% probability

(45.8%)	1635 - 1684 cal AD	(315 - 266 cal BP)
(40.1%)	1736 - 1805 cal AD	(214 - 145 cal BP)
(8.6%)	1935 - Post cal AD 1950	(15 - Post cal BP 0)
(0.9%)	1530 - 1538 cal AD	(420 - 412 cal BP)

68.2% probability

(36.7%)	1645 - 1669 cal AD	(305 - 281 cal BP)
(26.4%)	1780 - 1798 cal AD	(170 - 152 cal BP)
(5.1%)	1944 - Post cal AD 1950	(6 - Post cal BP 0)



Database used
INTCAL13

References
References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

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Calibration of Radiocarbon Age to Calendar Years

(High Probability Density Range Method (HPD): INTCAL13)

(Variables: d13C = -24.5 o/oo)

Laboratory number **Beta-478130**

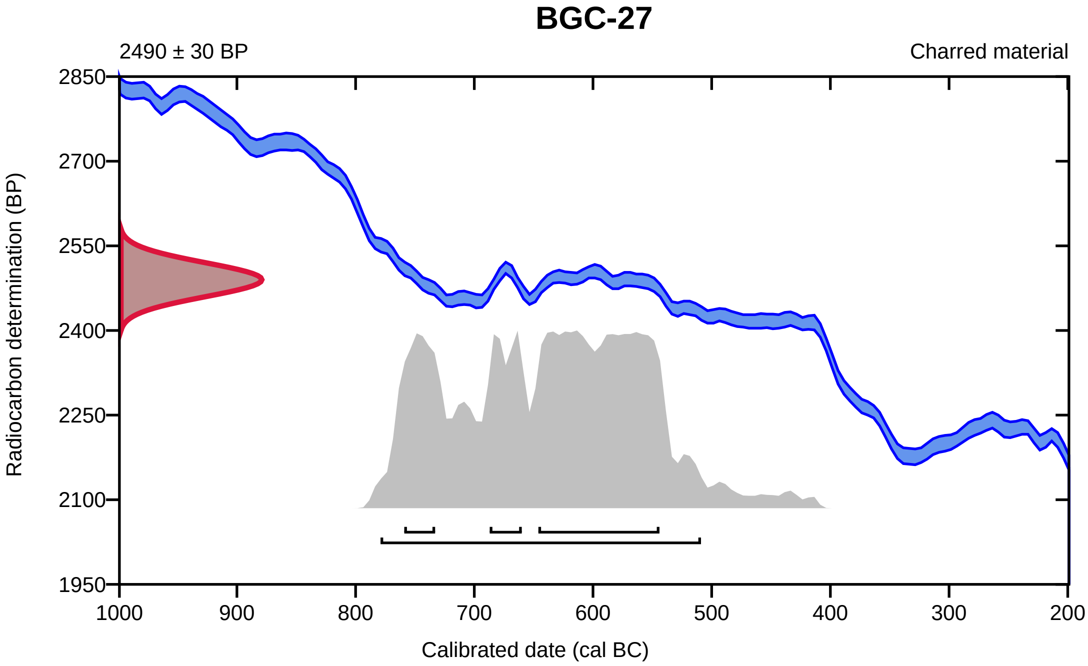
Conventional radiocarbon age **2490 ± 30 BP**

95.4% probability

(95.4%)	781 - 511 cal BC	(2730 - 2460 cal BP)

68.2% probability

(45.9%)	648 - 546 cal BC	(2597 - 2495 cal BP)
(11.4%)	761 - 735 cal BC	(2710 - 2684 cal BP)
(10.9%)	689 - 662 cal BC	(2638 - 2611 cal BP)



Database used

INTCAL13

References

References to Probability Method

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51(1), 337-360.

References to Database INTCAL13

Reimer, et.al., 2013, Radiocarbon55(4).

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Mr. Darden Hood
President

Mr. Ronald Hatfield
Mr. Christopher Patrick
Deputy Directors

ISO/IEC 2005:17025-Accredited Testing Laboratory

Quality Assurance Report

This report provides the results of reference materials used to validate radiocarbon analyses prior to reporting. Known-value reference materials were analyzed quasi-simultaneously with the unknowns. Results are reported as expected values vs measured values. Reported values are calculated relative to NIST SRM-4990B and corrected for isotopic fractionation. Results are reported using the direct analytical measure percent modern carbon (pMC) with one relative standard deviation. Agreement between expected and measured values is taken as being within 2 sigma agreement (error x 2) to account for total laboratory error.

Report Date: November 20, 2017
Submitter: Ms. Emily Moase

QA MEASUREMENTS

Reference 1

Expected Value: 129.41 +/- 0.06 pMC
Measured Value: 129.41 +/- 0.35 pMC
Agreement: Accepted

Reference 2

Expected Value: 0.44 +/- 0.10 pMC
Measured Value: 0.45 +/- 0.03 pMC
Agreement: Accepted

Reference 3

Expected Value: 96.69 +/- 0.50 pMC
Measured Value: 97.25 +/- 0.29 pMC
Agreement: Accepted

COMMENT: All measurements passed acceptance tests.

Validation: Darden Hood

Date: November 20, 2017

APPENDIX G
NUMERICAL MODELLING

APPENDIX G - NUMERICAL MODELING

G.1. INTRODUCTION

BGC modelled debris flows and debris floods numerically to estimate the extent and intensity of inundation associated with debris flow hazard scenarios on Bear/Pete's Creek and debris flood hazard scenarios on Whitecap and Spider creeks. The model outputs are used to develop interpreted hazard intensity maps, which in turn form the basis for the risk assessment. After risk evaluation which compares risks to risk tolerance threshold, mitigation concepts are developed and prioritized. Numerical modeling then allows to determine if the mitigation measures are adequately dimensioned.

This appendix describes the modelling methods and input parameters that were used to simulate debris flows on Bear/Pete's Creek and debris floods on Whitecap and Spider creeks. Debris flow runout and intensity maps for each modelled scenario are provided in Drawings 10 to 12 for Bear and Pete's creeks, Spider and Whitecap creeks, respectively.

G.2. BEAR CREEK DEBRIS FLOW MODELLING

G.2.1. Introduction

Numerical modelling of debris flows at Bear Creek provides the basis for the estimation of spatial impact probabilities (the chance of certain elements at risk being impacted) and corresponding debris-flow intensities. These serve as inputs to the quantitative risk assessment (QRA) described in Sections 4.6 of the main report, and in Appendix H. This section describes the debris-flow modelling approach, input and results. Pete's Creek was modeled for only the 10-30 year class as debris flows with larger return periods are believed to avulse from Pete's into Bear and vice versa.

G.2.2. Methodology and Input

Bear/Pete's creeks were modeled using the three-dimensional numerical model *DAN3D* (McDougall and Hungr 2004). *DAN3D* was developed specifically for the analysis of rapid landslide motion across complex 3D terrain and is well-suited to the simulation of coarse debris flows that deposit on relatively steep slopes, like the Bear/Pete's Creek fan. BGC has used *DAN3D* for the same purposes on other projects.

The model simulates landslide motion from initiation to deposition and requires the following inputs, as described in detail below:

- A digital elevation model (DEM) of the topography in the study area, which defines the sliding surface across which the simulated landslide travels
- A corresponding DEM that delineates the extent and thickness of the initial landslide
- A corresponding DEM that delineates the extent and thickness of erodible material along the path that could be entrained by the landslide as it passes

- A user-specified entrainment rate that determines how much of the available erodible material is picked up by the landslide
- User-specified flow resistance parameters that control how fast and how far the simulated landslide travels.

G.2.2.1. Sliding Surface

The sliding surface that was used for debris-flow modelling was based on the bare earth LiDAR DEM provided by UNBC and acquired in fall 2017. The LiDAR data were modified to a 5 x 5 m grid spacing and smoothed to reduce surface roughness and improve numerical model stability. This generalization results in some loss of topographic details (e.g., large boulders or channel constrictions that could locally affect the flow path and flow depth), but does not substantively affect the debris-flow modelling results, especially for larger events with longer runout.

G.2.2.2. Debris Flow Volumes and Source Locations

Debris-flow modelling was based on the 'best estimate' frequency-magnitude curve described in Appendix D. Five debris-flow volume scenarios were modelled (Table G-1). In all cases, constant entrainment rates were specified between the source area and the fan apex to achieve the desired final 'best estimate' volumes. The initial and final debris-flow volumes that were modelled are summarized in Table G-1. The total volumes of scenarios 3 to 5 were varied slightly (within 10%) to determine the sensitivity of changing volumes on runout. The differences were indistinguishable which provides some confidence that debris-flow volume precision is not warranted. The source area volume for scenario 5 was selected as a representative volume from analyses summarized in Appendix D. For scenarios 3 and 4, one third of the volume of scenario were selected based on judgment. For scenarios 1 and 2 the initial volume is thought to be minor (1000 m^3) as debris flows are believed to grow primarily be entrainment of channel fill material.

Table G-1. Summary of modelled debris flow volumes.

Volume Scenarios	Return Period (years)	Modelled Initial Volume[1] (m^3)	Modelled Final Volume Reaching Fan[1] (m^3)
1	10-30	1,000	11,000
2	30-100	1,000	70,000
3	100-300	25,000	150,000
4	300-1,000	25,000	240,000
5	1,000-3,000	75,000	320,000

Volume Scenarios 1 and 2 were assumed to initiate at source location A, shown on Figure G-1, where several lower order channels converge. Volume Scenarios 3, 4 and 5 were assumed to initiate at the upper part of the watershed at source location B, shown on Figure G-1, where slope deformation indicators (see Appendix D) suggest a rockslide may originate, which could trigger a large debris flow. Based on BGC's experience modelling debris flows on similar creeks in the region, the modelled results below the fan apex are not expected to be sensitive to the assumption of source area location.

All debris flows were modelled as single events (as opposed to events involving multiple source failures and/or surges that result in the same total event volume). This approach likely results in relatively conservative estimates of flow depth and velocity, and in turn vulnerability.

