THREE SISTERS CREEK DEVELOPMENT

Three Sisters Creek Hazard Assessment Update

Final Rev. 2
October 9, 2020

BGC Project No.:
1531003

Prepared by BGC Engineering Inc. for:
Three Sisters Mountain Village Properties Ltd.
c/o QuantumPlace Developments Ltd.

TABLE OF REVISIONS

ISSUE	DATE	REV	REMARKS
DRAFT	May 26, 2020		Original issue
FINAL	June 12, 2020	0	Final issue
FINAL	August 28, 2020	1	Revised issue
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LIMITATIONS

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EXECUTIVE SUMMARY

Three Sisters Mountain Village Properties Ltd. (TSMV) wishes to construct a comprehensive, mixed use development to the west of Three Sisters Creek. A small portion of the proposed development area is potentially at risk from debris floods. QuantumPlace Developments Ltd. (QPD), who is an authorized agent of TSMV, retained BGC Engineering Inc. (BGC) to assess debris-flood hazards on Three Sisters Creek alluvial fan.

Although debris-flood hazards and risks on Three Sisters Creek were previously assessed by BGC in 2014, the assessment assumed that the western portion of the fan would remain an undeveloped golf course. In accordance with the Town of Canmore's Mountain Creek Hazard Mitigation Program (Town of Canmore, 2016), the additional proposed development (i.e., the Resort Center ASP) on the western portion of the fan warrants updating of the hazard and risk assessment.

The present assessment includes three elements that had not been considered by BGC in 2014 as science had not advanced to include those satisfactorily. First, the current assessment considers the tendency of debris flood-prone creeks to erode their banks during high discharge. Bank erosion, when intercepting built environments, can lead to substantial damage as documented particularly along Cougar Creek in Canmore during the June 2013 floods. Second, long-term aggradation (accumulation of sediment in stream channels) can, over time, reduce the capacity of a channel to convey water. In the absence of a sediment-removal program, this can increase the likelihood of channel avulsions. An avulsion is defined as the sudden formation of a new channel that flows along a different path than the existing channel. In the case of Three Sisters Creek, an avulsion may travel into portions of existing or proposed development on the creek fan and immediately adjacent areas. Third, climate change will increasingly impact hydrological processes. Recent advances in our understanding on the effects of climate change allow predictions on changes in peak flow and changes in expected sediment transport due to an increase in extreme rainfall.

To assess the hazards posed by these geomorphic and climatic processes, BGC conducted three separate analyses. First, the amount of bank erosion was estimated probabilistically for return periods extending up to a 1000 to 3000-year return period event. Second, BGC estimated the volume of debris that could accumulate in the channel as a result of a sudden, event-related pulse of sediment, as well as the potential amount of long-term aggradation. To simulate the effects of aggradation (which are associated with substantial uncertainties), BGC modeled aggradation using post-2013 event lidar (October 2013). Third, peak flow estimates were adjusted to account for the effects of climate change using predictive tools. This was followed by numerically simulating debris floods for all return periods, aggradation and avulsion scenarios. The results demonstrate that the western (yet undeveloped) fan portions are affected substantially less than the eastern (currently developed) fan portions. This is likely attributable to the western portions being topographically higher than the eastern portions. The modeling re-emphasizes the need to protect the currently developed areas from debris flooding in a comprehensive mitigation strategy.

The findings from the current report will form the basis for the proposed option analysis to identify the optimal combination of mitigation works that fulfill the key mitigation objectives.

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1. INTRODUCTION

1.1. Background

Three Sisters Mountain Village Properties Ltd. (TSMV) wishes to construct an expansive, mixed-use resort village partially located on the western portion of Three Sisters Creek alluvial fan, Canmore, Alberta. Figure 1-1 shows a conceptual map of the proposed development area, which is partially located within the Three Sisters Creek fan.

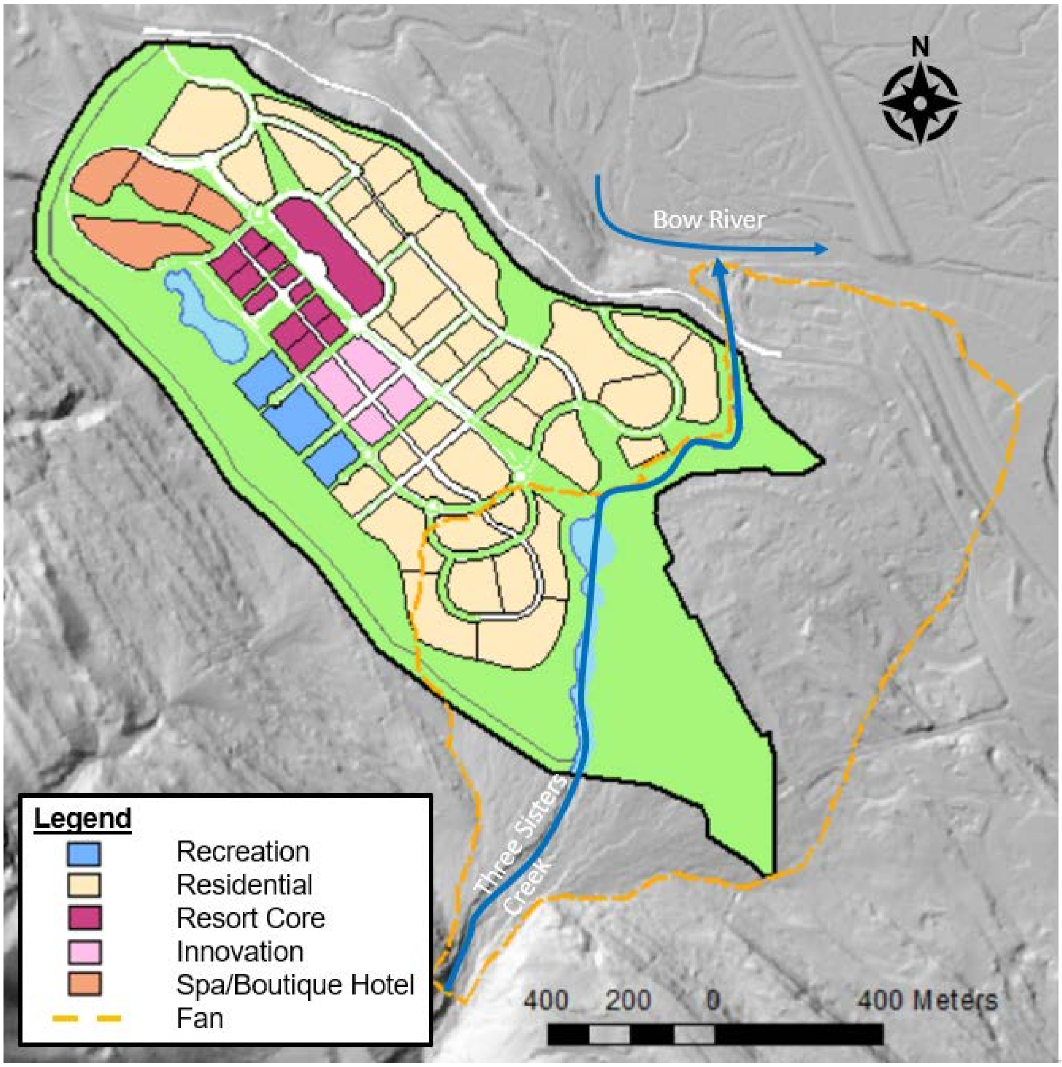

Figure 1-1. Proposed development area within the Three Sisters Creek fan (dashed orange line).

Parts of the proposed development area may be exposed to debris-flood geohazards. In June 2013, Three Sisters Creek experienced a debris flood resulting in damage to the existing, partially completed golf course infrastructure (pedestrian bridge, pond), and roads (Three Sisters Parkway and an access road) in the proposed development area (BGC, December 11, 2013). In response to the June 2013 event, the Town of Canmore (Canmore) retained BGC to complete a hazard and risk assessment on Three Sisters Creek (BGC, October 31, 2014; January 20, 2015).

The 2014 BGC hazard and risk assessment considered the existing development on the eastern portion of the fan but did not explicitly include the proposed development on the west side of Three Sisters Creek. The hazard and risk assessment showed that the western side of the fan generally has a lower likelihood of hazard impact than the eastern (developed) side due to its higher elevation than the eastern fan portions. However, the analysis did not attempt to quantify bank erosion, forced avulsions and climate change as neither had advanced to a scientifically satisfactory state at the time of BGC's reports (BGC, October 31, 2014; January 20, 2015). Since the 2014 study, methods have been developed by BGC and Davidson and Eaton (2018) to estimate bank erosion in steep creeks and to quantify the effects of climate change on runoff and sediment transport. The methods and calibration are explained in Section 3.4

In accordance with the Town of Canmore's Municipal Development Plan and Land Use Bylaw (Canmore, 2016; 2018), the additional proposed development on the western portion of the fan warrants updating of the hazard and risk assessment. To address this, QuantumPlace Developments Ltd. (QPD), an authorized agent of TSMV, requested that BGC provide an updated hazard and risk assessment for the proposed development.

1.2. Scope

BGC provided a proposal to QPD for an updated hazard and risk assessment on March 29, 2018. The proposed scope of work included the following tasks:

- Identifying and modeling new hazard scenarios for potential long-term aggradation and avulsions on the upper western fan portion and bank erosion along Three Sisters Creek that include considerations for climate change.
- Conducting a quantitative risk assessment (QRA) for individuals and for new development (the Resort Centre Area Structure Plan (ASP) amendment) using the new aggradation, avulsion, and bank erosion scenarios. Providing an updated group (societal) risk assessment for the Three Sisters Creek consultation zone.
- Developing and modeling conceptual risk reduction measures for the proposed Resort Centre ASP on the western portion of Three Sisters Creek fan and areas beyond that may be subject to flooding, as necessary pending the results of the risk assessment.
- Conducting a post-mitigation residual risk assessment for mitigation options.

The scope was revised during an in-person meeting with QPD attended by Drs. Matthias Jakob and Sarah Davidson of BGC on June 14, 2018. A residual risk assessment will be required for the proposed development following the selection of an appropriate mitigation system in the next phase of work. An amended work plan is provided in Table 1-1.

Table 1-1. Detailed work plan for updated hazard assessment.

Task	Description	Deliverables
1. Project Management	-	Client communication, cost control, scheduling.
2. Hydrologic assessment and climate change modeling	Apply recently developed methods to assess changes in runoff and sediment volumes.	Updated frequency-magnitude analysis of sediment volumes and peak flows
3. Development and modeling of new hazard scenarios (western fan)	Update modeling to include potential long-term aggradation and avulsions on the upper western fan portion.	Runout maps.
4. Bank erosion assessment	Model the potential bank erosion associated with a range of individual extreme flow events.	Erosion setbacks for the range of return periods considered in the original hazard assessment (BGC, October 31, 2014).
5. Development of conceptual mitigation options	Develop mitigation options to reduce the likelihood of avulsions and the predicted erosion magnitude. These options will allow for a reduction in the setback distance of the development.	Conceptual design options.
6. Post-mitigation hazard and risk assessments	Iterative assessments to confirm that mitigation concepts achieve desired hazard reduction.	Modeling runs for a subset of mitigated scenarios (pre-screened with QPD to avoid excessive modeling effort). Revised setback distances.
7. Reporting and meetings	Provide draft and final reports summarizing the methods and results of the modeling and providing recommendations for further work in collaboration with QPD. Meet with QPD to discuss scope (already completed) and to present results.	Draft, and Final reports.

On April 21, 2020, BGC and TSMV had another call in which the work program was amended further. This time, it was agreed that the development of conceptual mitigation options be included in an official option analysis report that will form the basis for later pre-design and design stages. Consequently, post-mitigation hazard and risk assessment will be postponed upon completion of the option analysis. The final work plan is summarized in Table 1-2.

Table 1-2. Updated detailed work plan for the updated hazard assessment.

Task	Description	Deliverables
1. Project Management	-	Client communication, cost control, scheduling.
2. Hydrologic assessment and climate change modeling	Apply recently developed methods to assess changes in runoff and sediment volumes.	Updated frequency-magnitude analysis of sediment volumes and peak flows
3. Development and modeling of new hazard scenarios (western fan)	Update modeling to include potential long-term aggradation and avulsions on the upper western fan portion.	Runout maps.
4. Bank erosion assessment	Model the potential bank erosion associated with a range of individual extreme flow events.	Erosion setbacks for the range of return periods considered in the original hazard assessment (BGC, October 31, 2014).
5. Reporting and meetings	Provide draft and final reports summarizing the methods and results of the modeling and providing recommendations for further work in collaboration with QPD. Meet with QPD to discuss scope (already completed) and to present results.	Draft, and Final reports.

This report provides an updated hazard assessment for the Three Sisters Creek fan, particularly in light of proposed development on the west side of the fan. The new hazard assessment aims to assess how the debris-flood hazard will change given:

- A change in channel configuration by the Town of Canmore, compared to the channel as modeled by BGC in 2014
- A change in discharge estimates that include climate change
- The predicted aggradation (accumulation of channel sediments over time or during single events)
- Inclusion of bank erosion in the modeling runs for different return periods

BGC developed representative hazard scenarios and conducted numerical modeling with the new channel topography to examine which portions of the proposed developments could be impacted. The hazard assessment is then juxtaposed with QPD's desire for future development west of the creek that would not be impacted by debris-flood inundation or erosion for the full spectrum of return periods considered, which then informs the type, scale and location of mitigation measures to protect the future development.

2. BACKGROUND

This section provides additional background on Three Sisters Creek including previous work completed, descriptions of the watershed and channel, and an overview of the 2013 debris flood event. More in-depth descriptions are provided in BGC (October 31, 2014).

2.1. Additional Work Completed

2.1.1. BGC (January 17, 2019)

As part of the ASP and the associated planning process, the Town of Canmore asked TSMV to delineate debris-flood hazards of those portions of Three Sisters Creek fan and adjacent areas that could be affected by debris floods of variable return periods, aggradation scenarios and bank erosion. This information would help TSMV undertake its conceptual and development work and help the Town of Canmore to make policy decisions relating to existing and future land use in the areas potentially being affected by debris floods and associated secondary effects (flooding and bank erosion).

QPD requested that BGC produce a drawing showing the extents of a 1000 to 3000-year return period debris flood on Three Sisters Creek using the conservative assumption of unmitigated and complete channel filling over time. QPD also requested BGC to prepare this memo and preliminary mapping to aid the Town of Canmore in identifying potential steep creek study area overlay for their land use.

BGC completed the above assignment (BGC, January 17, 2019) and provide the requested map as Drawing 01 in their memorandum. This report supersedes the findings and drawing of the BGC (January 17, 2019) report.