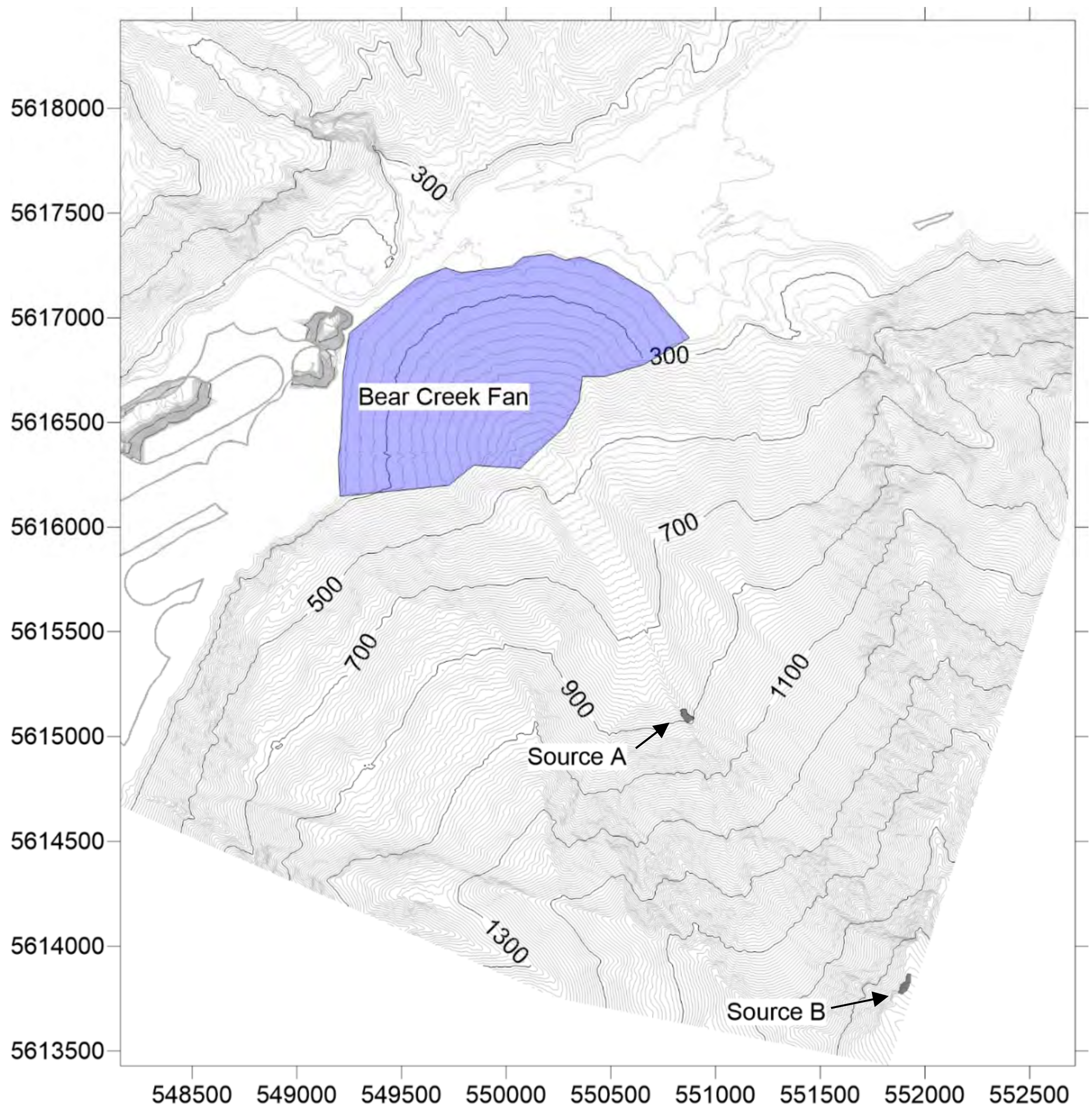

Figure G-1. Source locations for DAN3D modelling.

G.2.2.3. Avulsion Scenarios

Flow avulsions from the active creek channel can be caused by obstructions that develop during a debris flow, for example, due to tree jams, deposition of coarse debris lobes and levees, or channel bank collapses. These processes cannot be simulated automatically in

DAN3D. The Bear/Pete's fan surface is very uniform, and is expected to be prone to avulsions. It has been assumed that the modelled intensities of potential debris flow impacts are equivalent moving radially down the fan, and specific avulsion scenarios have not been modelled. The potential for avulsion is accounted for in the interpreted numerical modelling maps provided in Appendix H which formed the basis for the risk assessment.

G.2.2.4. Resistance Parameters

To simulate debris flows on Bear Creek, two flow resistance models were used to simulate the behavior of flows in the transport zone, and in the deposition on the fan and flood plain below. The Voellmy flow resistance model was used for the transport zone, and the Bingham flow resistance model was used on the fan and below.

The Voellmy model is governed by two parameters: 1) a friction coefficient, f, which determines the slope angle on which material begins to deposit (i.e., if the friction coefficient is higher than the local slope gradient, material will decelerate and begin to deposit); and 2) a turbulence parameter, ξ, which produces a velocity-dependent resistance that tends to limit flow velocities (similar to air drag acting on a falling object). Resistance parameter values of f = 0.15 and ξ = 200 m/s^2 were used to simulate a high mobility debris flow with a similar peak discharge to the 2016 debris flow event. The friction coefficient is approximately the overall fan gradient, and therefore is consistent with the behavior of events that have deposited on the fan in the past. The turbulence parameter of 200 m/s^2 was calibrated so that the peak discharge near the fan apex was 400 m^3/s, which approximates the estimate peak discharge of the 2016 event.

The Bingham model is governed by two parameters: 1) a yield stress coefficient, τ_{yield}, which determines the stress at which the material behaviour transitions from a rigid material to a viscous material; and 2) a viscosity coefficient, $\mu_{Bingham}$, which tends to limit the maximum velocity (similar to the Voellmy model, this resistance is velocity dependent). Resistance parameter values of τ_{yield} = 4 kPa and $\mu_{Bingham}$ = 1 Pa·s were used to simulate a shallow, highly mobile flow. These parameters were calibrated to approximately match the lateral spread and deposit depths on the Bear Creek fan and flood plain below observed in the 2016 event. Calculated velocities for events larger than the calibration events were judged to have an unrealistic velocity, and the viscosity coefficient was increased to $\mu_{Bingham}$ = 10 Pa·s.

G.2.3. Results

The *DAN3D* results indicate the maximum simulated debris-flow intensity index (Jakob et al. 2012) within the modelled inundation area on the fan. This index indicates the simulated destructive potential of a flow, and is calculated as flow depth multiplied by the square of flow velocity.

In general, larger modelled flow volumes resulted in longer modelled runout distances, larger modelled inundation areas and higher modelled intensities (Drawing 10). Relatively high intensities were also generally modelled within the active channel, as channel confinement resulted in relatively high modelled flow depths and velocities.

G.2.4. Limitations

DAN3D, as most numerical modeling packages is only a proxy of the actual predicted events. Precision cannot be guaranteed, nor is required to arrive at a reasonable risk estimate and mitigation design. The raw *DAN3D* model results should similarly not be used directly to estimate consequences and associated economic or safety risk. Additional interpretation and judgment is required to prepare hazard intensity maps that are suitable for risk analysis.

G.3. WHITECAP AND SPIDER CREEK DEBRIS FLOOD MODELLING

G.3.1. Introduction

Similar to debris flow modeling, numerical modelling of debris floods is the basis for the delineation of hazard intensity zones, which will serve as input to the quantitative debris flood risk assessment. Debris flood modelling is based on the following principal assumptions:

- The frequency-magnitude relation established in the previous section is a reasonable basis to simulate debris floods for return periods from 10 to 3,000 years.
- Bedload entrainment through exceedance of critical shear stress thresholds is the principal process to generate debris floods of return periods up to some 300 years.
- Landslide dam outbreak floods provide hazard scenarios that may correspond to debris floods including and exceeding the 300-year return period class. This does not imply that all debris floods corresponding to the return period class will necessarily be landslide dam outbreak floods.
- Erosion and re-deposition of debris on the fan cannot be modelled directly and needs to be assessed by judgment.

The differentiation of debris flood generation by process type requires a staged modeling approach that involves landslide dam outbreak modelling, followed by debris flood routing onto Whitecap Creek fan. The methods and results from landslide dam outbreak flood modeling have been discussed in Appendix D for both Whitecap and Spider creeks.

In order to estimate the flood intensity (maximum flow depth and velocity) and the extent of inundation on the fan, the breach outflow hydrographs were then routed downstream using the commercially available two-dimensional hydraulic model, FLO-2D (2007), a volume conservation model that conveys a flood within defined channel segments and as overland flow. Flow progression is controlled by topography and flow resistance. The governing equations include the continuity equation and the two-dimensional equation of motion (dynamic wave momentum equation). The two-dimensional representation of the motion equation is defined using a finite difference grid system, and is solved by computing average flow velocity across a grid element boundary one direction at a time with eight potential flow directions. Pressure, friction, convective and local accelerations components in the momentum equation are retained. Specifics can be found in FLO-2D (2007) and O'Brien and Julien (1988).

FLO-2D is suited for this type of application as it can model unconfined flows across fan surfaces and simulates flows of varying sediment concentrations. It has been applied numerous times worldwide and is on the U.S. Federal Emergency Management Agency's list of approved hydraulic models.

G.3.2. FLO-2D Modelling

The input hydrograph to FLO-2D was provided from the frequency-magnitude analyses presented in Appendix D and then routed downstream. Sediment concentration was not modeled as previous work by BGC showed that for minor (< 20%) sediment concentrations, the model outcome is insensitive.

Detailed topographic information, which is a key model input, was based on 2017 LiDAR data. The model setup process was slightly different for Whitecap and Spider creeks.

On Whitecap Creek, the base topography from the 2017 LiDAR was modified to include expected sediment deposition on Whitecap Creek fan and into the immediately adjacent Portage River as was observed during the 2015 and 2016 debris floods. A new fan surface was artificially created in Muck 3D, which is an engineering software which can be used to model fills and excavations. The volume of sediment for each return period is summarized in Table G-2. BGC assumed a depositional slope between 3 and 6% (about ½ to $^{2}/_{3}$ of the original bed slope). The respective debris flood return period peak flows (Table G-3) were assumed to flow over top of the newly created fan surface, hence mimicking pre-peak flow aggradation.

The inclusion of channel aggradation in the Whitecap Creek models is associated with substantial uncertainty, since the timing of aggradation with respect to flood peaks is not known. Hence, the assumption of peak flow occurrence after most sedimentation has occurred is conservative. Most sediment will likely be delivered during the flood peak, as it is associated with the highest shear stresses acting on the channel bed and banks. Considerable sediment deposition can be expected to occur in the falling limb of the hydrograph (after the peak flow) when the stream's conveyance capacity declines and lesser amounts of sediment are conveyed all the way to Portage River. The worst-case scenario, which was modelled here, is that the channel bed aggrades due to a first hydrograph peak, and is then followed by another peak flow event that runs over top of the freshly deposited debris. This can also occur if the sediment of a previous event is not removed (by post-event erosion or artificial channel works), as was likely the case during the 2016 debris flood. A similar event also occurred at Canyon Creek in Whatcom County (Washington State) which was described by Jakob and Weatherly (2008). Here a flood occurred exactly one year after one in November of 1989 and caused the most severe damage because the debris from a debris flood one year earlier had not been removed.