2.1.2. BGC (March 22, 2019)

To support the understanding of possible mitigation option and their impact on peak flows, BGC provided TSMV with draft model scenarios for conceptual-level mitigation structures summarized in a PowerPoint presentation in March 2019. This presentation was made available to TSMV. BGC's analysis demonstrated that with the proposed mitigation works (widened channel, deflection berms and slightly increased golf course pond capacity) significant increases to peak flows at infrastructure on the fan can be expected. Specifically, BGC concluded that with the fully mitigated assumption, the flows at the Three Sisters Creek footbridge and Three Sisters Parkway would be doubled to 240 m^3/s for the 1000 to 3000-year return period debris flood. For the footbridge, the 1000 to 3000-year return period event would exceed its capacity (120 m^3/s) by a factor of 2, while the culvert's capacity (24 m^3/s) would be exceeded by a factor of 10. These findings emphasized that the culvert beneath Three Sisters Creek Parkway is undersized for all debris-flood return periods considered, emphasizing its vulnerability to debris-flood impact.

However, the present report supersedes the discharge estimates and findings from this preliminary March 2019 work.

2.2. Study Area

Three Sisters Creek is located approximately 4 km southeast of downtown Canmore and flows north toward its confluence with the Bow River. Important site characteristics are detailed in the sections below. Drawings in the previous hazard assessment report (BGC, October 31, 2014) include outlines of the watershed and fan area as well as geomorphic mapping that were not duplicated for this hazard assessment update.

2.2.1. Watershed Description

The mainstem channel of Three Sisters Creek above the fan apex is deeply incised into a thick sequence of glacial sediments. The Quaternary deposits were largely deposited between 18,000 to 12,000 years before present in the waning stages of the last glaciation and likely supply significant sediment to the channel during debris flood events due to undercutting and upslope failure.

Additional sediment sources also exist in the higher alpine areas (exceeding approximately 2200 m elevation) in the form of talus slopes and colluvial cones. However, alpine denudation rates appear to be low as judged from the limited extent of talus slopes below bedrock cliffs. This observation suggests that most of the erodible sediment is being recruited from the lower channel reaches between elevations 1500 and 1900 m. The lower reaches of the creek, upstream of the fan apex, are incised several tens of meters into a thick sequence of late Pleistocene sediments that are actively raveling or slumping into the main and tributary channels of Three Sisters Creek. Deeper seated slumps along the late Pleistocene sediments may cause very shallow, short-lived (minutes to tens of minutes) dams that may result in some surging behavior once they are overtopped but are not expected to generate peak flows in excess of modeled debris floods. Test pits and natural channel exposures are indicative of such surges as they show very little to no sorting, imbrication and bedding. This finding also suggests high sediment concentration which is important as it facilitates further sediment entrainment and transport.

2.2.2. Alluvial Fan

The Three Sisters Creek fan spans an area of 1.33 km^2. Table 2-1 summarizes the key characteristics of the fan. Three Sisters Creek is a steep creek with gradients around 9% on the fan upstream of the golf course pond. It is subject to debris floods, and possibly hyperconcentrated flows (see Appendix A for a description of hazard types). Channel gradients along the mainstem of Three Sisters Creek are marginally steep enough to convey a debris flow upstream of the fan apex. At upstream gradients of 13%, a debris flow, even if fine-grained through entrainment of lateral glaciofluvial sediments and till, would most likely rapidly dilute downstream of the fan apex and evolve into a debris flood. In absence of field evidence indicating past debris flows near or upstream of the fan apex, no attempt was made by BGC to model debris flows.

Table 2-1. Watershed and fan characteristics of Three Sisters Creek.

Characteristic	Value
Watershed area[1] (km^2)	9.6
Fan area (km^2)	1.33
Maximum elevation (m)	2,890
Elevation at fan apex (m)	1,470
Average gradient mainstem (%)	13
Average gradient on fan (%)	8
Fan channel length (m)	1700
Total fan relief (m)	185

Note:

1. As measured to the fan apex.

For the purposes of the current work, the fan can be divided into three sections (Drawing 01):

- Upper Fan: the forested (undeveloped) portion of the fan extending from the fan apex to the southernmost extent of the proposed development.
- Middle Fan: the sparsely vegetated portion of the fan that extends from the southernmost extent of the proposed development to the north end of the golf course pond.
- Lower Fan: partially bedrock-controlled reach extending from the north end of the golf course pond to the Bow River. This reach is developed on the east side of the channel, with approximately 200 homes and commercial buildings constructed as of 2020.

Significant channel works were carried out during construction of the golf course in 2007, including extensive riprap placement along the channel banks and the addition of several grade control structures constructed from Class 3 or 4 riprap. The riprapped channel discharges into an approximately 8,000 m^2 surface area pond with a total water storage volume of about 40,000 m^3, which had previously functioned as a gravel pit. However, the riprapped channel upstream of the pond was destroyed during the June 2013 debris flood event and the pond was 75% infilled with sediment[1].

At the outlet of the pond, Three Sisters Creek is spanned by an access road bridge that also carries AltaLink high voltage transmission cables across the creek (labeled as the "AltaLink Bridge" on Drawing 01). Downstream of the pond, within the Lower Fan, the creek follows the northwestern boundary of the fan and is largely bedrock-controlled, with an average gradient of 7%. The creek meanders for about 600 m through an undeveloped portion of the fan before crossing under a pedestrian bridge along Three Sisters Pathway (Drawing 01). According to previous work, the capacity of the pedestrian bridge is approximately 120 m^3/s (BGC, October 14, 2016). About 120 m downstream of the pathway, Three Sisters Creek discharges into an approximately 50 m long concrete box culvert under the Three Sisters Parkway. The culvert has

[1] This sediment has since been removed by TSMV and other channel works have been installed in stages by the Town of Canmore (discussed further in Section 2.2.3).

an estimated capacity[2] of 23 m^3/s (BGC, October 14, 2016). From the culvert outlet, the creek continues for a further 175 m before discharging into Bow River (Drawing 01). Works to repair erosion and damage caused by the 2013 event upstream and downstream of Three Sisters Parkway were undertaken in 2018. This work included adding riprap and stone pitch walls as well as re-seeding the upper slopes of the banks for an approximate 400 m length of channel (200 m upstream and downstream of Three Sisters Parkway) (SweetTech Engineering Consultants, October 5, 2018). These repairs did not significantly alter the capacity of the channel but improved bank erosion protection (email from Felix Camire, personal communication, March 3, 2019).

2.2.3. Overview of the June 2013 Debris Flood

This section provides a description of the damage sustained during the June 2013 flood event, which occurred in response to a large precipitation event that occurred between June 19 and 21, 2013. The storm was an extremely rare event because of its long duration and large amount of associated total rainfall. According to BGC's detailed assessment of the hydroclimatic conditions during the event (BGC, August 1, 2014) the 1-day, 2-day and 3-day rainfall totals for this storm at Kananaskis, the nearest long-term climate station to Canmore, were the highest on record since observations began in 1939. However, the event was not extreme in terms of short term maximum hourly rainfall intensity, and similar intensities have occurred often in the region over the period of record. Antecedent moisture conditions appear to have been high prior to the storm and, combined with observations of frozen soils at higher elevations, suggest that a high percentage of the total rainfall translated into storm runoff.

The storm produced a 3-day flood that caused up to 20 m of channel widening on the mid-fan and up to 28 m of channel widening on the upper fan due to bank erosion along the fan reaches between the golf course pond and the fan apex (the Middle and Upper fan). Significant aggradation also occurred within this section of the fan. Although the aggradation increased the potential for avulsion on the right (east) bank, no avulsions occurred as a result of the event.

In a recent scientific contribution, Church and Jakob (2020, in print) used Three Sisters Creek as an example to illustrate the chronological sequence from a flood developing into a debris flood, then into a damaging and eventually catastrophic debris flood (Figure 2-1). This is based on the ratio of shear stress to critical shear stress. The shear stress is the force exerted by flowing water on the channel bed and banks. A critical shear stress is the stress acting on a grain of given size when the particle is mobilized by flowing water. When the shear stress exceeds the critical shear stress to mobilize large (at least the 80th percentile) grains in the channel, the bed and banks become unstable and begin to be entrained in the rushing water. Banks erode until a new equilibrium channel profile is reached which will be wider and shallower than it was before the flood or debris flood. When most of the bed has become mobile due to high shear stresses, a debris flood is initiated. It differs from a normal flood by its propensity to mobilize and transport large amounts of gravel, thereby changing the channel planform. The higher the ratio between the actual stress acting on the bed and banks and the critical shear stress for the D_{84} (the 84th

[2] The culvert capacity has been reported as several different values by SweetCroft (April 2015), BGC (October 14, 2016), and Felix Camire (personal communication, email March 3, 2019). BGC has chosen 23 m^3/s after a preliminary 1-D assessment but for mitigation design culvert capacity should be assessed in more detail in 2-D.

percentile grain), the more sediment will be moved per unit time. According to Figure 2-1, the "catastrophic" shear stress threshold was reached on June 20, 2013 for approximately 2 hours.

The Golf Course Pond (GCP) was filled to 75% by sediment, which meant that no sediment was transported through and past the GCP as bedload. All bedload mobilized downstream was derived from sources between the pond and Bow River. As there are bedrock-controlled reaches downstream of the GCP, the amount of mobilizable sediment was limited.

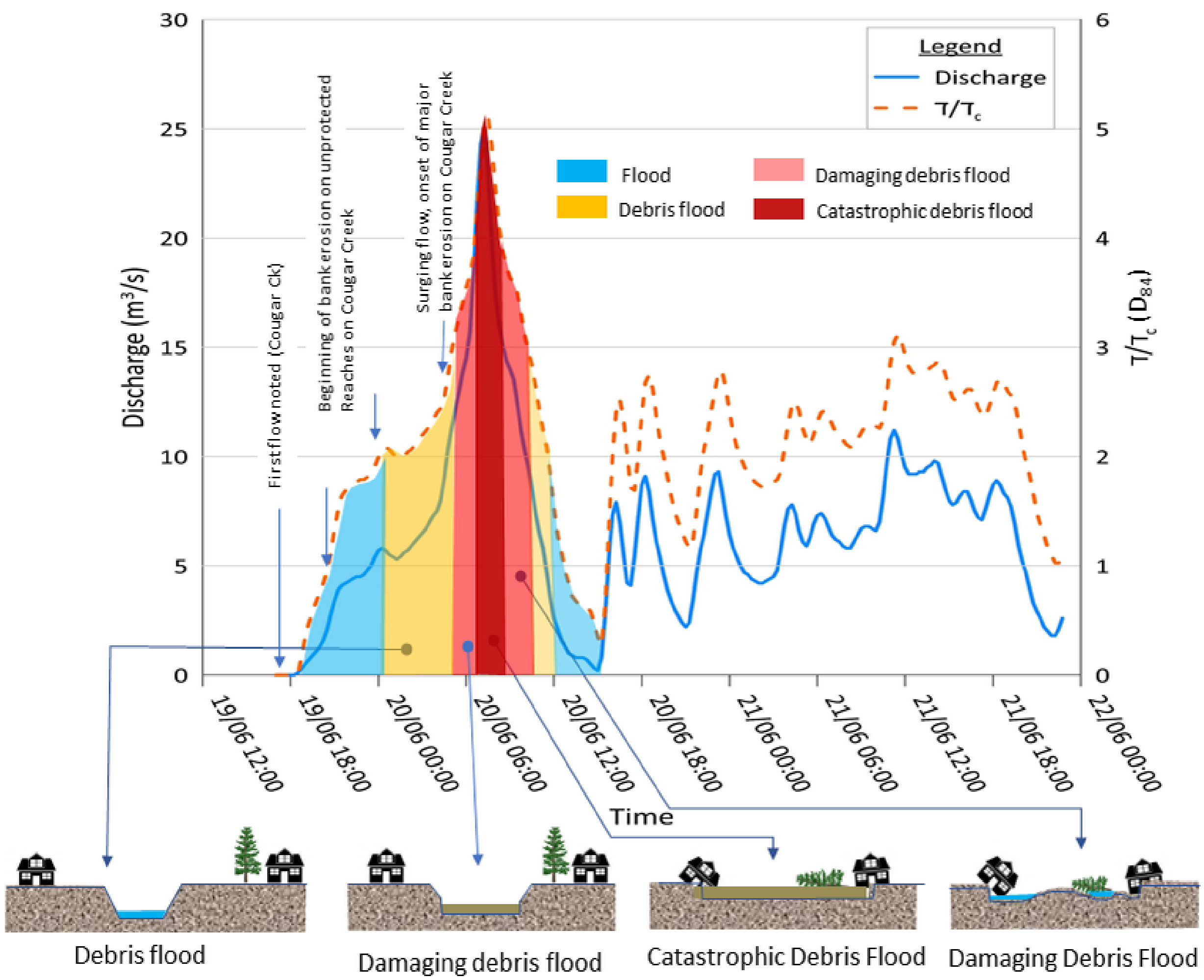

Figure 2-1. Hydrograph and shear stress ratio of the June 19-21, 2013 debris flood on Three Sisters Creek. Timing of damage is reported for Cougar Creek on the North Side of the valley for illustrative purposes. Only the first part of the storm is classified for example purposes. Debris flood stages are indexed by the shear stress ratio t/tc (from Church and Jakob, 2020)

Damages included (Drawing 01):

- Outflanking of the golf course pedestrian bridge upstream of the GCP (labelled as Upper Bridge on Drawing 01) on both banks

- Destruction of all channel works related to the golf course construction (e.g., grade control structures)
- Infilling of the golf course pond to about 75% of its capacity
- Destruction of a culverted access road downstream of the GCP
- Bank erosion and channel incision downstream of the golf course pond, especially downstream of Three Sisters Parkway (Figure 2-2).

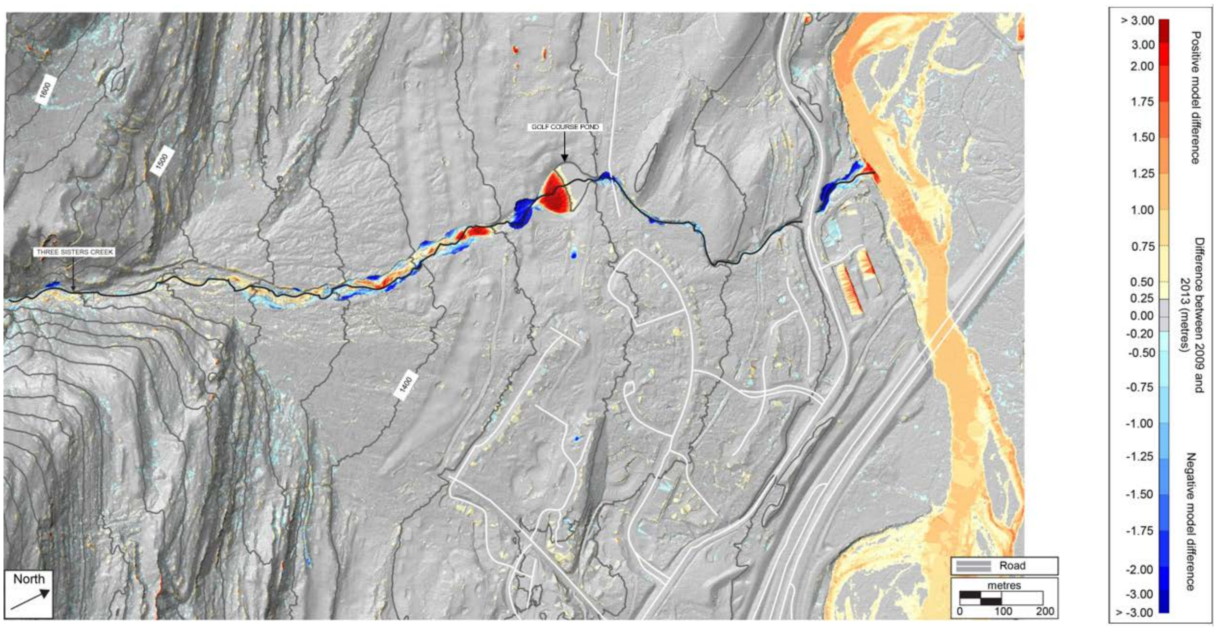

Figure 2-2. Lidar change detection completed using data collected in 2009 and 2013. Data were provided to BGC by Airborne Imaging and McElhanney. Contour interval is 20 m. Change detection results are projected onto triangulated model of 2013 lidar data and are shown with a limit of detection from -0.20 to +0.25 m. This figure is intended as a visual representative and is not provided to match a standard engineering scale. Net erosion is shown in blue and net deposition in red.

In the spring of 2014, the Town of Canmore conducted a mitigation campaign along Three Sisters Creek. The mitigation actions are summarized below:

- Debris was removed from the channel, banks, and culverts
- Approximately 36,000 m^3 of sediment was removed from the golf course pond (by TSMV) to restore storage capacity
- Articulated concrete mattresses were installed around the AltaLink Bridge just downstream of the GCP (Figure 2-3). These mattresses were designed to protect the bridge abutments from erosion. Riprap was placed at the downstream edge of the mattresses and along the left bank of the channel approximately 80 m downstream of the GCP to protect the bank as the creek turns eastward (Drawing 01)
- Approximately 1,400 m of the creek was re-channelized upstream of the GCP
- The channel was armoured 80 m upstream of the creek outlet to the Bow River to prevent erosion adjacent to the Three Sisters Parkway.

Figure 2-3. View of the golf course pond looking upstream from the AltaLink Bridge. Photo shows re-channelization work upstream of the GCP, as well as the concrete mattress erosion protection around the AltaLink Bridge (immediate foreground of photograph). BGC photograph June 14, 2018.

2.2.4. Proposed Development

BGC understands that the proposed development is limited to the western side of Three Sisters Creek and includes a combination of residential and retail buildings, including detached and multi-unit buildings. The eastern side of Three Sisters Creek, south of Hubman Landing, is proposed to remain as recreational greenspace and no occupied residential structures are planned to be constructed in this area. QPD has expressed an interest is using this green space as a mitigative buffer between the debris flood hazard and the proposed residences if possible but noted that minor buildings such as bathrooms or trailhead facilities may be constructed in the future, along with recreational amenities, pathways or parking lots near Three Sisters Boulevard.

3. HAZARD ASSESSMENT

This section summarizes the results of the debris flood hazard assessment. The methods used in each step of the analysis are outlined briefly within the results sections below, and additional detail about the methods is provided in the following appendices:

- B – Hydrologic Assessment and Climate Change
- C – Bank Erosion Analysis
- D – Numerical Modeling.

3.1. Site Reconnaissance

A site visit was completed by Drs. Sarah Davidson and Matthias Jakob in June 2018. During this field visit, the field team surveyed several cross-sections upstream of the GCP and obtained five Wolman grain size samples along the channel thalweg to inform the bank erosion analysis. The field team hiked upstream to the fan apex and recorded observations on channel and bank stability, and avulsion potential. The field team also hiked downstream from the GCP to the Bow River confluence to assess the erodibility of the channel banks, the distribution of bedrock, and the incision due to the 2013 flood.

3.2. Hydrology and Climate Change

Climate change is increasingly impacting hydrological processes. While climate change is expected to strongly increase temperatures in the future, it is also expected to affect the magnitude and frequency of extreme precipitation events (i.e. Prein et al., 2017). The frequency of extremes predicted to increase approximately 2-fold in southwestern Alberta in June, July, and August (Figure 3-1), (Prein et al., 2017). Changes in short-term precipitation extremes contributes to the frequency and magnitude of debris floods and debris flows.

The climate-adjusted variables are calculated using projections based on the Representative Carbon Pathway (RCP) 8.5 which is one of several models presented by the Intergovernmental Panel on Climate Change (IPCC) (Moss et al., 2008). The RCP 8.5 scenario assumes that only modest technological advances and improvements in energy efficiency are achieved (i.e., “business as usual”) and represents reaching a radiative forcing of 8.5 W/m^2 by 2100. RCP 4.5, which represents a “stabilization scenario” wherein the radiative forcing level stabilizes at 4.5 W/m^2 by 2100 , is also included in the frequency-sediment volume assessment presented below.

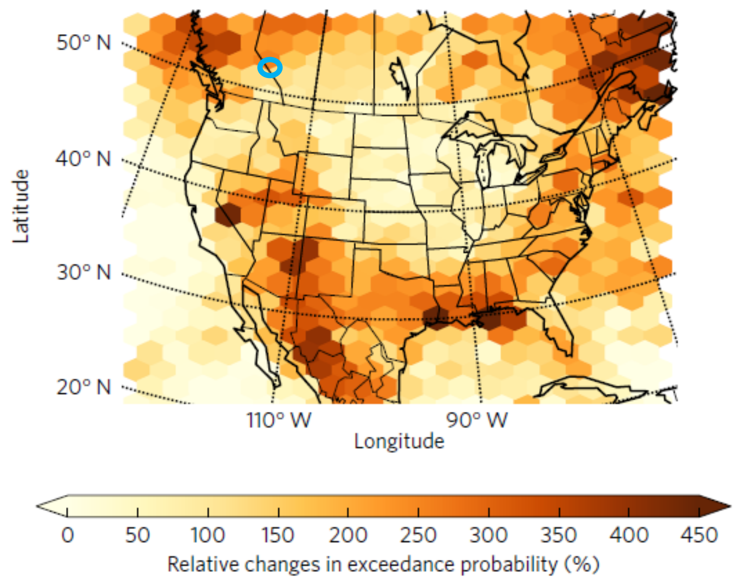

Figure 3-1. Change in the exceedance probability of hourly precipitation intensities for June, July, and August (Prein et al, 2017). The area of interest is circled in blue.

In this section, BGC focuses on two aspects: First, the projected changes in peak flows, and second, the associated volumes of sediment being transported. Peak flows are important for numerical modeling and all aspects of mitigation work design. Total sediment volume is important as it provides an understanding of the capacity needed for any sediment storage facilities such as debris basins.

3.2.1. Projected Changes in Peak Flows

Hydrologic analysis is a fundamental input into the assessment of credible hazard scenarios, as streamflow governs the intensity of both clearwater stream processes and hydrogeomorphic events. None of the steep creeks in the Bow Valley are gauged, including Three Sisters Creek. Therefore, BGC conducted rainfall-runoff modeling to predict peak discharge for return periods ranging from 10 to 3000 years. Modeling was completed using HEC-HMS (Version 4.3), a software developed by the US Army Corps of Engineers. Details of the analysis are provided in Appendix B.

Immediately following the 2013 debris flood event, BGC (October 31, 2014) measured three cross-sections above the fan apex where high-water marks were obvious. Back-calculation of the peak discharges associated with these high-water marks resulted in estimates ranging between 20 and 25 m^3/s (Appendix B). Hourly rainfall associated with the June 2013 storm was then input to the HEC-HMS model and model parameters adjusted until the model predicted peak discharges in the “observed” range. The calibrated model was then run with 24-hour rainfall totals for storms with return periods of up to 3000 years.

Rainfall-runoff modeling was then repeated for future conditions based on predicted changes to 24-hour rainfall amounts. While climate change is expected to alter temperatures and precipitation in the future, it is also expected to affect the magnitude and frequency of extreme precipitation events (Barnett, Brown, Murphy, Sexton & Webb, 2006; Wilcox & Donner 2007; Allan & Soden, 2008; Solaiman and Simonovic, 2011). Several resources were evaluated by BGC, which resulted in predicted increases in 24-hour rainfall of 20 to 30%. The higher value was selected for conservatism.

Table 3-1 summarizes the precipitation 24-hour rainfall estimates adopted for the HEC-HMS modeling.

Table 3-1. Summary of the estimated 24-hour rainfall for a range of return periods at the Kananaskis (3053600) climate station. Results are shown for both the current timeframe (based on historical data) and for the future period from 2050 to 2100.

24-hour Rainfall (mm)	Return Period (Years)						
	10	30	100	300	1000	3000	PMP
Existing Conditions	75	100	132	167	213	263	300-400
Climate Change (2050-2100)	100	130	170	215	275	340	

Note:

1. Historical precipitation was estimated using data available for the period from 1940 to 2019 for the Kananaskis (3053600) climate station.

Table 3-2 shows the predicted peak streamflow discharge for each return period event under the current and future timeframes compared to the previous hazard assessment (BGC, October 31, 2014). Slight differences are noted between the 2014 and 2020 peak flow estimates for current conditions, as the rainfall frequency analysis was updated for the 2020 analysis.

Table 3-2. Estimated peak discharge for Three Sisters Creek based on historical precipitation at Kananaskis Climate Station and under possible climate change conditions.

	Units	Return Period (Years)					
		10	30	100	300	1000	3000
BGC (October 31, 2014)	m^3/s	10	-	19	29	42	54
BGC, 2020	m^3/s	2	6	15	27	45	66
2050-2100 RCP 8.5	m^3/s	5	14	30	48	73	102

3.2.2. Projected Changes in Sediment Transport Volumes

During August 21-23, 2005 severe flooding occurred in a large area of northern Switzerland with significant morphological changes in stream channels (Jäggi, 2007). Similar to the June 2013 southeastern Albertan flood, this event was associated with more than 200 mm of rain within three days with corresponding return periods exceeding 100 years. Unlike the flood in southeastern Alberta, there was no snowmelt contribution in the Swiss storm. As many mountain creek hazards have been mitigated by catchment basins, the sediment volumes could be determined.

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 Jaeggi (1992), Recking et al. (2008), and D'Agostino et al. (1996). Rickenmann and Koschni (2010) found reasonable agreements between modeled 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:

$$logV_S = 0.753 logV_R - 0.553,\ \ R^2 = 0.79 \qquad \text{[Eq. 3-1]}$$

$$logV_S = -1.55 + 0.877 logV_R + 0.019S,\ \ R^2 = 0.81 \qquad \text{[Eq. 3-2]}$$

where V_S is the total sediment volume displaced and V_R is the total rainfall. The difference between the two formulae is the inclusion of channel slope S in Equation 3-2. However, since the increase in variance is very small (2%), the effect of slope appears small. Neglecting slope would not be appropriate had the entire dataset been used as that also includes debris flows. Therefore, the formula presented above is only appropriate for debris floods with channel gradients from approximately 2 to 24%.

In addition to the Swiss dataset, BGC created a dataset with 14 creeks in the Bow Valley[3] that experienced debris floods during the June 2013 storm. Sediment volumes deposited on each fan were estimated by comparing 2008 or 2009 lidar to 2013 lidar. Runoff 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 and a linear regression was applied to the combined data which resulted in Equation 3-3, which shows very little difference from the Swiss dataset regression. This combined regression was used in further analyses and yielded the following formula:

$$logV_S = 0.7375 logV_R - 0.4493,\ \ R^2 = 0.78 \qquad \text{[Eq. 3-3]}$$

where V_S is the total sediment volume displaced and V_R is the total runoff volume. The regression analysis of the combined data is shown in Figure 3-2 below.

[3] This analysis was restricted to the general vicinity of Canmore and Exshaw.

As illustrated by Figure 3-2, the rainfall-sediment relation observed in the Bow Valley correlates well with the Swiss dataset. This observation suggests that a relationship between runoff and sediment mobilized is location independent, as similar results were seen in the Rocky Mountains as in the Alps. While this relation appears to be location independent, it has not been verified for temporal or geological independence. It is still unknown as to whether this relation holds for different storms of different magnitudes for individual creeks.

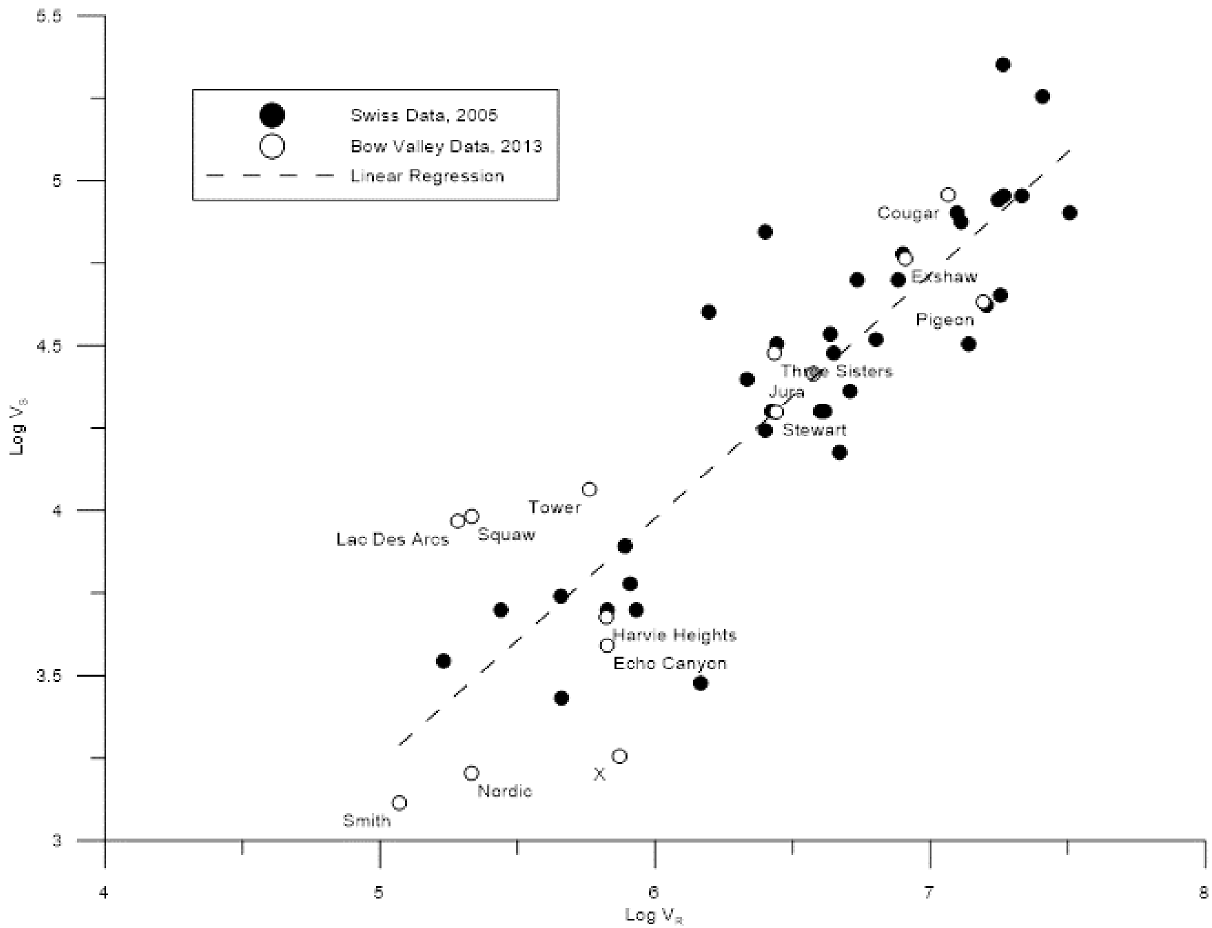

Figure 3-2. Log transformed sediment (V_S) and runoff (V_R) data from the Swiss and Bow Valley datasets complied by Rickenmann and Koschni (2010) and BGC, respectively (from Jakob, Schnorbus & Owen, 2018).