BGC did not allow for sediment added through adjacent slope failures such as observed in November 2016 which could add further sediment and thus increase the new fan elevation. This omission is believed to balance the conservative assumption of post-deposition peak flow.

The modified topography was input to FLO-2D's preprocessing program, GDS, to generate a square grid for flow modeling purposes. A 5 m x 5 m grid size was used for the models to balance the detail needed for risk assessment and computing time. The model was started at the fan apex for Whitecap Creek as there are no upstream elements at risk. The model domain included all of Portage River, from Anderson Lake at the upstream to Seton Lake at the downstream.

For Spider Creek, the base topography was not modified to include sediment as there were no indications from previous events that substantial sediment aggradation occurred. Spider Creek was modelled with a 3 m x 3 m grid, starting at the outlet of the bedrock channel. The model domain included about 150 m of Portage River downstream of the Spider Creek confluence, and about 50 m upstream.

Flow resistance of the turbulent and dispersive shear stress components are combined in FLO-2D into an equivalent Manning's n-value for the flow. For Whitecap Creek, Manning's n was estimated as 0.05 for the majority of the model domain, with roads, railways tracks and parking lots assigned a Manning's n of 0.03. For Spider Creek, Manning's n was estimated as 0.075 for the entire model domain as the area is largely undeveloped. Manning's n values were selected from FLO-2D user documentation.

G.3.3. Model Runs

Table G-2 summarizes the specific model runs that were performed and key input parameters including peak discharge. Model outputs include grid cells showing the velocity, depth, and extent of debris flood scenarios. These outputs are imported into GIS and overlaid on base maps.

Table G-2. Simulated scenarios and input parameters.

Creek	Return Period (yrs)	Sediment Volume Estimate (m^3)	Peak Flow (m^3/s)	Hydrogeomorphic Processes
Whitecap Creek	10 to 30	30,000	60	Flooding/Debris flood
	30 to 100	38,000	130	Debris flood
	100 to 300	46,000	275	Debris flood/LDOF
	300 to 1000	59,000	410	LDOF
	1000 to 3000	66,000	600	LDOF
Spider Creek	1000 to 10,000	28,000	500	LDOF
	1000 to 10,000	28,000	750	LDOF
	1000 to 10,000	28,000	1000	LDOF

G.3.4. Results

Drawing 11 and 12 present the results of debris flood modelling on Whitecap and Spider creeks, respectively. Table G-3 summarizes key results including a brief description of areas impacted. These descriptions are provided for context but should not be interpreted as an assessment of risk, which will be assessed in BGC's forthcoming risk assessment report.

Two different sets of grid cell values are shown on Drawing 11 and 12. For areas with low flow velocity (< 1 m/s), only flow depths are shown. For areas of higher velocity (≥ 1 m/s), a flow "intensity" index is shown, calculated as modelled flow depth multiplied by the square of flow velocity (Jakob et al. 2012). This intensity parameter was chosen as it is useful to characterize the destruction potential of modelled flows. Further description of debris-flood intensity parameters and their application to estimate debris-flood risk are included in Appendix H.

Table G-3. Results from numerical debris flood modelling based on the 2017 LiDAR-generated DEM and interpretations by BGC.

Return Period (Years)	Results	
	Whitecap Creek	**Spider Creek**
10-30	• Flow stays mostly in the current channel but substantial amount of sediment is expected to reach Portage River. Low chance of Portage River damming. • Bank to bank flooding near Whitecap Creek bridge. • Minor bank erosion along Whitecap Creek channel. • Whitecap Creek bridge will likely survive.	• Flow will stay in Spider Ck. channel and reach Portage River • Possible blockage of Spider Ck. Road culvert • Clearwater flows exceed the capacity of the Spider Ck. Road culvert
30-100	• Flow stays mostly in the current channel but substantial amount of sediment is expected to reach Portage River. Moderate to high chance of Portage River damming. • Some bank erosion on the south bank of Portage River. • Moderate bank erosion along Whitecap Creek channel. • Bank to bank flooding near Whitecap Creek bridge. • Whitecap Creek bridge may be outflanked or abutments eroded.	• Flow will stay in Spider Ck. channel and reach Portage River • Portage River possibly being deflected into opposing low-lying floodplain to the North • Likely blockage of Spider Ck. Road culvert and overtopping with access loss
100-300	• Flow covers lower terraces and large volumes (10s of thousand of m^3) are expected to reach Portage River. High chance of Portage River damming. • Substantial bank erosion on the south bank of Portage River expected once dam breaches. • Substantial bank erosion along Whitecap Creek channel • Whitecap Creek bridge likely to be outflanked or abutments eroded, leading to bridge collapse	• Flow will stay in channel and reach Portage River • Portage River likely being deflected into opposing low-lying floodplain to the North • Very likely blockage of Spider Ck. Road culvert and overtopping with access loss
300-1000	• Flow begins to cover upper terraces (TDC offices and BC Hydro cabins) • Substantial bank erosion on the south bank of Portage River expected once dam breaches • Major bank erosion along Whitecap Creek channel • Whitecap Creek bridge very likely to be outflanked, abutments eroded, leading to bridge collapse, or covered by debris • Moderate change of Portage River being diverted into the Seton Portage area	• Flow will flood lower (undeveloped) terraces, block • Portage River very likely being deflected into opposing low-lying floodplain to the North • Erosion expected at northern river terraces adjacent to Portage River floodplain • River channel change downstream of confluence • Likely destruction of Spider Ck. Road crossing
1000-3000	• Flow is likely to cover upper terraces (TDC offices and BC Hydro cabins) • Bank erosion along Whitecap Creek is likely to reach TDC offices and BC Hydro cabins • Large volumes of sediment entrained and likely eroded from fan margins • Whitecap Creek bridge very likely to be destroyed • High chance of Portage River being diverted into the Seton Portage area	• Flow may overtop paleo-terraces (for 1000 m^3/s scenario only) and impact one home on the eastern paleofan • Portage River very likely being deflected into opposing low-lying floodplain to the North • Erosion expected at northern river terraces adjacent to Portage River floodplain • Likely destruction of Spider Ck. Road crossing

G.4. UNCERTAINTIES

Natural landslide dam breaches and subsequent inundation involve complex and dynamic physical processes that are variable in space and time. No two debris flows or debris floods, even with identical volumes, are expected to results in the same inundation pattern, avulsions, bank erosion and channel bed aggradation. This is due to the shape of the actual sediment/water hydrograph which in turn hinges on the meteorology of the debris flow or debris flood triggering storm.

A strong double-fronted storm may lead to two distinct rainfall intensity peaks, while a single front storm would lead to a single peak, perhaps amplified or lagged by snowmelt contribution. The hydrograph shape will influence the rates of sediment recruitment and deposition. Similarly, a landslide dam failure may be followed by an additional one as the bank erosion over-steepens the failed material that subsequently slumps again.

Given the impracticality of creating all conceivable hydrograph shapes and modelling these, several simplifying assumptions have to be made. As such, a number of uncertainties exist that influence the model outcomes. In this context, it is critical to ensure that model outputs are appropriately used. Model results can be used for the following purposes: (a) determine economic and life loss risk in affected zones and (b) evaluate measures to reduce the risk of debris floods to elements at risk. Model results should not be used to determine exactly which buildings are or are not free of hazard since model uncertainty does not allow such decisions. Similarly, velocity estimates are approximations and may vary according to microtopography and various flow obstacles or channelization that may develop during the flow.

In addition to uncertainties associated with model input variables such as debris flow and debris flood volumes, peak flows, and hydrograph shapes (e.g., those uncertainties described in the preceding sections), model uncertainties include the following:

- The rheological input parameters that affect flow depth and inundation area (somewhat significant)
- The topographic input (little significance after having made channel planform adjustments)
- The detailed effects of buildings and roads on the flow behaviour (possibly significant as their effects will change if obliterated)
- Fan surface erosion (possibly significant, especially if knickpoints develop)
- Sediment transport and deposition processes (very significant because these will be transient in space and time).

It is not possible to accurately forecast the location and extent of erosion and deposition on either Bear/Pete's and Whitecap Creek fan. However, by conducting multiple models runs with differing rheologies and sensitivities, confidence has been gained that the scenarios ultimately used for the generation of the composite hazard map and input to the risk assessment reasonably represent possible debris flow and debris flood outcomes.

REFERENCES

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APPENDIX H
RISK ASSESSMENT

APPENDIX H – RISK ASSESSMENT

H.1. GENERAL

Risk assessment involves estimation of the likelihood that a hydrogeomorphic scenario will occur, impact elements at risk, and cause particular types and severities of consequences. In this study, the assessment involves estimating the risk that debris flows or debris floods occurring on Bear/Pete's Creek, Whitecap Creek, or Spider Creek will impact residential buildings and cause loss of life.

The primary objective of the risk assessment is to support risk management decision making. Importantly, the assessment does not consider all possible risks that could be associated with a debris flow or debris flood. Rather, the risk assessment considers key risks that can be systematically estimated, compared to risk tolerance standards, and then used to optimize mitigation strategies. These mitigation strategies, once implemented, would also reduce relative levels risk for a broader spectrum of elements than those explicitly considered in this report. Debris-flow or debris-flood impact and resulting consequences are determined by relating the characteristics of debris-flow or debris-flood scenarios (flow velocity and depth, or bank erosion) to impacted elements at risk at a given location.

This assessment uses two different metrics to estimate safety risk: individual risk and group risk. Individual risk evaluates the chance that a specific individual (the person judged to be most at risk) will be affected by the hazard. For example, an assessment of individual risk evaluates the chance that a specific person living in a dwelling would be affected by the hazard. Individual risk is independent of the number of people exposed to the hazard, as it focusses on a single individual.

Group risk, also known as societal risk, evaluates the chance that any people present in the area will be affected by the hazard. A low-frequency, high magnitude event might result in a very small, tolerable risk to an individual, but the same event may be considered intolerable if a large number of people are affected. Group risk assessments are completed in addition to individual risk assessments because society is less tolerant of events that affect multiple people. In a given home, the probability of any individual being affected (group risk) will be at least as high as the probability of a specific individual being affected (individual risk).

This risk assessment considers the existing channel configuration and does not consider any additional debris-flow mitigation. This approach provides a baseline estimation of risk to facilitate comparison of different debris-flow risk reduction options. As described in Section H.5, BGC conservatively assumes that no evacuation of persons is possible during the event.