The analysis suggests an increase of approximately 36% in expected sediment volume transported in a 100-year return period 72-hour rainstorm could be expected by the 2080s (2071 to 2100) (see Figure 3-3). This work had not been extended to higher return periods, but assuming the same percentage increase, the new frequency-magnitude data pairs are summarized in Table 3-3.

Figure 3-3. Frequency-sediment volume curve for Three Sisters Creek under baseline (blue) and RCP 8.5 scenarios for the 2050s (yellow) and 2080s (red). The RCP 4.5 and 8.5 for the 2080s are almost identical (blue dashed and red). The grey dashed lines show the confidence bounds for the baseline data (from Jakob et al., 2018).

Table 3-3. Climate change-adjusted debris flood sediment volumes for Three Sisters Creek. Frequency-magnitude data for current climate conditions are from BGC (October 31, 2014). The future climate condition sediment volumes are updated as part of this study.

Return Period (years)	Current Climate Conditions Sediment Volume (m^3)		Future Climate Conditions (RCP 8.5) Sediment Volume (m^3)	
	Best Estimate	Maximum Estimate	Best Estimate	Maximum Estimate
10-30	10,000	13,000	14,000	18,000
30-100	14,000	20,000	19,000	27,000
100-300	18,000	27,000	24,000	37,000
300-1000	22,000	35,000	30,000	48,000
1000-3000	26,000	41,000	35,000	56,000

Table 3-3 suggests that, assuming little is done to curb greenhouse gas emissions in the future, debris flood volumes discharged onto the fan of Three Sisters Creek could reach up to 56,000 m^3 for a 1000 to 3000-year return period event. This is 26,000 m^3 more than the estimated total volume of the June 2013 debris flood (approximately 30,000 m^3). It does not imply that up to 56,000 m^3 would have to be stored, and some residual risk associated with avulsions of some sediment are likely tolerable. This will be the subject of the follow-up option analysis which will be presented under separate cover.

3.3. Channel Aggradation

"Channel capacity" represents the total volume of sediment that can be accommodated by Three Sisters Creek channel between the fan apex and the outlet of the golf course pond (i.e., the Upper and Middle Fan on Drawing 01). In other words, it represents the volume of sediment required to completely infill the constructed channel. To assess channel capacity, BGC used the 2015 lidar (Airborne Imaging, 2015) and "filled" the channel in Muk3D software (Minebridge, 2019). A surface was created between the left and right active banklines delineated from satellite imagery that is approximately parallel to the creek bed, and then the volume difference between the 2015 lidar and surface connecting the banks was calculated by the software (Figure 3-4).

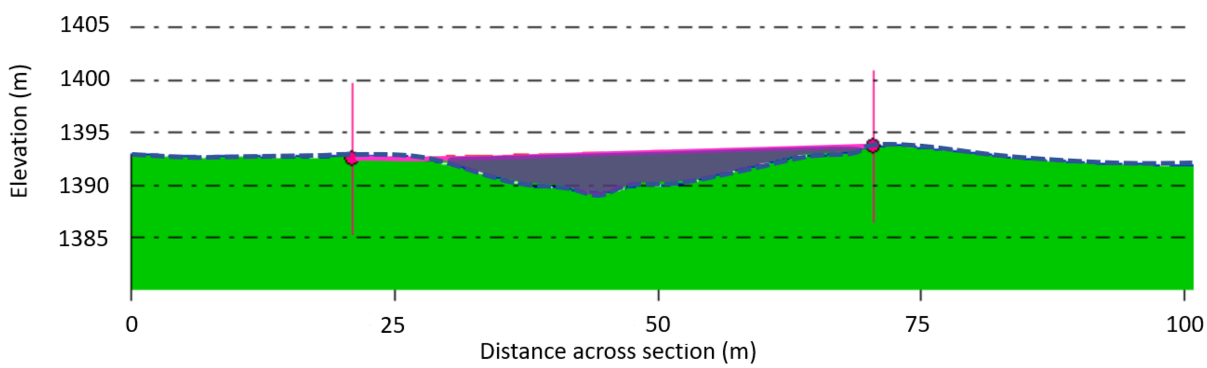

Figure 3-4. Example section of channel used to estimate channel capacity. Blue dashed line is 2015 lidar surface, pink dots show extent of active banks, pink solid line is surface created between active banks, and purple shaded area represents volume between surface.

BGC also used the cross-sections surveyed during the June 2018 fieldwork to validate the channel capacity estimates. The estimates for the total current channel capacity from each method are nearly identical, ranging from 75,000 m^3 to 77,000 m^3. This volume estimate is substantially higher than the estimated 1000 to 3000-year return period debris flood volume with climate change adjustment (56,000 m^3, Section 3.2.2).

The channel capacity estimates only consider the channel itself and do not include additional storage capacity provided by the GCP. 22,000 to 26,000 m^3 of sediment was stored in the GCP as a result of the June 2013 debris flood event (BGC, October 31, 2014), though the pond likely has a total storage capacity of approximately 40,000 m^3. Therefore, the total current channel capacity of Three Sisters Creek between the fan apex and the GCP outlet is approximately 115,000 m^3. It is important to note that this volume estimate is somewhat fictitious in that the capacity of the channel will change as banks erode and the eroded sediment becomes part of the debris flood.

Avulsions involve the formation of a new channel on the floodplain or fan surface, often in unpredictable locations, and pose a hazard to development. Avulsions typically occur when the water surface elevation exceeds bank and may be triggered by channel blockages (e.g., woody debris) that locally raise water level or by bed aggradation. To assess the hazard related to avulsions on the Three Sisters Creek fan BGC used the best available proxy for a strong aggradational event which is the June 19 to 21, 2013 debris flood. The logic is that this event mimics either a single large event or sediment accumulation over time. Other geometrical methods were attempted but there is too much uncertainty involved in predicting where aggradation and erosion occur to rely on such analyses. Using the immediate post-2013 event topography as a surrogate for short- and long-term aggradation assumes that no mitigative measures are taken to increase channel capacity. While this may appear unlikely, it is possible that in a substantial event (like the June 2013 event) there is insufficient time to recreate channel capacity prior to another storm given that numerous creeks in the area will also have been aggraded. Assuming substantial aggradation is thus a conservative assumption leading to conservative runout results compared to using the present (2015) channel topography.

3.4. Bank Erosion

In addition to potential damage from the inundation of fans with water and debris, debris floods damage infrastructure through bank erosion due to the high shear stresses exerted on stream channel beds and banks. In the Bow Valley, the steep creek banks on fans consist predominantly of unconsolidated, loose, and non-cohesive sandy gravels. Removal of trees along Three Sisters Creek during construction of the golf course has also limited the bank strength from vegetation along the channel, which is an important source of apparent cohesion in coarse-grained creeks. The combination of non-cohesive bank material with little root strength makes the banks of Three Sisters Creek particularly susceptible to bank erosion, as evidenced by the extensive erosion that occurred during the June 2013 debris flood (Figure 3-5).

Figure 3-5. Aerial view of Three Sisters Creek looking downstream. The Upper Bridge was outflanked on both banks during the June 2013 debris flood. BGC photograph of July 23, 2013.

BGC analyzed the potential for bank erosion along Three Sisters Creek with two methods: a historical assessment of air photos and satellite imagery and a probabilistic numerical modeling approach. Each of these methods is described in detail in Appendix C and summarized in the following sections.

3.4.1. Historical Imagery Analysis

BGC georeferenced several years of air photos and satellite imagery dating from 1947 to 2015 in a geographic information system (GIS). The imagery was used to identify changes in the size and location of the Three Sisters Creek channel over time. The channel banks were also delineated for eight of the photo years to facilitate measurements of channel width throughout the fan.

Drawing 02 shows the air photos and satellite imagery used in the analysis and a detailed description of channel observed changes is provided in Appendix C. Although the channel location remained relatively consistent throughout the period of air photo record (Drawing 02), it appears that a large debris flood occurred sometime prior to the first air photo in 1947. This event is evidenced by a partially revegetated avulsion channel on the right (east) side of the floodplain. The avulsion diverted flows toward the existing development on Hubman Landing. Judging from the degree of re-vegetation in the avulsion channel this event may have occurred decades before the air photograph and was possibly associated with a storm in 1923 which caused the second highest discharge at the Bow River at Banff hydrometric station.

Table 3-4 summarizes the average channel width in each of the imagery years shown in Drawing 02. There is evidence of several debris flood events from 1947 to 2015, though no new avulsion channels formed throughout the remainder of the period. Channel widening and deposition were observed in the 1975 and 1997 air photos, suggesting that small debris floods may have occurred between 1962 and 1975, and between 1984 and 1997 (Table 3-4).

Table 3-4. Summary of changes in channel width in the Upper, Middle, and Lower Fan over time. Years with widening are presented in bold.

Image Year	Average Width (m)		
	Upper Fan	Middle Fan	Lower Fan
1949	18	25	-
1962	21	21	5
1975	**24**	**28**	**4**
1984	11	9	5
1997	**10**	**24**	**5**
2008	8	16	4
2013	**36**	**37**	**6**
2015[1]	39	45	7

Note:

1. Increased width from 2013 to 2015 is attributable to in-stream mitigation works (e.g. channelization upstream of the GCP) rather than a debris flood event.

The largest debris flood in the historic record occurred in June 2013. The 2013 event caused considerable bank erosion throughout the Upper and Middle sections of the fan (Table 3-4) and also resulted in extensive damage to infrastructure (Section 2.2.3). Drawing 03 shows the channel before and after the event, as well as following post-flood mitigation in 2015. The channel width increased close to five times in the undeveloped Upper Fan, and more than doubled in the Middle Fan, which was already wider prior to the event due to vegetation removal and construction of the golf course (Table 3-4). The 2013 debris flood did not produce any new avulsions or reactivate the pre-existing avulsion channels on the east side of the fan. This is likely attributable to the presence of a berm, which was constructed between 1997 and 2008[4], along the right (east) bank at the upstream end of the historical avulsion (Drawing 01).

The channel is significantly narrower in the Lower Fan than in the Middle Fan or Upper fan in all image years; the channel displayed a consistent average channel width of 4 to 5 m throughout the period from 1962 to 2008 in the reach extending from the GCP outlet to Three Sisters Parkway. Although the channel width increased by 50% as a result of the 2013 flood, this only represents average erosion of 2 m throughout the part of the Lower Fan adjacent to the proposed

4 TSMV reports that this creek mitigation work was designed by Alberta Urban Municipalities Association and installed in the early 2000's.

development, which is within the 5 m measurement error associated with the historical imagery analysis.

The relative stability and narrow channel width in the Lower Fan reflects the strength of the bed and bank material throughout the reach, which is composed intermittently of till and bedrock with a thin veneer of alluvial materials (Figure 3-6). Drawing 03 shows the location of till or bedrock outcrops identified during the June 2018 site investigation, as well as the locations that experienced the greatest erosion in 2013.

Figure 3-6. Bedrock outcrop on the left side of the channel in the Lower Fan. BGC photograph of June 14, 2018.

3.4.2. Probabilistic Numerical Modeling

BGC used a probabilistic, physically-based model to predict the amount of bank erosion that could occur during a single event (see Appendix C for a detailed description). The model is based on experiments conducted by Eaton, MacKenzie, Jakob, and Weatherly (2017) and relies on the following assumptions:

- Bank erosion occurs when the coarse material on the channel bed is fully mobilized, as the bed destabilizes leading to undercutting the banks and rapid retreat.
- The threshold for erosion can be defined in terms of the critical shear stress, τ_c required to fully mobilize the coarse fraction (D_{84}) of the bed material.

- Erosion occurs rapidly during a single debris flood and proceeds until the flow depth reaches the critical value, leading to re-stabilization of the D_{84} and prevent further widening. As a result, the magnitude of bank erosion can be predicted based on flood discharge.

The modeling was conducted using a probabilistic (or stochastic) approach where variability is introduced into model inputs (e.g., grain size, channel gradient, channel roughness) and a series of Monte Carlo simulations are conducted. Additional model details are presented in Appendix C.

BGC calibrated the model using the imagery analysis presented in Section 3.4.1; the model was adjusted to approximately match the measured erosion in the 2013 event, which had a return period of approximately 300 years. The modeled erosion of 25 m for the 100 to 300-year return period debris flood (Table 3-5) approximates the observed erosion of 28 m on the Upper Fan and 20 m on the Middle Fan. The calibrated model was then used to estimate bank erosion for each return period event using the bulked peak discharge estimates for both the current timeframe and the RCP 8.5 climate change scenario. The modeling was conducted for the coarse-grained Upper Fan and Middle Fan reaches which have little bank cohesion. The model was not used for the Lower Fan as the till and bedrock provide resistance to erosion, thereby limiting the potential for channel widening during debris flood events.

The predicted erosion based on climate change adjusted (i.e., 2050-2100) hydrologic conditions is presented in Table 3-6. The median (i.e., 50% probability of exceedance) predicted erosion is also shown as corridors on Drawing 05a and 05b. A 95th percentile means that there is only a 5% or lesser chance that the bank erosion as indicated will be exceeded. Similarly, a 5th percentile implies that there is a 95% chance that the indicated bank erosion will be exceeded. Hence, for a 10 to 30-year debris flood, the most likely bank erosion is 6 m, though it is unknown if this occurs on one bank or on both with different proportions (e.g., 2 m on the west side, 4 m on the east side). There is a 5% chance the total erosion will only be at least 2 m, but also a 5% chance that it will be greater than 11 m.

Table 3-5. Summary of predicted erosion for the current (i.e., historical) hydrological conditions. The bold row indicates the event used to calibrate the bank erosion model.

Return Period (Years)	Bulked Peak Discharge (m^3/s)	Predicted Erosion (m)				
		5%[1]	25%	50% (Median)	75%	95%
10-30	6	0	0	0	0	0
30-100	16	3	5	6	8	11
100-300	**28**	**17**	**21**	**25**	**29**	**36**
300-1000	50	52	61	69	78	92
1000-3000	73	73	84	94	105	124

Note:

1. The percentages represent the probability of non-exceedance. For example, there is a 5% probability that erosion will not exceed the 5% predicted erosion and a 95% probability that it will exceed this value.