Lastly, this assessment was done at a building lot level of detail, where the likelihood of debris-flow impact is based on the location of a given building in relation to hazard areas. For the purposes of land use planning, lots containing buildings that exceeding risk tolerance criteria were identified at a lot level of detail on risk maps (Drawing 15).

H.2. GEOHAZARD SCENARIOS

This risk analysis is based on debris-flood and debris-flow scenarios, which are defined as hydrogeomorphic events with particular volumes and likelihoods of occurrence.

Geohazard scenarios were chosen to represent the spectrum of possible debris-flow or debris flood event magnitudes on each creek, from the smallest and most frequent to the largest credible. Along with their probability of occurrence, these scenarios are the primary outcome of the hazard assessment that is carried forward into the risk analysis.

Drawings G01 to G05, G06 to G10, and G11 show the geohazard scenarios considered for Bear and Pete's Creek, Whitecap Creek, and Spider Creek, respectively. Methods to develop these maps are described in Section 3.5 of the main report. The results were evaluated against risk tolerance criteria defined in Section 3.6 of the main report.

H.3. ELEMENTS AT RISK

This section describes "elements at risk" potentially exposed to (at risk from) the geohazard scenarios considered in the risk analysis.

H.4. BACKGROUND

The study area encompasses the community Seton Portage. Development is concentrated on the valley bottom, which separates Anderson and Seton Lakes and is bisected by the Portage River. Further description of the community is provided in the main report, and Table H-1**Error! Reference source not found.** lists the elements at risk considered in this assessment. Table H-1 does not include all elements that could suffer direct or indirect consequences due to a geohazard event, but focuses on those that can be reasonably assessed, based on the information available. Sections H.4.1 to H.4.2 describe methods used to identify and characterize elements at risk, and lists data gaps and uncertainties.

Table H-1. List of elements at risk considered in the risk assessment.

Element at Risk	Description
Building Structures	Commercial, institutional, residential, transportation.
Persons	Persons located within buildings.
Lifelines	Sewerage, stormwater management, gas distribution, electrical power and telephone line distribution, railway, roads[1], bridges[2].
Critical facilities	School, Hotel, Canada post/Corner store/restaurant (all one building), Church, Pumphouse in Necait.
Business activity	Businesses located on the fan that have the potential to be directly impacted by geohazards, either due to building damage or interruption of business activity due to loss of access.
Cultural/ecological significance	Seton Portage Historic Park, graveyard, other.

Notes:

1. Local roads include: Highline Road, Seton Portage Road (referred to as Seton Road west of the hotel), Cresta Road, Scott Road, Edwards Road, Williams Lane, Spider Creek Road, Mission Reserve Road, S Slosh Reserve Rd (also referred to as Bull Alley).
2. The location of bridges and rail crossings are illustrated on Drawing 13.

H.4.1. Buildings

Information on building types and occupancy was obtained from BC Assessment data, census data, a questionnaire for residents, and correspondence with the community of Tsal'alh (pers. comm. Cliff Casper, Tsal'alh land manager). The locations of buildings (building footprints) were digitized by BGC from data acquired by UNBC during the October 10, 2017 LiDAR survey. These data were used in the risk analysis to identify location(s) of buildings within parcels that could be impacted by geohazard scenarios.

The questionnaire for residents was prepared by BGC in November 2017 and distributed by the Tsal'alh land manager Cliff Casper. The questions and average responses are summarized in Table H-2.

Table H-2. List of questions and summary of responses received to characterize the built environment at Seton Portage.

Question	Response
1. BGC Building ID (see maps)	Various
2. Is this building occupied? (Yes/No)	24 Yes, 16 No
3. How many building residents are there? (#)	Average of 2.6 for occupied buildings
4. Do building occupants live here full-time or part-time?	Full-Time
5. If part-time, when (i.e. time of year, length of stay)	n/a
6. How many stories is this building?	Average of 2.1 for occupied buildings
7. Does this building have a basement?	11 Yes, 4 Crawl Space, 25 No
8. If yes, are there any bedrooms in the basement?	9 Yes
9. Approximately how high is the main floor above the surrounding ground elevation?	Average of 1.2 m

The consultation zone contains approximately 84 residential dwellings (typically single detached houses), 54 outbuildings, 12 trailers, 2 religious buildings (1 of which is abandoned), 2 commercial buildings, and 1 hotel. These are estimated from BC assessment data, questionnaire responses, field review and review of imagery in the absence of assessment data.

Each land parcel contains a unique identification number ("PID") and unique lookup code identifying the primary use and type of building within the parcel. In the case of single buildings (e.g., residential houses), each parcel typically contains only one assessed land and building value. However, many parcels contain more than one occupied building (e.g., Necait and Mission Indian reserve lands), therefore the assessment was completed at the building level of detail. Data on building structure type or contents were not available.

The total estimated value of buildings development in the study area is $16.7 M. This includes $11.7 M in taxable buildings "improvements" (BC Assessment 2017), approximately $3.7 M of development on First Nations Land (pers. comm., Cliff Casper, Tsal'alh), and approximately $1.3 M assigned as average values to buildings where no data were available. Assessed building values do not necessarily correspond to replacement value, which may be higher.

Table H-3 summarizes the main uncertainties associated with the buildings attributes data provided.

Table H-3. Building data uncertainties.

Type	Description
Building Value	Building value was assigned as the total improvement value within a given parcel according to BC Assessment (BCA 2017) or data provided by Tsal'alh. However, buildings exist within some parcels where no improvement value was listed. In these cases, BGC assigned an improvement value corresponding to the average assessed value of similarly classed parcels within the study area.
Building Structure	Limited information describing building structure was available (i.e., approximately 40 survey responses), such as construction type, foundation type, number of stories, presence of sub-grade basement, Flood Construction Level (FCL), first-floor elevation, or floor area. These data gaps will decrease confidence in damage and risk estimation. BGC applied average values from the survey responses in cases where no data were available.
Building Type	Information on exact building types within parcels was not directly available. Building types were assigned based on review of imagery (i.e., Google Maps) and BCA primary actual use codes grouped into residential, commercial, industrial, agricultural, government and religious categories.
Building Location	Ambiguities exist where multiple buildings exist within parcels and where building footprints overlap parcel boundaries.

H.4.2. Lifelines

Lifelines considered in this assessment include transportation networks (local roads, bridges and railway). Lifelines within the study area are shown on Drawing 14. Local roads include the following:

- Anderson Lake Road (also referred to as Highline Road)
- Broadhead Road
- Bull Alley (also referred to as S Slosh Road)
- Cresta Road
- Edwards Road
- Scott Road
- Seton Portage Road (referred to as referred to as Seton Road west of the Lil'Tem' Mountain hotel)
- Spider Creek Road (also referred to as Mission Reserve Road)
- Williams Lane.

Local bridges include the following:

- Anderson Lake Road bridge
- Seton Road bridge.

H.4.3. Critical Facilities

Critical facilities are defined as those that:

- Provide vital services in saving and avoiding loss of human life
- Accommodate and support activities important to rescue and treatment operations
- Are required for the maintenance of public order
- House substantial populations
- Confine activities that, if disturbed or damaged, could be hazardous to the region
- Contain hazardous products or irreplaceable artifacts and historical documents.

Critical facilities within the study were identified by Tsal'alh community members. They include: the Lil'Tem' Mountain Hotel, Canada Post/Corner store/Restaurant (all one building), and the church and pumphouse in Necait. The locations of the critical facilities within the consultation zone are delineated on Drawing 14.

H.4.4. Persons

Population estimates used in this assessment are based on 2016 Census data (Statistics Canada 2017), population estimates from the Tsal'alh, business data (Hoovers 2017), and questionnaire responses.

Assessment of risk at a building level of detail requires estimation of the number of persons in each building on the fan. However, Census data do not provide estimates at this resolution. As such, individual building populations were estimated using the steps listed below:

1. BGC identified which buildings were occupied through visual assessment of the building size (i.e., smaller buildings were assumed to be unoccupied outbuildings) and questionnaire responses.
2. Where available, the number of residents were obtained from the questionnaire responses (data were available for 24 of 34 occupied lots on-reserve land). No survey responses for Private land were provided.
3. For buildings on reserve land where no questionnaire response was provided, an occupancy rate of 3 was assigned. This is close to the average occupancy rate of 2.6 for on-reserve buildings from survey responses. The value was rounded up to 3 to account for uncertainties in the population estimate described in Table H-4.
4. For buildings on private land, an occupancy rate of 2 was assigned. This is similar to the average household size of 1.9 for SLRD B, Regional district electoral area (Census Subdivision) from the 2016 Census (Statistics Canada 2017). Specific population data for Private land in the Seton Portage area was not available.

Population estimates for non-residential parcels are based on the number of employees listed in business data obtained from Dun & Bradstreet (Hoovers 2017). Population data for the Lil'Tem' Mountain Hotel were requested but not available at the time of writing. As such, an approximate occupancy rate of 25 was used for the risk assessment.

Table H-4 summarizes calculated populations used in the risk analysis. Table H-4 lists factors affecting confidence in these estimates, with implications for possible over- or underestimation of group safety risk depending on whether the number of persons was over- or underestimated, respectively. BGC believes that the accuracy of population estimates is sufficient to allow risk management decisions. However, the estimates should not be used for detailed assessment of individual parcels (e.g., for building permit applications) without being manually checked.

Table H-4. Summary of calculated population estimates used in risk analysis.

Building Type	Population Total
Residential	196
Hotel	25
Cabin	9
Trailer	14
Business	20
Total	**264**

Table H-4. Uncertainties associated with estimating the number of occupants of a building.

<table>
<tr><th>Uncertainty</th><th>Implication</th></tr>
<tr><td>Average occupancy rates may not correspond to actual occupancy rates for a given dwelling unit. For example, according to the Tsal'alh the on-reserve population is approximately 250. BGC identified approximately 34 occupied buildings on-reserve land which corresponds to an unrealistic occupancy rate of 7.8. It is possible that this population estimate includes areas outside of the study area or that more buildings are occupied than what was identified in the visual assessment.</td><td rowspan="7">Over- or underestimation of occupant numbers</td></tr>
<tr><td>Seasonal population fluctuations (including tourists) exist that were not accounted for.</td></tr>
<tr><td>No employee data available (either not listed in Dun and Bradstreet (D&B) (Hoovers 2017)) or could not be assigned to specific parcels.</td></tr>
<tr><td>Errors in employee data sourced from Dun and Bradstreet (D&B) (Hoovers 2017) may exist. These data were not verified by BGC.</td></tr>
<tr><td>Errors in assignment of D&B employee data to specific parcels may exist, due to inconsistencies in building address data.</td></tr>
<tr><td>Overlap between some population types (e.g., employees might also live in the consultation zone).</td></tr>
<tr><td>Occupancy rates for the hotel are higher or lower than BGC's estimate.</td></tr>
<tr><td>Distribution of persons within a building are unknown. As such, the number of persons most vulnerable to geohazard impact on the first floor or basement is unknown.</td><td></td></tr>
<tr><td>Seasonal visitors may occupy private residences, and additional visitors temporarily occupy service businesses.</td><td>Uncertainty in estimation of human vulnerability to geohazard impact</td></tr>
</table>

H.4.5. Business Activity

Approximately six businesses employing 24 people are located within the Seton Portage area. Annual business revenues data were available for three of the six businesses and totals approximately $680,000 (Hoovers 2017).