Table 3-6. Summary of predicted erosion for the year 2050 to 2100 under the RCP 8.5 climate change scenario. "Median" can be interpreted with the "most likely" scenario.

Return Period (Years)	Peak Discharge (m^3/s)	Predicted Erosion (m)				
		5%[1]	25%	50% (Median)	75%	95%
10-30	15	2	4	6	8	11
30-100	32	20	25	29	34	41
100-300	50	40	49	55	62	74
300-1000	80	84	98	110	122	143
1000-3000	112	121	141	156	173	202

Note:
1. The percentages represent the probability of non-exceedance. For example, there is a 5% probability that erosion will not exceed the 5% predicted erosion and a 95% probability that it will exceed this value.

Drawing 05a and 05b show the predicted bank erosion corridors. A bank erosion corridor is not to be interpreted as the total bank erosion as per Table 3-6 as it is not known on which side of the channel bank erosion will occur. In some cases, the elevation of the surrounding topography can be used to predict the distribution of bank erosion; laboratory experiments have shown that more erosion is likely to occur on the lower elevation side of the channel, as a smaller volume of bank material must be eroded to produce the same erosion distance (Bufe, Turowski, Burbank, Paola, Wickert, & Tofelde, 2019). However, in the case of Three Sisters Creek, the difference in bank elevation is sufficiently small that it is not possible to predict the distribution of bank erosion based on the topography. To reflect this uncertainty, Drawing 05a and 05b show the total predicted erosion on either side of the channel.

QPD has specified a desired maximum setback distance of 20 m, which flow events with return periods exceeding 100 years have a high likelihood of exceeding. This implies that for events of return periods in excess of 30 to 100-year return period, bank erosion could reach the desired setback. To maintain such setback, mitigation works are needed.

3.5. Numerical Debris Flood Modeling

BGC modeled debris floods numerically to estimate the extent and intensity of inundation associated with debris flood hazard scenarios on Three Sisters Creek. To determine realistic modeling scenarios, BGC needed to account for:

- Expected long-term or short-term aggradation of the channel bed typically observed during debris floods.
- Possible avulsions associated with log jams or other debris blockages.
- Sediment and woody debris bulking the peak discharge

It is not possible to model all possible permutations as they are quasi-infinite. Instead, BGC chose scenarios that are thought to be representative, as summarized in Table 3-7. Peak discharges include a bulking factor to represent the sediment and woody debris volume likely entrained in the flow. Higher return periods have higher bulking factors as a higher proportion of debris would be entrained from side slope landslides upstream of the fan apex. Although debris volume is important for some types of mitigation design, they are only used for a comparison to the modeling results, rather than an input. BGC modeled each scenario in FLO-2D as described in Appendix D. Of note is that for each return period range, the peak flow for the upper bound of the range was selected for modeling.

Table 3-7. Summary of FLO-2D modeling scenarios.

Scenario ID	Return Period (years)	Bulking Factor	Bulked Peak Flow (m^3/s)	Scenario Description
1a	10-30	1.05	15	Current channel, no blockage, no aggradation (2015 lidar)
1b				Aggraded channel, some sediment infilling (2013 lidar)
2a	30-100	1.05	32	Current channel, no blockage, no aggradation (2015 lidar)
2b				Aggraded channel, some sediment infilling (2013 lidar)
3a	100-300	1.05	50	Current channel, no blockage, no aggradation (2015 lidar)
3b				Aggraded channel, some sediment infilling (2013 lidar)
4a	300-1000	1.1	80	Current channel, no blockage, no aggradation (2015 lidar)
4b				Aggraded channel, some sediment infilling (2013 lidar)
4c				Main channel blocked, simulating an avulsion (2015 lidar, with blockage)
5a	1000-3000	1.1	112	Current channel, no blockage, no aggradation (2015 lidar)
5b				Aggraded channel, some sediment infilling (2013 lidar)
5c				Main channel blocked, simulating an avulsion (2015 lidar, with blockage)

Table 3-8 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. Drawing 05a and 05b present the raw model results of selected scenarios modeled on Three Sisters Creek.

Table 3-8. Results from numerical debris flood modeling and interpretations by BGC.

Return Period (Years)	Results
10-30	• The flow is confined to the channel upstream of the golf course pond on the current topography model run. Downstream of the golf course pond, flow overtops the banks in several locations and ponds against and eventually flows across Three Sisters Parkway to rejoin Three Sisters Creek downstream.[5] • Flow over an aggraded topography avulses towards the east near the fan apex and reaches the developments of Hubman Landing and Miskow Close with shallow (< 0.3 m) flows.
30-100	• On the current topography, flow is confined to channel upstream of the golf course pond. Flow avulses to the west downstream of the golf course pond between the two kame terraces and to the east just upstream of Three Sisters Parkway into the development adjacent to the channel and down Casale Place. • In the aggradation scenario, flow avulses east near the fan apex. More of the existing development on the eastern side of the fan is inundated and flow is ponding up to 2 m deep along the upstream side of Riva Heights in localized depressions. • The culvert capacity at Three Sisters Parkway is exceeded and flow ponds against the road and flows over the road to the east and west of the culvert crossing.
100-300	• On the current topography, flow is confined to channel upstream of the golf course pond. Flow avulses to the west downstream of the golf course pond in several locations and makes it to Three Sisters Parkway. Flow also avulses to the east just upstream of Three Sisters Parkway into the development adjacent to the channel and down Casale Place. • In the aggradation scenario, flow avulses east near the fan apex. The majority of the existing development is inundated with shallow (< 0.4 m) flows. Flow reaches Three Sisters Parkway and, in some locations, overtops the road and reaches TransCanada Highway. Flow is ponding up to 2 m deep in localized depressions near Riva Heights and Three Sisters Parkway. • The culvert capacity at Three Sisters Parkway is exceeded and flow ponds against the road and flows over the road to the east and west of the culvert crossing.
300-1000	• On the current topography, shallow (< 0.5 m) flow avulses to the east near the fan apex and reaches some of the existing development at Hubman Landing. Flow avulses to the west downstream of the golf course pond in several locations and makes it to and across Three Sisters Parkways to inundate Cairns Landing. Flow also avulses to the east just upstream of Three Sisters Parkway into the development adjacent to the channel and down Casale Place. • In the aggradation scenario, flow avulses east near the fan apex. The majority of the existing development is inundated with shallow (< 0.5 m) flows. Flow reaches Three Sisters Parkway and, in some locations, overtops the road to reach the TransCanada Highway. Flow is ponding up to 2.5 m deep in localized depressions near Riva Heights and Three Sisters Parkway. • During the blockage scenario, most of the existing development is inundated with flow up to 0.6 m deep. Flow velocities are higher than for other avulsions as the main flow is through the existing development on the eastern side of the fan (up to 3.5 m/s). Flow does not avulse to the western side of the fan, toward future

5 At this return period, flows should pass through the culvert if there are no obstructions. Model results as shown may reflect grid size limitations therefore, overflow may or may not occur at this return period.

Return Period (Years)	Results
	development. Flow is ponding up to 3 m deep in localized depressions near Riva Heights and Three Sisters Parkway. • The culvert capacity at Three Sisters Parkway is exceeded and flow ponds against the road and flows over the road to the east and west of the culvert crossing. Flow overtopping Three Sisters Parkway to the east flows into the existing development downstream of the road (Crossbow Landing).
1000-3000	• On the current topography, shallow (< 0.6 m) flow avulses to the east near the fan apex and reaches existing development down to Dyrgas Gate. Flow avulses to the west downstream of the golf course pond in several locations and makes it to and across Three Sisters Parkways to inundate Cairns Landing. Flow also avulses to the east just upstream of Three Sisters Parkway into the development adjacent to the channel and down Casale Place. • In the aggradation scenario, flow avulses east near the fan apex. The majority of the existing development is inundated with shallow (< 0.5 m) flows. Flow reaches the Three Sisters Parkway and, in some locations, overtops the road to reach the TransCanada Highway. Flow is ponding up to 2.5 m deep in local depressions near Riva Heights and Three Sisters Parkway. • For the blockage scenario, most of the existing development is inundated with flow up to 0.6 m deep. Flow velocities are higher than for other avulsion scenarios as the main flow is through the existing development on the eastern side of the fan (up to 4 m/s). Flow does not avulse to the western side of the fan, towards future development. Flow is ponding up to 3 m deep in localized depressions near Riva Heights and Three Sisters Parkway. • The culvert capacity at Three Sisters Parkway is exceeded and flow ponds against the road and flows over the road to the east and west of the culvert crossing. Flow overtopping Three Sisters Parkway to the east flows into the existing development downstream of the road (Crossbow Landing).

Note that the various scenarios modelled have been assigned probabilities of occurrence at each return period (Table 3-8). The aggradation scenario is a conservative assumption at lower return periods (< 30 years).

3.5.1. Uncertainties

Debris floods involve complex and dynamic physical processes that are variable in space and time. No two debris floods, even with identical volumes, are expected to result 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.

Given the impracticality of creating all conceivable hydrograph shapes and modeling 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 could 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 determinations. 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 flood volumes, peak flows, and hydrograph shapes (e.g., those uncertainties described in the preceding sections), model uncertainties include the following:

- 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 as the module of FLO-2D used does not allow for morphodynamic changes to the input topography (possibly significant, especially if knickpoints develop)
- Sediment transport and deposition processes as FLO-2D does not accurately model sediment at concentrations of <20% and therefore only clearwater inflow as used in the modelling (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 Three Sisters Creek fan. However, by conducting multiple models runs with differing assumptions of blockages and channel aggradation, 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 flood outcomes.

Auxiliary hazards are not reflected in the modeling. For example, water flowing uncontrolled over Three Sisters Parkway, in case of a debris flood exceeding the culvert capacity at the Parkway, are likely to erode into the northern road embankment leading to gullying, retrogressive erosion and possible severance of the Parkway with a deep (several metres) gully connecting the upstream Parkway ditch with the confluence of the overflow with the lower Three Sisters Creek. Such auxiliary hazards need to be accounted for in the option analysis which will be presented under separate cover.

3.6. Composite Hazard Mapping

3.6.1. Composite Impact Force Frequency Map

BGC prepared a “composite” hazard map that unites the results from all modeled scenarios in a single map. The composite hazard map is intended for hazard communication and decision making, where different zones on the map may be subject to specific land use prescriptions, covenants, bylaws or other limiting clauses for both existing and proposed development.

The composite hazard rating map is based on an impact force frequency (IFF) geohazard mapping procedure that consists of two key components: the intensity expressed by an impact force and the frequency of the respective events. The underlying equation is:

$$IFF = v^2 \times \rho_f \times d_f \times P(H) \quad \text{[Eq. 3-4]}$$

where v is flow velocity (m/s), d_f is the fluid's flow depth (m), ρ_f is the fluid density (kg/m^3) to obtain a unit of force per metre flow width for the three left terms in Equation 3-4 and $P(H)$ is the annual probability of the geohazard. The unit of IFF is then Newtons or kilo-Newtons per metre per year (kN/m per yr).

Equation 3-4 can be translated into a matrix in which the impact force (*IF*) is on one axis and the return period (annual probability or *P(H)*) on the other. The matrix is then colour-coded to indicate the total hazard from yellow (low hazard) to dark red (extreme hazard) (Figure 3-7).

A further area designated a "very low" hazard, is also presented as areas likely to not be affected by any of the modeled scenarios up to the 3000-year return period debris floods, but which are not hazard free. Very low hazard zones could be impacted by flows of higher return periods, or if, over time, the channel bed aggrades, or the channel or fan surface is artificially altered. This designation is not classified using impact force and frequency and is therefore not included in Figure 3-7.

Return Period Range (years)	Representative Return Period (years)	Geohazard Intensity				
		Very Low	Low	Moderate	High	Very High
1 - 3	2					
10 - 30	20					
30 - 100	50					
100 - 300	200					
300 - 1000	500					
1000 - 3000	2000					
3000 - 10,000	5000					

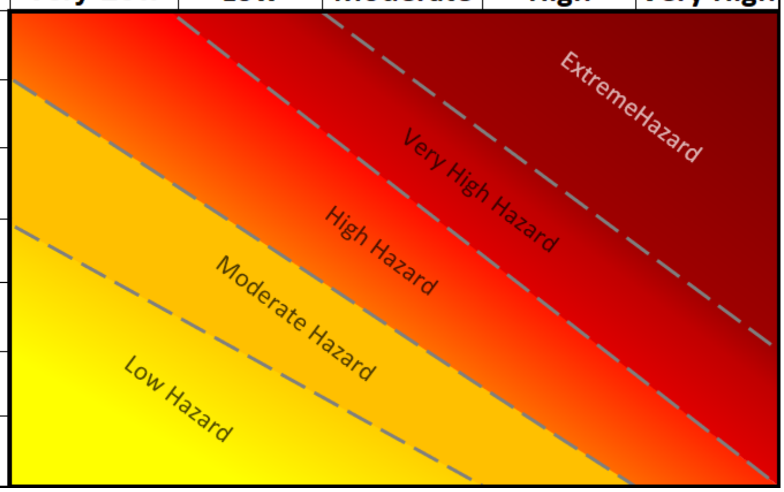

Figure 3-7. Simplified geohazard impact intensity frequency matrix.

The advantage of this mapping type is that a single map immediately codifies which areas are exposed to what hazard. Given that impact force is a surrogate for the destructiveness of a geohazard, *IFF* maps are relative proxies for risk assuming relatively homogenous elements at risk (i.e. a subdivision of single-family homes) are present in the specific hazard zones. The hazard zones do not represent an absolute level of risk, which also depends on their vulnerability and their presence in the hazard area at the time of impact.

Interpreted hazard maps showing *IFF* values were developed for each return period class at all locations within the study area. For the composite hazard rating map, the different intensities were interpreted by BGC to homogenize zones into easily identifiable polygons that are likely to fall into the range of intensity bins reported above. In some cases, individual properties may have been artificially raised and are thus less prone to flood or debris flood impact.

Not all scenarios (aggradation vs. no aggradation, or channel blockage) have the same chance of occurring. Hence, BGC added an estimated probability of each scenario adding to 100% for each return period class (Table 3-9). The scenario probabilities are based on professional judgment. They consider the potential for incremental channel sediment aggradation prior to (assuming no routine sediment removal) or instantaneously during the falling hydrograph limb as part of a debris flood. The likelihood for severe channel aggradation increases with return period as proportionally more debris is being mobilized and deposited. Impact forces for each scenario were then multiplied by these probabilities and then summed for each return period.

Table 3-9. Model scenario probabilities.

Scenario ID	Return Period (years)	Scenario Description	Scenario Probability (%)
1a	10-30	Current, no blockage, no aggradation (2015 lidar)	70
1b		Aggradation (2013 lidar)	30
2a	30-100	Current, no blockage, no aggradation (2015 lidar)	50
2b		Aggradation (2013 lidar)	50
3a	100-300	Current, no blockage, no aggradation (2015 lidar)	40
3b		Aggradation (2013 lidar)	60
4a	300-1000	Current, no blockage, no aggradation (2015 lidar)	20
4b		Aggradation (2013 lidar)	70
4c		Blockage (2015 lidar, with blockage)	10
5a	1000-3000	Current, no blockage, no aggradation (2015 lidar)	20
5b		Aggradation (2013 lidar)	60
5c		Blockage (2015 lidar, with blockage)	20

The composite hazard impact force frequency (IFF) map (Drawing 06) demonstrates that the majority of the active fan of Three Sisters Creek is located within the yellow (low) hazard area. The orange (moderate) and red (high) hazard areas are confined to the main channel.

3.6.2. Composite Hazard Intensity Map

The preceding sub-section explained a modernized version of hazard map that was developed by BGC in 2020. At the request of the Town of Canmore, BGC supplied a composite debris-flood hazard intensity (I_{DF}) map that had previously been developed and used by BGC for other creeks in Canmore, the Municipal District of Bighorn and elsewhere in BC. It was also used for Three Sisters Creek in BGC's previous hazard assessment (Drawing 07, BGC, January 11, 2014). It is based on the following formula:

$$I_{DF} = v^2 \times d_f \quad \text{[Eq. 3-5]}$$

BGC included both the composite hazard IFF map and the composite hazard intensity map to compare the two map types and show the differences arising from inclusion of debris-flood frequency in the mapping. In the composite hazard IFF map (Drawing 06), the higher hazard of the avulsion channels shown in Drawing 07 disappears because avulsions at this location only occur at high return periods (i.e., at low frequencies). This results in a more homogenous hazard distribution for the composite hazard IFF map. BGC favours the composite hazard IFF map as it systematically allows for differences in frequencies.

A detailed hazard assessment for individual property building permits is still required to obtain appropriate design parameters for on-site debris-flood mitigation.

4. CONCLUSIONS

BGC revisited and updated the 2014 debris-flood hazard assessment with quantification of climate change effects on peak flows and sediment volumes, bank erosion and aggradation/channel blockage scenarios. BGC believes that this constitutes a substantial refinement to the previous 2014 work which did not benefit from recent advances in the respective sciences.

The results from the updated numerical modeling once again demonstrate that the eastern fan sector is substantially more prone to inundation compared to the western fan sector on which the proposed Three Sisters Village Area Structure Plan development is to be constructed. Given that projected climate change will result in increased peak flows, the model results reflect larger areas being inundated, with somewhat higher flow depth and flow velocities than in the BGC (October 31, 2014) report. This is particularly true for the channel blockage scenario, which, while being conservative, is a reality on alluvial fans that tend to shift their channel entirely during extreme events into a new bed.

The bank erosion results indicate erosion amounts from 6 m (10 to 30-year return period, 50th percentile) to approximately 160 m (1000 to 3000-year return period, 50th percentile). QPD indicated that they would like to develop within 20 m of the western creek bank, which implies that west bank erosion protection or channel widening on the east bank is required to avoid future development impact. Irrespective of future development west of Three Sisters Creek, the hazard to the existing development east of the creek will persist due to its relatively lower elevation compared to the western fan portions.

In 2020, BGC developed a new approach on how to map geohazards through combining geohazard intensities (expressed as an impact force) with their respective frequencies. BGC applied this map making technique and generated a composite hazard map for the unmitigated case. It demonstrates that outside the channel, the hazard is low, but widespread. This implies a relatively low life loss potential though BGC did not attempt to quantify life loss during this hazard analysis update.

The results from numerical modeling are presently being used to inform a detailed option analysis in which a subset of credible options is being developed and compared using a variety of criteria. This report will be presented to QPD under separate cover.

5. 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,

BGC ENGINEERING INC.
per:

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APPENDIX A
HYDROGEOMORPHIC PROCESSES

APPENDIX A – HYDROGEOMORPHIC PROCESSES

A.1. INTRODUCTION

Steep creeks (here-in defined as having channel gradients steeper than 3°, or 5%) may be subject to a spectrum of sediment transport processes ranging with increasing sediment concentration from so-called clearwater floods to debris floods, hyperconcentrated flows (in fine-rich sediment) to debris flows. They can be referred to collectively as hydrogeomorphic[1] processes because water and sediment (in suspension and bedload) are being transported. Depending on process and severity hydrogeomorphic processes can alter landscapes.

Floods can transition into debris floods upon exceedance of critical bed shear stress thresholds to mobilize most grains of the surface bedload layer. As more and more fines (clays, silts and fine sands are incorporated) hyperconcentrated flows may develop. Debris flows are typically triggered by side slope landslides or progressive bulking with erodible sediment in particularly steep (>15°) channels. Debris bulking is specifically observed after wildfires at moderate to high burn severity when ample surface sediment is exposed without the sheltering vegetative cover. Dilution of a debris flow through partial sediment deposition on lower gradients (approximately less than <15°) channels, and tributary injection of water can lead to a transition towards hyperconcentrated flows or debris floods and eventually floods. Most steep creeks can be classified as hybrids, implying variable hydrogeomorphic processes at different return periods.

Figure A-1 provides a simple schematic to illustrate the continuum of steep creek processes.

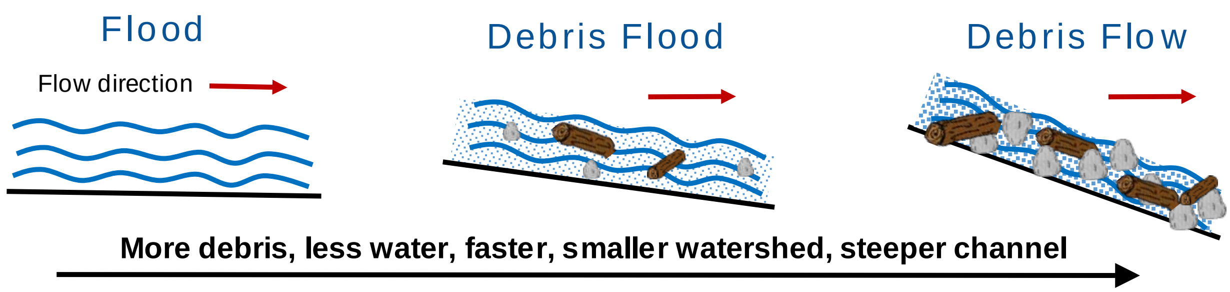

Figure A-1. Hydrogeomorphic process continuum demonstrating the increased channel gradient and sediment concentration observed on debris flood and debris flow channels. BGC-created figure.

A.2. STEEP CREEK WATERSHEDS AND FANS

A steep creek watershed consists of hillslopes, small feeder channels, a principal channel, and an alluvial fan composed of deposited sediments at the lower end of the watershed.

Every watershed and fan are unique in the type and intensity of mass movement and fluvial processes, its morphology and the hazard and risk profile associated with such processes.

[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 & Onda, 2004).

Figure A-2 schematically illustrates two fans side by side. The steeper one on the left is dominated by debris flows and perhaps rock fall near the fan apex, whereas the one on the right with the lower gradient is likely dominated by debris floods.

Figure A-2. Typical steep and low-gradient fans feeding into a broader floodplain. On the left a small watershed prone to debris flows has created a steep fan that may also be subject to rock fall processes. On the right a larger watershed prone to debris floods has created a lower gradient fan. Development and infrastructure are shown to illustrate their interaction with steep creek geohazard events. Artwork: Derrill Shuttleworth.

In steep basins, most mass movements on hillslopes directly or indirectly feed into steep mountain channels from which they begin their journey downstream. Viewed at the scale of the watershed and over geologic time, distinct zones of sediment production, transfer, erosion, deposition, and avulsions may be identified within a drainage basin (Figure A-3). To understand the significance of these different modes of sediment transfer, it is useful to consider the anatomy of a steep channel system.

Steep mountain slopes deliver sediment and debris to the upper channels by rock fall, rock slides, debris avalanches, debris flows, slumps and raveling. Debris flows and debris floods characteristically gain momentum and sediments as they move downstream and until they spread across an alluvial fan where the channel enters the main valley floor and momentum is lost through diffusion, decrease in flow depth and sediment deposition.

Landslides in the watershed may also create temporary dams impounding water, which usually fail catastrophically through overtopping or piping. In these scenarios, a debris flow or Type 3 debris flood may be initiated in the channel that travels further than the original landslide (Type 1, 2, and 3 debris floods are described in detail in Section A.4.

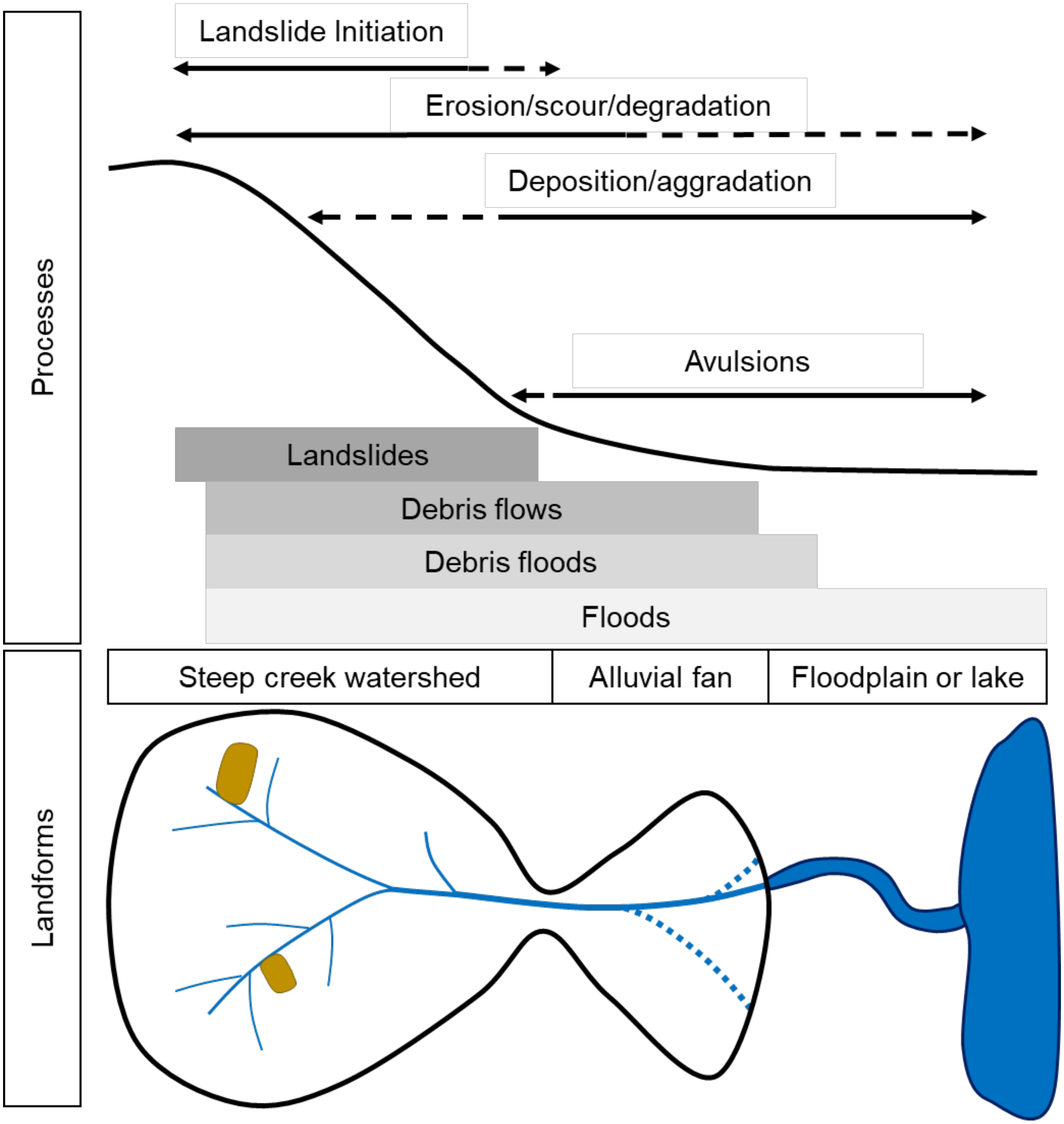

Figure A-3. Schematic diagram of a steep creek watershed system that shows the principal zones of distinctive processes and sediment behaviour. The alluvial fan is thought of as the long-term storage landform with a time scale of thousands to tens of thousands of years. Sketch developed by BGC from concepts produced by Schumm (1977), Montgomery & Buffington (1997), and Church (2013).

The alluvial fan represents a mostly depositional landform at the outlet of a steep creek watershed. This landform is more correctly called a colluvial fan or colluvial cone when formed by debris flows because debris flows are classified as a landslide process, and an alluvial fan when formed by clearwater floods (those which do not carry substantial bedload or suspended load) or debris floods. For simplicity the term alluvial fan is used herein irrespective of geohazard type. “Classic” alluvial fans are roughly pizza slice-shaped in plan form, but most fans have irregular shapes influenced by the surrounding topography. Sediments that arrive from the upstream channel or have previously been deposited near the fan apex are often redistributed to the lower flatter fan through bank erosion and channel scour. Identification of an inflection point, i.e., where erosion switches to deposition is important for assessments of proposed or existing buried linear infrastructure (Lau, 2017).

Stream channels on the fan are prone to avulsions, which are rapid changes in channel location, due to natural cycles in alluvial fan development and from the loss of channel confinement during hydrogeomorphic events (e.g., Kellerhals & Church, 1990; van Dijk, Postma & Kleinhans, 2009; van Dijk, Kleinhans, Postma & Kraal, 2012; de Haas et al., 2018). Alluvial fans are dynamic and potentially very dangerous (hazardous) landforms that represent the approximate extent of past and future hydrogeomorphic processes.

A.3. DEBRIS FLOWS

'Debris flow', as defined by Hungr, Leroueil and Picarelli (2014), is a very rapid, channelized flow of saturated debris containing fine grained sediment (i.e., sand and finer fractions) with a plasticity index of less than 5%. Debris flows originate from a single or distributed source area(s) of sediment 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. Post-fire debris flows are a special case where the lack of vegetation and root strength can lead to abundant rilling and gullying that deliver sediment to the main channel where mixing leads to the formation of debris flows. In those cases, no single source or sudden liquefaction is required to initiate or maintain debris-flow mechanics.

Sediment bulking is the process by which rapidly flowing water entrains bed and bank materials either through erosion or preferential "plucking" until sediment saturation is reached (often at 60-70% sediment concentration by volume). 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. 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 behaviour 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, Pierson & Scott, 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 depositional legacy. Similarly, depositional lobes are formed where frictional resistance from unsaturated 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.