Business activity impacts listed in this report are likely underestimated due to uncertainties in the business data. Table H-5 summarizes sources of uncertainty. In addition to these uncertainties, business activity estimates do not include individuals working at home for businesses located elsewhere or businesses that are located elsewhere but that depend on transportation routes through geohazard areas. Inclusion of these figures would substantially increase the level of business activity that could be affected by a geohazard event. Such estimates are outside the scope of this assessment.

Table H-5. Business data uncertainties.

Type	Description
Revenue data	Missing for three workplaces (not available from D&B).
D&B data quality	BGC has not reviewed the accuracy of business data obtained for this assessment.
Worker location	Whether the employee primarily works at the office or some other location is not known. The estimates also do not include individuals working at home for businesses located elsewhere.
Source of revenue	Whether a business' source of revenue is geographically tied to its physical location (e.g., a retail store with inventory, versus an office space with revenue generated elsewhere) is not known and is outside the scope of this assessment.

H.5. QUANTITATIVE RISK ASSESSMENT (QRA)

H.5.1. Risk Equation

Risk (P_E) was estimated using the following equation:

$$P_E = \sum_{i=1}^{n} P(H)_i P(S:H)_i P(T:S)_i \, N \qquad \text{[Eq. H-1]}$$

where:

$P(H)_i$ is the annual hazard probability of geohazard scenario i of n, defined as an annual frequency ranges.

$P(S:H)_i$ is the probability that the scenario would reach the element at risk, given that it occurs.

$P(T:S)_i$ is the probability that the element at risk (e.g., persons within buildings) is in the impact zone, given that the scenario reaches the location of the element at risk. This parameter is considered certain (equal to 1) for buildings and infrastructure.

$N = V_i E_i$ describes the consequences [Eq. H-2]

where:

V_i is the vulnerability, which is the probability elements at risk will suffer consequences given hazard impact with a certain severity. For persons, vulnerability is defined as the likelihood of fatality given impact. For buildings, it is defined as the level of damage, measured as a proportion of the building replacement cost or as an absolute cost.

E_i is a measure of the elements at risk, quantifying the value of the elements that could potentially suffer damage or loss. For persons, it is the number of persons exposed to hazard, equal to 1 in the case of individual risk assessment. For buildings, it is defined as the assessed value of buildings potentially subject to damage.

Risk is estimated separately for individuals and groups (societal) risk. Estimated risk for combined debris-flow scenarios is calculated by summing the risk quantified for each individual debris-flow scenario.

Individual risk is reported as the annual Probability of Death of an Individual (PDI). Individual risk levels are independent of the number of persons exposed to risk.

Group risk was estimated as the probability of a certain number of fatalities, represented graphically on an F-N curve as shown in **Error! Reference source not found.** 3-6 of the main report. The Y-axis shows the annual cumulative frequency, f_i, of each hazard scenario, and the X-axis shows the estimated number of fatalities, N_i, where:

$$f_i = \sum_{i=1}^{n} P(H)_i P(S:H)_i P(T:S)_i \quad \text{[Eq. H-3]}$$

and N_i is represented by equation [H-2].

H.5.2. Hazard Probability

Hazard probability, $P(H)_i$, corresponds to the annual probability of occurrence of each hazard scenario, which are defined as annual frequency ranges. The bounds of a given range are exceedance probabilities. For example, the 10 to 100-year scenario represents the probability that the event will be larger than the 10-year event but not larger than the 100-year event.

Given a scenario with the annual exceedance probability range P_{min} to P_{max}, the probability of events within this range corresponds to:

$$P(H)_i = P_{min} - P_{max} \quad \text{[Eq. H-4]}$$

For example, for the 1:10 to 1:100 -year range, this would correspond to:

$$P(H)_i = \frac{1}{10} - \frac{1}{100} = \frac{1}{11} \quad \text{[Eq. H-5]}$$

The upper and lower bounds of each range were used in the risk analysis as approximate upper and lower uncertainty bounds for each frequency range.

H.5.3. Spatial Probability

For creeks subject to debris floods (Whitecap Creek and Spider Creek), overall flow and bank erosion extents are shown by interpreted model results. Compared to creeks prone to debris floods, a wider range of flow characteristics is possible for a given debris-flow magnitude at Bear and Pete's Creek. Specifically, more watery flows are expected to run out further than those with higher sediment concentration. Moreover, flow avulsions near the fan apex can result in flow trajectories primarily towards a certain sector of the fan. For a given hazard scenario, these factors influence the spatial probability of debris-flow impact.

As such, spatial probability estimates for a given lot were based on the product of two factors. The first factor, runout exceedance probability, considers the probability flows will exceed a certain runout extent. Values used in the analysis are shown by the runout exceedance probability isolines on Drawings G01 to G05. This factor addresses the question, "given an event, what is the chance that a flow will extend at least as far as a given dwelling?"

The second factor considers lateral impact probability. This was estimated for each volume class based on the typical width of a simulated flow path in relation to the possible corridor through which it might travel. This factor addresses the question, "what is the chance that a flow will follow a particular trajectory that results in impact to a building (as opposed to travelling past but missing a dwelling)?" Values used in the analysis are shown in Table H-6. They are based on the results of modelling and judgement and were estimated by dividing the anticipated flow path width by the total approximate width of the runout zone in the vicinity of elements of risk.

Table H-6. Lateral impact probability.

Scenario (Return Period Range)	$P(S{:}H)_3$
10-30	0.10
30-100	0.15
100-300	0.25
300-1000	0.30
1000-3000	0.35

H.5.4. Temporal Probability

Temporal probability considers the proportion of time residents spend within their dwelling. All else being equal, safety risk is directly proportional to the time residents spend at home (e.g., a resident who is rarely home has less chance of being struck by a debris flow or debris flood).

There is strong variation in the proportion of time residents spend in dwellings within the study area, from occasional cabin users to full time occupants. There is also seasonal variation and likely variations from year to year. Survey responses suggest that most residents are full time, therefore BGC assumed full time occupancy to assess baseline risk.

BGC assumed full-time occupancy to assess baseline risk for land use planning and permitting. "Full-time" is defined in this report as occupancy about 50% of the time on average, 365 days/year. For non-residential buildings (e.g., hotel, businesses), BGC assumed building were occupied approximately 25% of the time on average, 365 days/year. For the cabins on Whitecap Creek used for BC Hydro accommodation, BGC assumed the cabins were occupied only 6 months of the year.

H.5.5. Vulnerability

Table H-7 lists vulnerability criteria for buildings, which were developed from judgement with reference to Jakob et al. (2012). The values used are also consistent with those used by BGC to quantify debris-flow risk at Catiline Creek (BGC 2015a), and assess debris-flood and debris-flow risk for alluvial fans in the Town of Canmore and Municipal District of Bighorn (e.g., BGC 2014, 2015a-e, 2016). The vulnerability estimates contain uncertainty due to factors that cannot be captured at the scale of assessment, such as variations in the structure and contents of a given building and the location of persons within the building at the time of impact.

Table H-7. Vulnerability criteria for buildings.

Hazard Intensity Index (Range)	Building Damage Description		Building Vulnerability[1]
	Category	Description	Best Estimate
<1	Minor	Low likelihood of building structure damage due to impact pressure. High likelihood of major sediment and/or water damage. Damage level and cost primarily a function of flood-related damages.	0.15
1-10	Moderate	High likelihood of moderate to major building structure damage due to impact pressure. Certain severe sediment and water damage. Building repairs required, possibly including some structural elements.	0.5
10-100	Major	High likelihood of major to severe building structure damage due to impact pressure. Certain severe sediment and water damage. Major building repairs required including to structural elements.	0.8
>100	Complete	Very high likelihood of severe building structure damage or collapse. Complete building replacement required.	1

Note:
1. Value indicate estimated proportion of building replacement value.

Table H-8 shows the criteria used to estimate the vulnerability of persons within buildings to debris-flow or debris-flood impact, where vulnerability is primarily an indirect outcome of building damage or collapse.

Table H-8. Vulnerability criteria for persons within buildings.

Hazard Intensity Index (Range)	Debris Flows (Bear/Pete's Creek)	Debris Floods (Whitecap and Spider creeks)
	Best Estimate	Best Estimate
<1	~0	~0
1-10	0.2	0.01
10-100	0.6	0.1
>100	0.9	0.5

Note: Values indicate estimated probability of loss of life given impact

For areas subject to bank erosion, BGC assumed building destruction given bank erosion exceeds approximately 1 m depth, which was estimated to be the case at the creeks assessed. Vulnerability estimates equivalent to those for I_{DF} > 100 were assigned to estimate vulnerability in these areas.

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APPENDIX I
RISK REDUCTION ASSESSMENT

APPENDIX I – MITIGATION DESIGN COST ESTIMATES

I.1. UNIT RATES

The unit rates used in the cost estimates are summarized in Table I-1.

Table I-1. Unit rate assumptions for cost estimation.

Item	Unit rate	Unit
Clearing, grubbing and stripping	$10	m^2
Bulk excavation	$10	m^3
Fill hauling, placement and compaction	$30	m^3
Disposal of excess material	$20	m^3
Riprap supply and placement	$150	m^3
Road base supply and placement	$50	m^3
Swale construction	$150,000	LS
Outlet structure construction	$500,000	LS
Miscellaneous construction costs	10%	LS
Engineering, environmental, and surveying design and construction review services	20%	LS
Design and construction contingency	30%	LS

I.2. BEAR AND PETE'S CREEK MITIGATION OPTIONS

Cost estimates for the Bear and Pete's Creek mitigation options are provided in Table I-2, Table I-3 and Table I-4. These estimates were based on the following assumptions, in addition to the geometry assumptions stated in the main report:

- For the berms, riprap is assumed to be 1.5 m thick and to cover a length (in cross-section) of about 10 m, from the berm toe to the berm crest. The following riprap lengths were assumed for each option:
  - Option 1 – 1000 m of riprap; 800 m on the north berm and 200 m on the south berm.
  - Option 2 – 700 m of riprap.
  - Option 3 – 200 m of riprap on the south berm.
- For the debris basin at the apex (all options), erosion protection at the inlet is assumed to be 1.5 m, 100 m long and to cover a length (in cross-section) of about 10 m.
- All options assume a cut/fill balance between excavation and berm fills.
- All options assume that about 500 m of access road are required, and that the access road would be 5 m wide with a 150 mm thick road base.