Coarse granular 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})[2], 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 fine grained (especially clay) sediment content, and hence the slower the sediment-water mixture will lose its pore water, the lower the ultimate stopping angle. The clay fraction is 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 during debris flows are at least an order of magnitude larger than those of comparable return period floods and can be 50 times larger or more (Jakob & Jordan, 2001; Jakob et al., 2016). 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, Stein & Ulmi, 2012). Similarly, linear infrastructure such as roads and railways are subject to complete destruction. On the medial and distal fan (the lower 1/3 to 2/3), debris flows tend to deposit their sediment rather than scour. Therefore, exposure or rupture of buried infrastructure such as telecommunication lines or pipelines is rare. However, if a linear infrastructure is buried in the proximal fan portions that undergo cycles of incision and infill, or 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 or may rupture due to boulder impact or abrasion. This necessitates understanding the geomorphic state of the fans being traversed by a buried linear infrastructure.

Channel avulsion occurs when the creek migrates out of an existing channel and forms a new channel. Avulsions are likely in poorly confined channel sections (particularly on the outside of

2 For volcanic debris flows, transport can occur at even lower gradients.

channel bends where debris flows tend to super-elevate). 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 challenge to numerical modelers seeking to create an equivalent fluid (Iverson, 2014).

A.4. DEBRIS FLOODS

Within the past 20 years the English term ‘debris flood’ has come into use to describe severe floods involving exceptionally high rates of transport as bedload of coarse sediments, usually occurring in steep channels (Hungr, Evans, Bovis & Hutchinson, 2001; Wilford, Sakals, Innes, Sidle & Bergerud, 2004). Specific classifications have been proposed much earlier in Europe (Stiny, 1931; Aulitzky, 1980) using the German terms “murstossfähige-, murfähige, geschiebeführende and hochwasserführende Wildbäche”. This was translated by G. Eisbacher into “debris-flow”, “debris flood”, “bedload transporting” and “flood” creeks. The first two terms are somewhat confusing as they translate directly into “debris-flow (mur), surge/push (stoss), capable (fähig)” and “debris-flow capable”. Hence the only difference is the term “stoss”. The absence or presence of surges is not a sufficiently discriminatory criterion between debris flows and debris floods and could only be distinguished if the event is observed in action.

The English term “debris flood” is favored by geotechnical engineers and engineering geomorphologists who share responsibility to protect society and its infrastructure from such events. A recent authoritative review of landslide-like phenomena defines debris flood as “very rapid flow of water, heavily charged with debris, in a steep channel. Peak discharge is comparable to that of a water flood.” (Hungr et al., 2014: p.185). The text continues: “the stream bed may be destabilized causing massive movement of sediment. Such sediment movement (sometimes referred to as “live bed” or “carpet flow” by hydraulicians) can reach transport rates far exceeding normal bed load movement through rolling and saltation. However, the movement still relies on the tractive forces of water.” (Hungr et al., 2014). Accordingly, debris floods represent water driven flood flows with high bedload transport of gravel to boulder size material and significant damage potential. Unfortunately, in much of the technical literature they remain classified as hyperconcentrated flows, a quite different phenomenon. However, BGC defines debris floods more precisely in the following paragraphs.

Bedload transport in gravel-bed channels has been characterized in three stages (Carling, 1988; Ashworth & Ferguson, 1989). In stage 1, fine material – typically sand – overpasses a static bed or is mobilised by winnowing from an otherwise static bed. The force of the flowing water is insufficient to mobilize the local bed material. In stage 2, local bed material is entrained and redeposited at low rates. Individual clasts are mobilised from the bed surface independently of other entraining events (except when movement of a relatively large clast liberates finer material that was hiding in its shadow). Most of the bed remains stable most of the time (a state defined as “partial transport” by Wilcock and McArdell (1993)). In stage 3, the entire streambed or a continuously connected portion of it becomes mobile and activity may extend to a depth of several median grain sizes below the surface as the result of momentum transfer by grain-grain collisions. In many instances, the channel itself is modified by erosion and sedimentation. *A debris flood is, then, a case of stage 3 transport*.

Debris floods are relatively rare because stage 3 transport is rare in gravel-bed channels. In such channels, where bed and banks consist of similar non-cohesive materials the banks are readily eroded due to inherent weakness and the gravitational assist (Lane, 1955) so that the channel widens, with consequent reduction in flow depth, until the flow is just able to transport the incoming bed material load at rates near the threshold for transport and near-bank currents are no longer effective (Parker, 1978; 1979). The shear force exerted by the flow on the bed remains near the threshold value for entrainment of the bed material. Debris floods occur when this condition is exceeded. Steep mountain channels (in which the width remains limited because the banks consist of rock or other non-erodible material) may experience stage 3 flow and debris flood relatively frequently (every few years; cf. Theule, Liébault, Laigle, Love & Jaboyedoff, 2015). Larger, but still relatively steep, channels carrying extraordinary floods (floods of order 100-year return period or greater) also are prone to debris flood occurrence. Such floods are distinctly two-phase flows, with ‘clear water’ or water with a substantial suspended sediment load, overlying a slurry-like flow – characterised as an “incipient granular mass flow” by Manville and White (2003) – containing a high concentration of bed material, the finest fractions of which may be episodically suspended.

For practical purposes we define a debris flood as “a flood during which the entire bed, possibly barring the very largest blocks, mobilizes for at least a few minutes and over a length scale of at least ten times the channel width”.

Debris floods typically occur on creeks with channel gradients between 5 and 30% (3-17^{o}), but in contrast to common belief, can also occur on lower gradient gravel bed rivers. Due to their initially relatively low sediment concentration, debris floods can be more erosive along low-gradient alluvial channel banks than debris flows. 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. Debris floods can be initiated on the fan itself through rapid bed erosion and entrainment of bank materials, as long as the stream power is high enough to transport clasts larger than the median grain size (D_{50}). Because typical long-duration 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). Similarly, debris floods triggered by outbreak floods may lead to single or multiple surges irrespective of hydrograph fluctuations that can lead to cycles of bank erosion, scour and infill. This is important for interpretations of field observations as only the final deposition or scour can be measured. This is relevant where a pipeline or telecommunication line is to be buried. Maximum scour during a debris flood may be much deeper than what is viewed and measured during a field visit.

Church and Jakob (2020) developed a three-fold typology for debris floods, which have previously not been defined well. This is summarized in Table A-1. Identifying the correct debris-flood type is key in preparing for numerical modelling and hazard assessments. Type 1 is considered in clearwater flood on fan process described in Section A.5, due to similar regional scale characteristics. Type 2 debris floods are generated from diluted debris flows. Type 3 are generated by natural or man-made dam breaches.

Hyperconcentrated flows are a special case of debris floods that are typical for volcanic sources areas or fine-grained sedimentary rocks. They can occur as Type 1, 2 or 3 debris floods. The term “hyperconcentrated flow” was 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 discharge (water flow) and debris flow (or mudflow)”. The use of the term “hyperconcentrated flow” should be reserved for volcanic or weak sedimentary fine-grained slurries.

Table A-1. Debris-flood classification based on Church and Jakob (2020).

Term	Definition	Typical sediment concentration by volume (%)	Typical Qmax factor compared to calc. clearwater	Physical Characteristics	Typical impacts	Typical return period range (years)
Type 1 Meteorologically-generated debris flood	Rainfall/snowmelt generated through exceedance of critical shear stress threshold when most of the surface bed grains are being mobilized.	< 5	1.05 (or higher should there be multiple side slope landslides expected or large organic debris)	Steep fans (1 to 10%), shallow but wide active floodplain, widespread boulder carpets, clast to matrix-supported sediment facies, poorly sorted, subrounded to rounded stones, imbrication of elongate clasts, occasional cross-bedding, disturbed riparian vegetation, frequent avulsions on fan	Widespread bank instability, avulsions, alternating reaches of bed aggradation and degradation, blocked culverts, scoured bridge abutments, damaged buried infrastructure particularly in channel reaches upstream of fans	>2
Type 2 Debris flow to debris flood dilution	Transitional as a consequence of debris flows. Substantially higher sediment concentration compared to a Type 1 debris flood and accordingly greater facility to transport larger volumes of sediment. All grain calibers mobilized, except from lag deposits (big glacial or rock fall boulders).	< 50	2-5 (but possibly larger at the transition zone)	As for Type 1 but rarely clast-supported and with higher matrix sediment concentration, unsorted, inverse grading near debris flow tributary. Stones subangular to angular, boulder carpets on fans often display abrupt sediment deposit edges	Widespread bank instability, avulsions, substantial bed aggradation particularly on fans, blocked culverts, scoured bridge abutments, damaged and buried infrastructure on fans	>50
Type 3 Outbreak floods	Outbreak flood in channels with insufficient steepness for debris-flow generation. Critical shear stress for debris flood initiation exceeded abruptly due to sudden outbreak flood. All grain sizes mobilized in channel bed and non-cohesive banks.	< 10 (except immediately downstream of the outbreak where it can reach greater than 30%)	2 to 100 depending on size of dam and distance to dam failure.	High matrix fines content especially in volcanic sources or fine-grained soil (e.g. loess), sometimes inverse grading near outbreak flood source, unsorted near source. Increasing sorting and stratification with downstream distance, erosion and fill structures	Extreme bank erosion, avulsions, substantial bed degradation along channels and aggradation on fans, destroyed culverts, outflanked or overwhelmed bridges, damaged and buried infrastructure on channels and fans	>100 (can be singular events in the case of a moraine dam or glacial breach)

A.5. CLEARWATER FLOODS ON ALLUVIAL FANS

Clearwater floods are defined as "riverine and lake flooding resulting from inundation due to an excess of clearwater discharge in a watercourse or body of water such that land outside the natural or artificial banks which is not normally under water is submerged". Note that for most creeks in Canmore, a water depth sufficient to submerge land outside the creek banks is – by Church and Jakob's (2020) definition – a Type 1 debris flood. Hence, clearwater floods are likely to occur at low return periods.

Most of the severe flooding in the Bow Valley occurs between May and June due to snow melt (freshet). In contrast to other areas in BC and Alberta, flooding is not typically driven solely by intense winter rainstorms or rain-on-snow events. Flood severity can vary considerably depending on:

- The amount and duration of the precipitation (rain and snowmelt) event
- The antecedent moisture condition of the soils
- The size of the watershed
- The floodplain topography
- The effectiveness and stability of flood protection measures.

For example, excessive rainfall, rain-on-snow, or snowmelt can cause a stream or river to exceed its natural or engineered capacity. Overbank flooding occurs when the water in the stream or river exceeds the banks of the channel and inundates the adjacent floodplain in areas that are not normally submerged (Figure A-4). Climate change also has the potential to impact the probability and severity of flood events by augmenting the frequency and intensity of rainfall events, altering snowpack depth, distribution, timing, snow water equivalent (SWE), and freezing levels and causing changes in vegetation type, distribution and cover. Impacts are likely to be accentuated by increased wildfire activity and / or insect infestations (British Columbia Ministry of Environment, 2016).

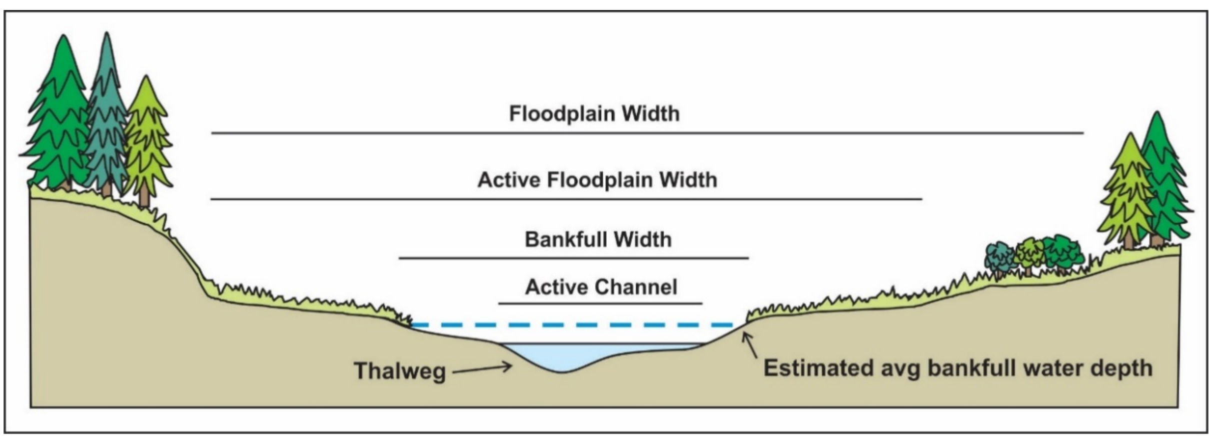

Figure A-4. Conceptual channel cross-section in a typical river valley.

In Alberta, the 100-year return period flood is used to define floodplain areas. The 100-year flood is the annual maximum river flood discharge (and associated flood elevation) that is exceeded with an annual exceedance probability (AEP) of 1.0% or 0.01. While flooding is typically associated with higher return events, such as the 100-year return period event, lower return period events (i.e., more frequent and smaller magnitude events) have the potential to cause flooding if the banks of the channel are exceeded.

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APPENDIX B
HYDROLOGY AND CLIMATE CHANGE ASSESSMENT

APPENDIX B – HYDROLOGY AND CLIMATE CHANGE ASSESSMENT

B.1. INTRODUCTION

Hydrology and climate change are a fundamental input into the assessment of credible debris flood hazard scenarios. BGC conducted rainfall-runoff modeling using HEC-HMS (Version 4.3), a software developed by the US Army Corps of Engineers (USACE) to determine the peak discharge for a range of return periods. BGC also conducted a climate change assessment to evaluate the changes in precipitation and peak flow during the period from 2050 to 2100. Both analyses are described in the sections below.

B.2. RAINFALL-RUNOFF MODELING

The purpose of conducting the rainfall-runoff modelling was to develop a flood frequency analysis (FFA) from nearby historical precipitation data, in lieu of a gauge to directly measure discharge, to predict peak discharge for return periods ranging from 10 to 3000 years. The U.S. Soil Conservation Service (SCS) unit hydrograph method (USDA, 1986) was used, which requires the following inputs:

- A storm hyetograph (rainfall distribution over time) or a 24-hour precipitation depth together with specified Soil Conservation (SCS) standard rainfall distribution (USDA, 1986).
- The time of concentration (conceptually the time needed for water to flow from the most remote point in a watershed to the watershed outlet), which was estimated using the SCS lag time method.
- Initial abstraction (I_a) refers to all initial losses such as surface depression storage, vegetation interception, and infiltration).
- The SCS runoff curve number (CN)[1], which takes a value between 0 and 100 and determines the proportion of the rainfall that infiltrates into the soil and is stored as soil moisture (i.e., does not contribute to the storm hydrograph and thus the effective runoff). The CN value is a function of soil type, ground cover and antecedent moisture condition (AMC) which describes the soil moisture condition at the beginning of a storm.