- For Option 2, an outlet structure and channel are assumed to convey water into Portage River or Spider Creek. The channel is assumed to be 150 m long and 1 m deep with a 5 m base width and 1.5H:1V side slopes. An allowance of 500 m^3 of riprap was assumed for local armouring of the channel, such as in steeper sections or on the outside of bends.

Table I-2. Bear and Pete's creeks Option 1 quantities and cost estimate.

Category	Item	Quantity	Unit	Cost
Basin and berm construction	Clearing, grubbing and stripping	50,000	m^2	$500,000
	Bulk excavation - basin	45,000	m^3	$450,000
	Fill hauling, placement and compaction	45,000	m^3	$1,350,000
	Riprap supply and placement (Class 1000 kg)	17,000	m^3	$2,550,000
	Road base supply and placement	500	m^3	$25,000
	Swale construction	1	LS	$150,000
General	Miscellaneous construction fees	1	LS	$490,000
	Engineering design and construction review services	1	LS	$975,000
	Design and construction contingency	1	LS	$1,465,000
			Total (rounded)	**$8,000,000**

Table I-3. Bear and Pete's creeks Option 2 quantities and cost estimate.

Category	Item	Quantity	Unit	Cost
Basin and berm construction	Clearing, grubbing and stripping	60,000	m^2	$600,000
	Bulk excavation - basin	50,000	m^3	$500,000
	Fill hauling, placement and compaction	50,000	m^3	$1,500,000
	Riprap supply and placement (Class 1000 kg)	10,000	m^3	$1,800,000
	Road base supply and placement	500	m^3	$25,000
Outlet and channel construction	Outlet structure construction	1	LS	$500,000
	Channel excavation	1000	m^3	$10,000
	Riprap for channel armouring	500	m^3	$75,000
General	Miscellaneous construction fees	1	LS	$500,000
	Engineering design and construction review services	1	LS	$1,000,000
	Design and construction contingency	1	LS	$1,505,000
			Total (rounded)	**$8,000,000**

Table I-4. Bear and Pete's creeks Option 3 quantities and cost estimate.

Category	Item	Quantity	Unit	Cost
Basin and berm construction	Clearing, grubbing and stripping	60,000	m^2	$600,000
	Bulk excavation - basin	80,000	m^3	$800,000
	Fill hauling, placement and compaction	80,000	m^3	$2,400,000
	Riprap for berm armouring	5,000	m^3	$750,000
	Road base supply and placement	500	m^3	$25,000
General	Miscellaneous construction fees	1	LS	$460,000
	Engineering design and construction review services	1	LS	$915,000
	Design and construction contingency	1	LS	$1,375,000
			Total (rounded)	**$7,300,000**

I.3. WHITECAP CREEK MITIGATION OPTIONS

Cost estimates for Whitecap Creek mitigation Options 1 and 2 are provided in Table I-5, and Table I-6. These estimates were based on the following assumptions, in addition to the geometry assumptions stated in the main report:

- Options 1 and 2 require riprap along the entire berm length (100 m and 350 m, respectively). Riprap is assumed to be 1.5 m thick for this conceptual cost estimate, and the covers a length of about 6 m, from the key-in, to the berm toe, to the berm crest.
- Berms are 2 m high with 1.5H:1V side slopes and 4 m crests, not including the riprap width

Table I-5. Whitecap Creek Option 1 quantities and cost estimate.

Category	Item	Quantity	Unit	Cost
Berm construction	Clearing, grubbing and stripping	100	m^2	$10,000
	Fill placement and compaction	1,400	m^3	$42,000
	Riprap supply and placement (Class 1000 kg)	900	m^3	$135,000
General	Miscellaneous construction fees	1	LS	$20,000
	Engineering design and construction review services	1	LS	$35,000
	Design and construction contingency	1	LS	$55,000
			Total (rounded)	**$290,000**

Table I-6. Whitecap Creek Option 2 quantities and cost estimate.

Category	Item	Quantity	Unit	Cost
Berm construction	Clearing, grubbing and stripping	3,500	m^2	$35,000
	Fill placement and compaction	5,000	m^3	$150,000
	Riprap supply and placement (Class 1000 kg)	3,200	m^3	$480,000
General	Miscellaneous construction fees	1	LS	$65,000
	Engineering design and construction review services	1	LS	$135,000
	Design and construction contingency	1	LS	$200,000
			Total (rounded)	**$1,070,000**

APPENDIX J
POSSIBLE EFFECTS OF CLIMATE CHANGE

APPENDIX J - POSSIBLE EFFECTS OF CLIMATE CHANGE

J.1. INTRODUCTION

Several limitations to the F-M analysis in Section 4 have been discussed. These are primarily based on the uncertainties related to the available analytical techniques as well as time-dependent changes in geomorphic activity as a function of their geological legacy and climate change, and the lack of a rigorous way to cross-check the results. In this section, the specific issue of climate change is revisited because mitigation measures proposed for Bear Creek would be designed to last at least several decades. Therefore, climatic shifts affecting geomorphic process should be considered explicitly.

It is now scientifically accepted that humans have measurably altered Earth's thermal climate over the past 50 to 60 years (IPCC 2014). The relevance of climate change with regard to Bear Creek debris-flow hazards is that the predicted warming of the troposphere will very likely[1] increase the pattern of precipitation and temperature, both of which influence the frequency, possibly magnitude and runout behaviour of debris flows at Bear Creek. Due to more intensive energy exchanges in the vertical air column, as well as the projected intensification of air mass exchange between the low and high latitudes, it is expected that extreme precipitation events will increase in frequency and severity (IPCC 2012; IPCC 2014). If this prediction were to materialize or has already commenced, this could result in several undesirable outcomes with respect to mountain creek hazards. To provide a semi-quantitative basis to estimate future changes to debris flow activity on Bear Creek, BGC Engineering Inc. (BGC) used available climate change ensembles that allow visualization and quantification of changes as summarized in the following section.

To investigate likely effects of climate change, a new tool was employed. The **Climate Change Hazards Information Portal** (CCHIP) is a fee-based subscription that provides visualized historical and projected climate data and analyses for various industry sectors. It is designed to allow access to customized climate information based on quality controlled data drawn from various sources and packaged in a 'one-stop' location. It includes direct linkages to location-specific, infrastructure climate design values (from Canadian codes and standards) as well as information on key agricultural thresholds and the ability to customize analyses relative to threshold settings.

In the first step, the location of interest is chosen. The second step specifies the data of interest, which in the present case is primarily precipitation, in the second instance temperature as that effects changes to the suspected permafrost as well as the timing and potentially volume of snowmelt.

CCHIP automatically selects the nearest meteorological station when users enter a location. Most basic parameters of daily temperature and precipitation are generally available, but data for certain climate elements (such as wind for example) and variables (such as short duration rainfall

[1] See IPCC (2014) for a definition of "very likely" in the context of that report.

intensities) these are typically available only at airport locations. To supplement analysis for short-term data, BGC obtained rainfall data from BC Hydro and determined observed changes in one-hour intensities.

J.2. CLIMATE PROJECTION DATA

Official IPCC statements predominantly rely on international research centres to contribute model projection information and this is the basis of climate projections provided currently on CCHIP. The most recent assemblage of models was for the Intergovernmental for Climate Change (IPCC) 5th Assessment of 2013. In this assessment, some 40 international models were used with multiple runs per model, resulting in approximately 75 projection estimates from which to calculate possible future conditions. Maximum, minimum and mean temperature are standard output variables from these models, as is precipitation.

CCHIP makes use of this same IPCC set of internationally vetted GCM model data. The suite of models used in AR5 is from the Fifth Coupled Model Inter-comparison Project (CMIP5), coordinated by the World Climate Research Program, and was retrieved from the data portal.

J.3. UNCERTAINTY

The use of many model estimates allows for the calculation of central tendency as well as the range of future values. Based on the 'spread' of these models, different characterizations of uncertainty can be provided. In other words: a variable which shows less spread among many models is more reliable than a variable which has a very large range of projected outcomes. This is critical in the consideration of uncertainty. Beneath charts with model projections, CCHIP provides 'box and whisker' plots of the full range of all model run projections. The top horizontal bar is the highest model value, the bottom horizontal bar is the lowest model value, the box represents the range of 50% of the models with the top being the 75th percentile value, the bottom being the 25th percentile value. The median is represented by the horizontal line in the centre of the shaded box.

BGC only examined changes to the Representative Concentration Pathway (RCP) (previously named "emission scenario" for the 8.5 W/m^2. While this is the most extreme scenario, recent research by Sanford et al. (2014) indicated that, at present, the most likely trajectory is indeed the worst-case.

J.4. CLIMATE CHANGE PROJECTIONS FOR SETON PORTAGE

Precipitation

Figure J-1 shows the projected changes in total annual precipitation for the model ensembles considered. Precipitation is projected to increase by an average of 10% by the 2080s with one standard deviation varying from 6 to 12%. This projection does not match the observed downward trend in precipitation from 1963 to 2004 (see Figure J-2), a trend, however which may not be statistically significant if the missing data were added.

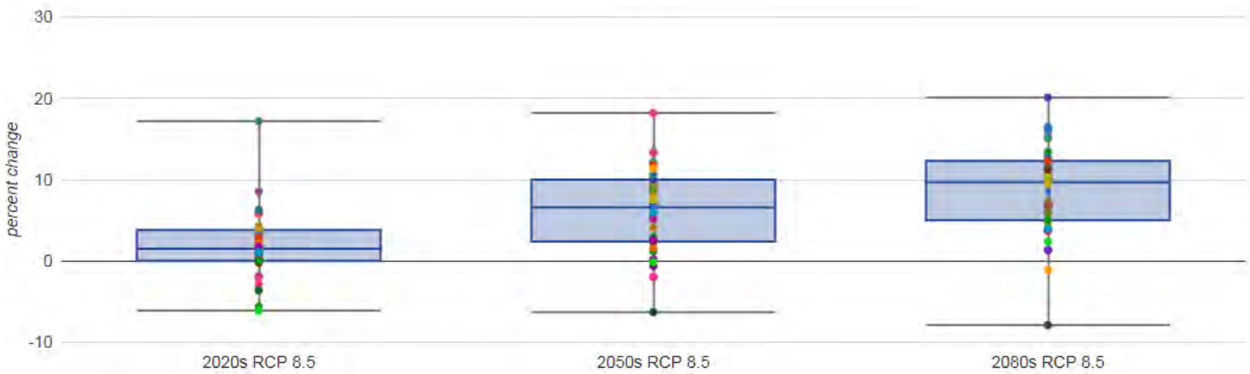

Figure J-1. Changes in annual precipitation for RCP 8.5 and a large number of model ensembles. For the purpose of this assessment the RCP 8.5 scenario was considered.

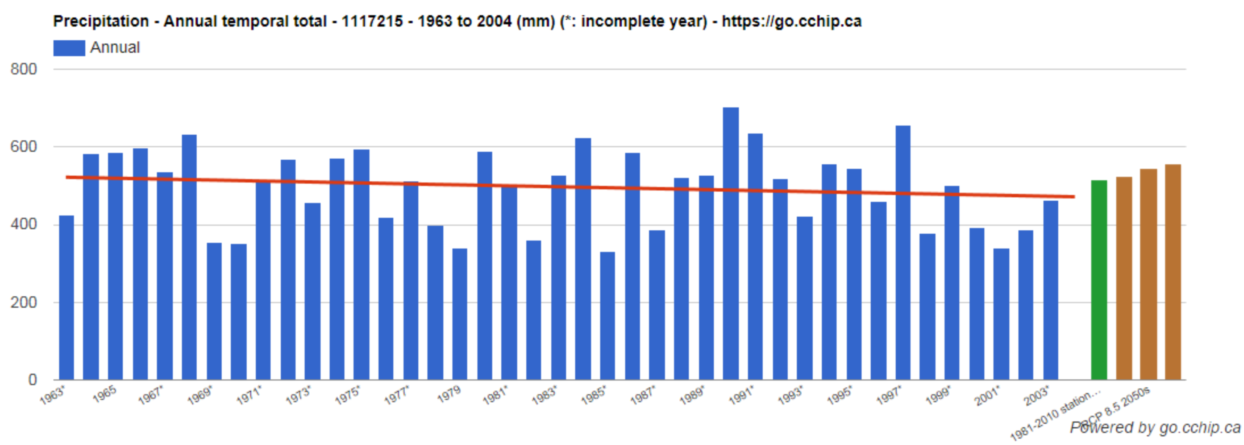

Figure J-2. Observed changes in annual precipitation and projected mean annual precipitation changes predicted to the 2080s for RCP 8.5.

In addition to annual precipitation, BGC analysed projected climate changes for months with known debris-flow activity (May to September). The analysis showed that for the month of May a mean increase of approximately 10% can be expected to 2080, with one standard deviation reaching up to 25%. This projection is supported by the observed trend in May precipitation between 1963 and 2003. For June there is no statistically significant trend expected, nor has it been observed for 3, 5 and 7-day rainfall accumulations. For the month of July, a gradual decrease in monthly rainfall is expected, which reaches a mean predicted decrease of some 20% by the 2080s assuming the RCP 8.5 scenario. This contrasts an observed increase in July rainfall amounts beginning in 1981. For August, the model ensembles predict similar rainfall decreases as for July and no discernible trend has been identified in the time series from 1963 to 2016. Finally, for the month of September, no significant change in monthly rainfall is predicted by the 2080s.

In summary, for the RCP 8.5 scenario, total annual rainfall is predicted to increase, however, rainfall during months of debris-flow activity predictions vary significantly between significant increases of expected precipitation in May, no changes for June, decreases for July, August and

September. The analysis does not inform on short-term rainfall intensities although a correlation between monthly rainfall and hourly rainfall has been demonstrated by Jakob and Lambert (2009).

With respect to debris flows, the analysis does not allow any conclusions as to increases in their occurrence except that increases in temperatures discussed in the following subsection in addition to projected increases in precipitation in May, may lead to clustering of debris flows during the snow melt season.

Temperature

For the same RCP scenario (8.5) and model ensembles, temperatures are projected to increase by approximately 4 to 6° Celsius by the 2080s (Figure J-3 and Figure J-4).

This implies less precipitation falling as snow, later transition from rain to snow in the year, and earlier transition to snowmelt in spring. Furthermore, snow water equivalent may increase. The consequences for debris flows could be an extension of the debris flow season and potentially higher water runoff volumes. Changes in the frequency and magnitude of convective storms cannot yet be predicted with confidence.

If permafrost were to be confirmed in the upper talus slopes of the Bear Creek watershed, it could disappear within this century. This would go hand-in-hand with the disappearance of the interstitial ice that provides cohesion at depth. A loss of cohesion would provide substantially more talus to be subject to failure than in its frozen state. Without confirmation of the existence of permafrost in the upper watershed, this conclusion is still speculative.

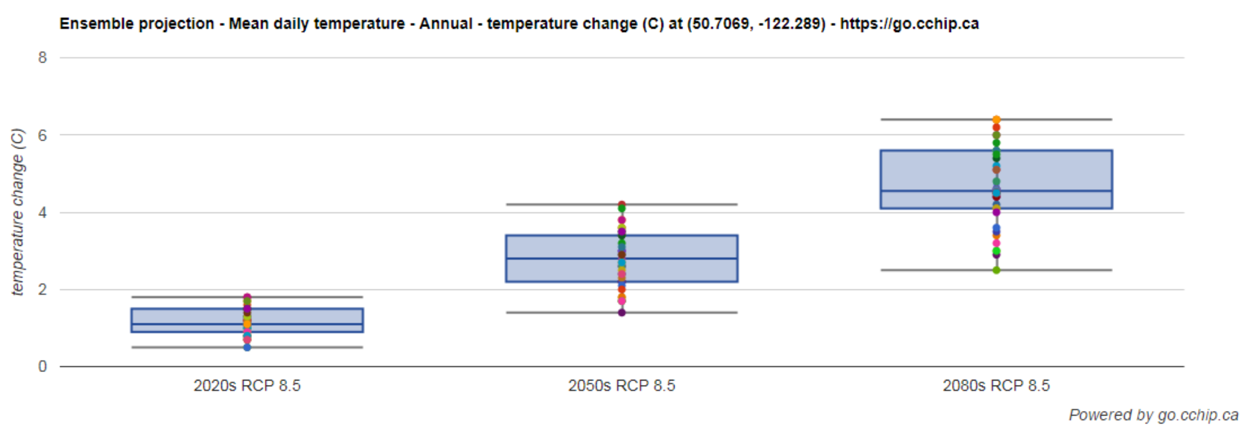

Figure J-3. Projected increase in main daily temperature up to the 2080s for RCP 8.5.

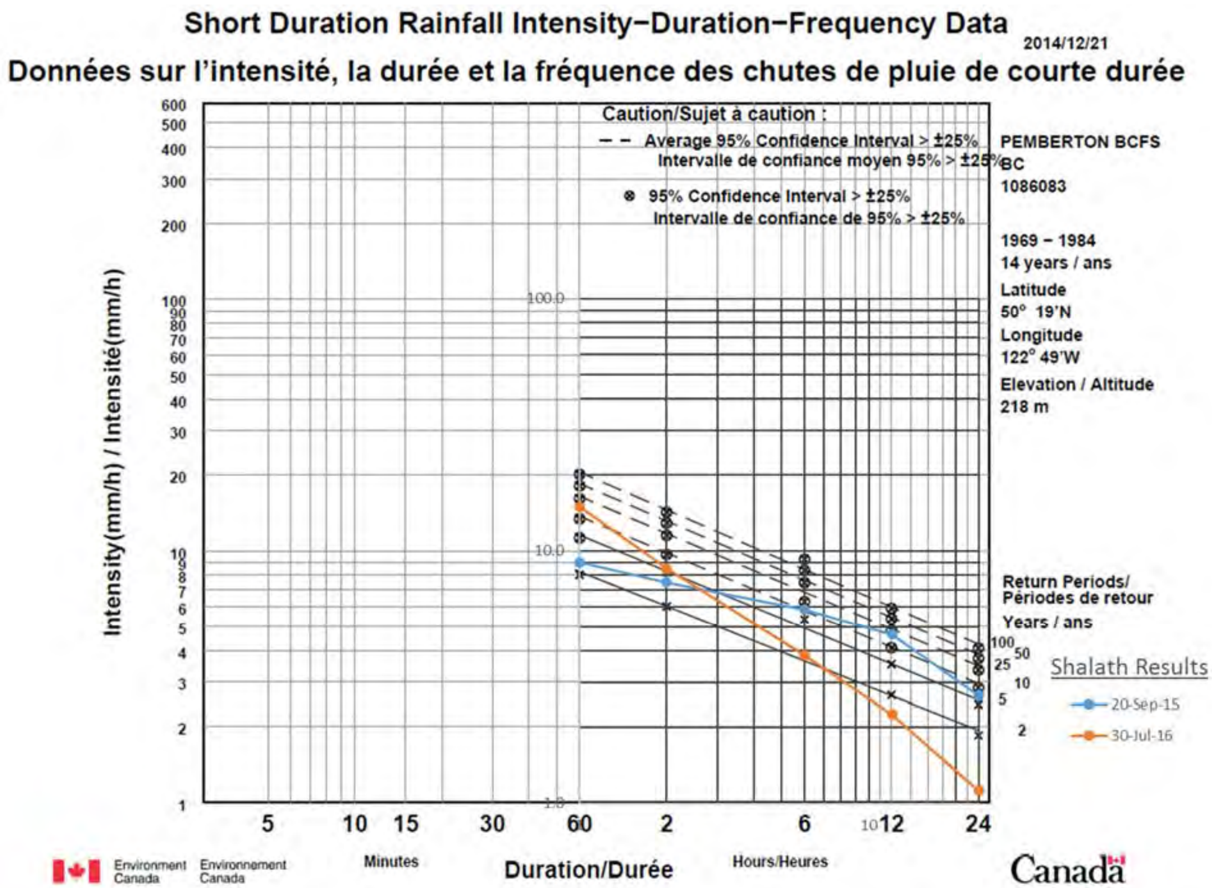

Figure J-4. IDF magnitudes for the September 20, 2015 (blue) and July 30, 2016 (orange) debris flow events compared to the calculated Pemberton Climate Station values.

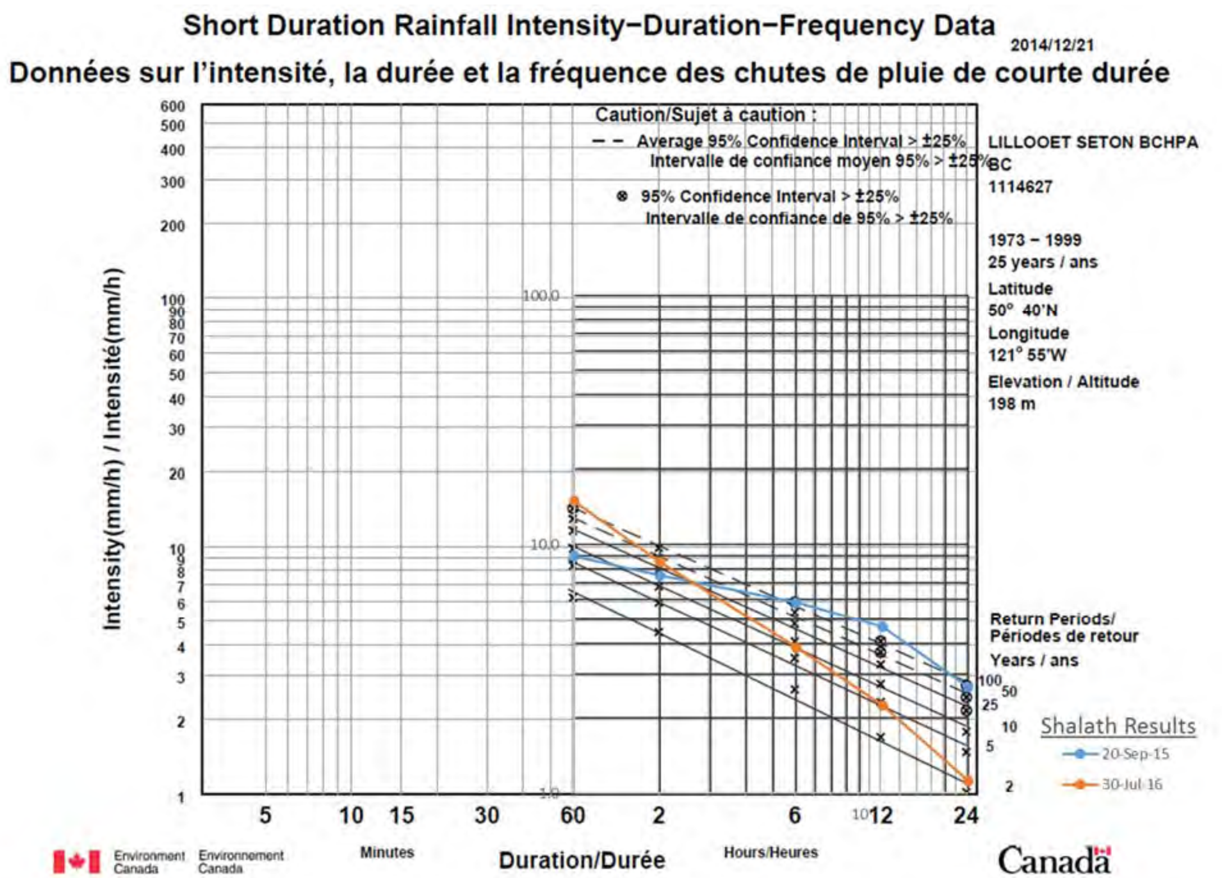

Figure J-5. **IDF magnitudes for the September 20, 2015 (blue) and July 30, 2016 (orange) debris flow events compared to the calculated Lillooet Climate Station records.**

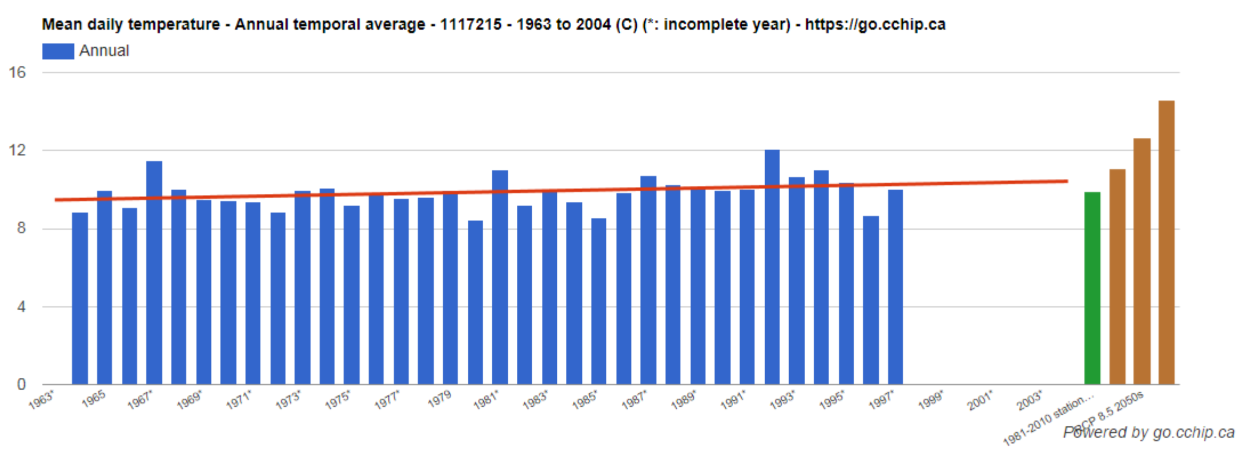

Figure J-6. **Observed and projected changes in mean daily temperature at Seton Portage to the 2080s for RCP 8.5.**

J.5. HIGH INTENSITY RAINFALL CHANGES

In a recently published paper, Prein et al. (2016) note that extreme precipitation intensities have increase almost everywhere in the conterminous United States and that the increases can be scaled, roughly, to 7% increases were degree C, in accordance with the co-called Clausius-Clapeyron relationship. However, scaling rates depend strongly on temperature and moisture availability. Prein et al.'s work showed that in areas with high moisture content and energy-limitation rainfall intensities are particularly high. In contrast, they decrease abruptly in dry, moisture-limited environments. Fortunately, Prein et al.'s work includes mapping that reaches into the southern portions of Canada and some general conclusions can be gleaned for the present study area. For details on the method the reader is referred to the original paper. Their results are projected to a 95-year ensemble monthly mean climate change signal from 19 coupled model intercomparisons and are as follows:

- Hourly extreme rainfall intensity has been increasing for the summer months (June/July/August) by over 30%.
- The exceedance probability of extreme rainfall intensities during the summer months will increase by approximately 200%. This implies a three-fold increase in the probability of extreme rainfall intensities.

The reason for the increase is a climate-change-induced shift of extremes-producing environments to moister and warmer conditions. The close presence of Anderson and Seton Lakes may further enhance the available moisture and lead to more vigorous convection.

J.6. LONG TERM CHANGES

Climate has always changed and will continue to change in British Columbia. The fundamental difference now as opposed to any climate changes of the past is that climate change is driven by human greenhouse gas emissions and the rate of change is faster than what was observed in the past (IPCC, 2014). Figure J-7 summarizes climates in BC over the past 12 thousand years as compiled by Friele et al. (2017). It contextualizes temperature and precipitation during the Holocene era with respect to possible future changes. As noted in Figure J-7, this implies a high likelihood that geomorphic processes will change in unison with higher precipitation intensities.

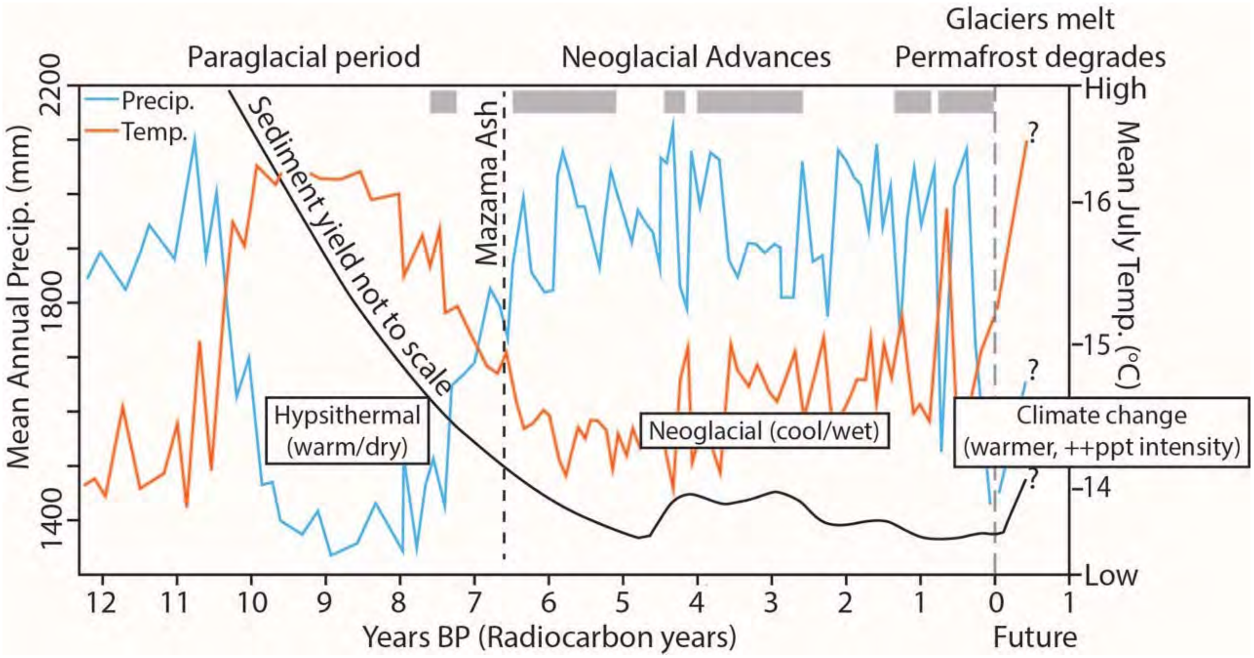

Figure J-7. Sediment yield in relation to past and future climate and associated geomorphic drivers. Compiled by Friele et al. 2017.

J.7. SUMMARY

This preliminary analysis has shown that there is little evidence for notable trends in monthly rainfalls from May to September, nor do predictions suggest that rainfall during those months will increase. An exception is May where an upward trend has been identified and which appears to continue based on global circulation model predictions. Hourly rainfall intensities, however, are predicted to increase in both magnitude and frequency for the study area. These predicted changes will both increase the frequency and volume of debris flows on Bear Creek although the magnitude of such changes cannot be predicted with confidence.

Significant increases in temperatures are expected by the 2080s for RCP 8.5. Those will shift the timing of spring runoff and are likely to melt ice should permafrost prevail in the upper Bear Creek watershed. Such melt could result in an increase in the frequency and magnitude of debris flows, though this conclusion is still somewhat speculative.

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