B.2.1. Model Calibration

The HEC-HMS model was calibrated by attempting to replicate the June 19 to 22, 2013 peak discharge estimate using hourly rainfall data from Fisera Ridge at the Marmot Research Basin[2], located approximately 15 km southeast of Three Sisters Creek (see BGC, October 31, 2014). These stations recorded a peak hourly rainfall of 13 mm during the 2013 debris flood. In comparison the Kananaskis Boundary Auto climate station recorded peak hourly rainfall of 16 mm, and a climate station operated by a private residence in Canmore recorded peak hourly rainfall of 17 mm. For the simulation, it was decided to use the Marmot Research Basin rainfall

1 SCS-CN is the Soil Conservation Service curve number which is dimensionless and lumps the effects of land use and hydrologic conditions on surface runoff. It relates direct surface runoff to rainfall.
2 The Marmot Research Basin is operated by the University of Saskatchewan.

data but replace the peak hourly rainfall with the value of 17 mm from the private residence climate station, as it is likely that the highest rainfall intensities were experienced in the upper reaches of the watersheds.

The lag time was estimated using the SCS lag time method (29 minutes), while a composite CN value of 63 was used for the watershed (i.e., a lumped model). The SCS unit hydrograph method is highly dependent on the CN value; a higher CN value will cause a higher peak flow as less precipitation goes into soil storage. The initial abstraction coefficient (I_a = 0.2S, where S = 1000/CN - 10) traditionally used for such an analysis is 0.2; however, a recent study prepared for the National Resource Conservation Service (NRCS) recommends adopting a value of 0.05 (Hawkins et al., 2010) but with adjusted CN values. Both values were adopted by BGC as a sensitivity analysis.

Using the above parameter set and the SCS unit hydrograph method, a range of peak flows of 22 m^3/s (with I_a = 0.2S) to 26 m^3/s (with I_a = 0.05S) is estimated for the June 2013 rainfall event at Three Sisters Creek (Figure B-1). These values are considerably lower than the peak flow estimates of 40-50 m^3/s provided in BGC (October 31, 2014), which were based on high water marks in steep (10-14%), bouldery channel sections (e.g., Figure B-2). Manning's n values of 0.045 to 0.065 were used for those estimates. However, using those roughness values results in Froude numbers of 1.8 to 2.0. Several authors have proposed that in mobile bed rivers, channel adjustment limits Froude numbers from exceeding 1, except for short distances of short periods of time (e.g., Piton, 2019; Jarrett, 1984; Grant, 1997). Therefore, BGC used the formulation of Jarrett (1984) to estimate channel roughness and also iteratively solved for discharge by adjusting Manning's n until a Froude value of 1 was obtained. The first approach resulted in peak flow estimates of 16 to 25 m^3/s, while the second yielded a range of 22 to 30 m^3/s[3]. Both ranges are consistent with the calibrated HEC-HMS model values of 22 and 26 m^3/s.

[3] BGC conducted a number of detailed hazard assessments for the Town of Canmore and Municipal District (MD) of Bighorn. Of these watersheds, Three Sisters Creek was the first creek with a detailed hydrologic assessment, including evaluation of high-water marks. For the other creeks with high-water marks, channel roughness values were evaluated using Jarrett (1984).

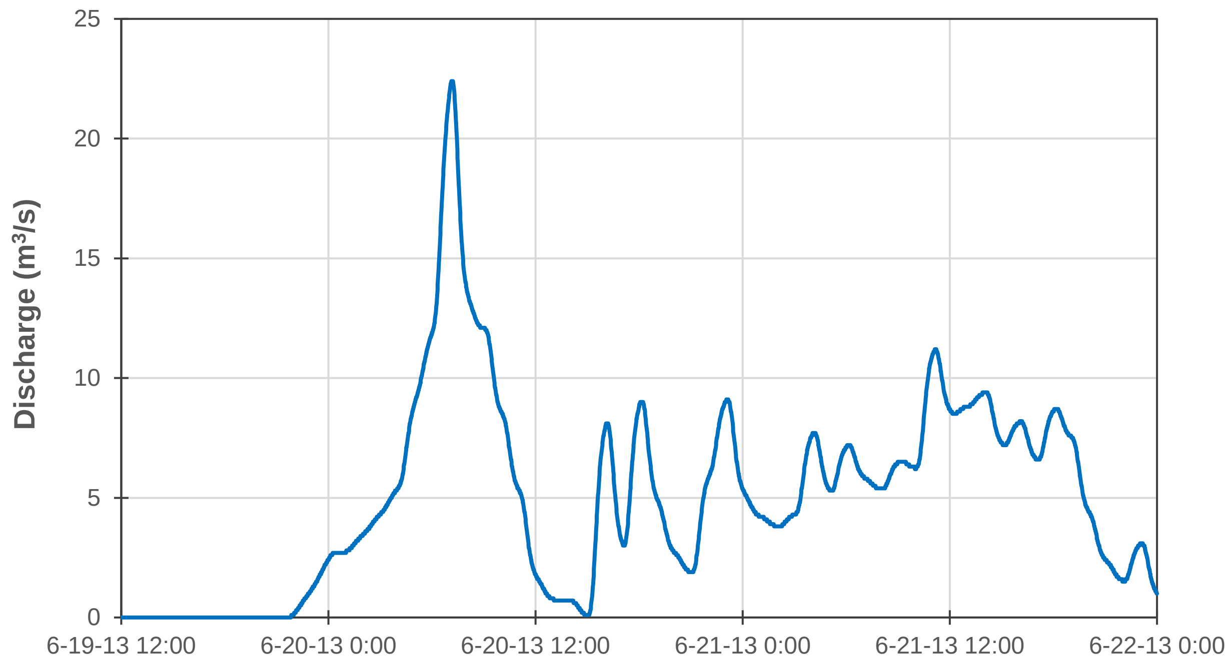

Figure B-1. HEC-HMS hydrograph for June 2013 flood on Three Sisters Creek (I_a = 0.05S).

Figure B-2. Upstream view of Three Sisters Creek high water mark at WP3. BGC photograph of May 29, 2014.

B.2.2. Rainfall

BGC (October 31, 2014) had used Environment and Climate Change Canada (ECCC) published intensity-duration-frequency (IDF) rainfall data from the Kananaskis climate station (ID 3053600) for rainfall-runoff modelling of Three Sisters Creek peak flows (Table B-1). Rainfall depths for the longer return periods of 300, 1000, and 3000 years, the data were extrapolated in BGC (October 31, 2014) based on a semi-log relation.

Table B-1. ECCC IDF rainfall data for the Kananaskis climate station (ID 3053600, 1982-1998).

Return Period (years)	Rainfall Depth (mm)				
	30-min	1-hr	2-hr	6-hr	24-hr
2	7	10	14	25	42
10	14	21	28	52	75
25	17	26	35	66	91
30	18	27	36	68	94
50	20	30	40	76	103
100	22	34	45	86	115
300	27	41	54	104	136
1000	31	49	64	122	158
3000	36	55	72	139	178

Values shaded in light red were interpolated/extrapolated from published values.

The Kananaskis IDF 24-hour rainfall totals were used as input to the 2014 HEC-HMS modelling. However, the ECCC frequency analysis was completed with a Gumbel distribution for which higher return periods cannot necessarily be extrapolated based on a semi-log distribution. Furthermore, the quantiles summarized in Table B-1 are based on a limited dataset (12 years), resulting in significant uncertainty for higher return period estimates. Therefore, for the analysis here-in, BGC extended the 24-hour rainfall dataset by analyzing daily rainfall data for the 1940-2019 period from the Kananaskis station. Maximum annual daily rainfall totals were abstracted from the record and converted to 24-hour values by a factor of 1.1 (Figure B-3), which is the average ratio between 24-hour and daily maximum values for the overlapping period (1982-1998) of record at the Kananaskis station. Updated 24-hour totals are provided in Table B-1 and Figure B-4 based on four probability distributions: Pearson Type III (PIII), log Pearson Type III (LPIII), Generalized Extreme Value (GEV, linear moments (lm)), and GEV (maximum likelihood estimate (mle)). Significant differences between the distributions are noted at higher return periods.

Table B-2. Historical 24-hour rainfall quantile estimates for the Kananaskis climate station (ID 3053600) based on data from the period 1940-2019.

Return Period (years)	24-hour Rainfall (mm)				
	1940-2019 Dataset				IDF (1982-1998) Dataset
	GEV_lm	LPIII	GEV_mle	PIII	
2	42	**43**	43	42	42
10	75	**75**	75	78	75
30	103	**100**	100	103	103
50	118	**113**	114	115	118
100	142	**132**	135	130	142
300	189	**167**	174	155	189
500	215	**186**	196	167	215
1000	256	**213**	228	183	256
3000	336	**263**	289	208	336

* Interpolated/extrapolated value.

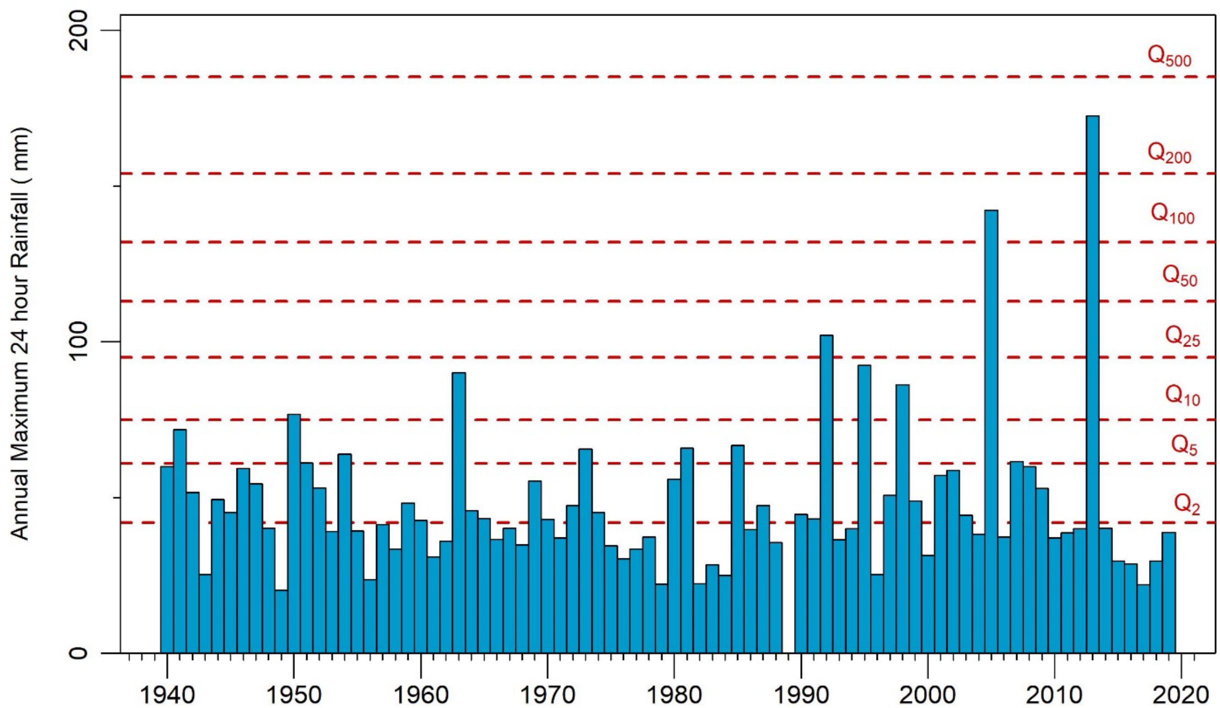

Figure B-3. 24-hour maximum annual rainfall at the Kananaskis climate station (1940-2019).

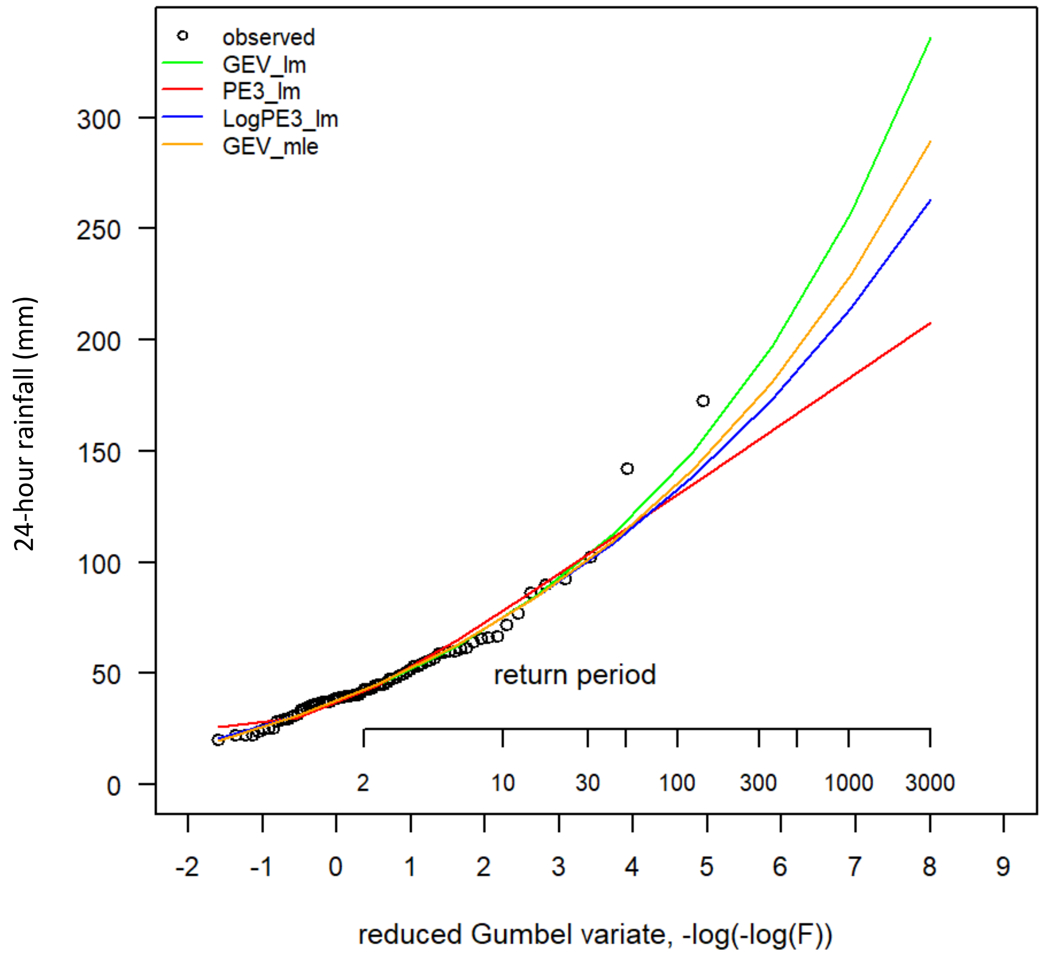

Figure B-4. R-generated **24-hour rainfall frequency analysis of the Kananaskis climate station from using data from 1940 to 2019 with multiple probability distributions.**

Although the gauge has a long period of record (79 years), the uncertainty associated with the rainfall estimates increases considerably for return periods exceeding the record length (i.e., >100-year return period estimates). To assess which 3000-year return period rainfall estimates were reasonable, they were compared with 24-hour probable maximum precipitation (PMP) values recently estimated by Kappel et al. (2018) for the adjacent Elbow River basin (Kappel et al., 2018). That analysis estimated general storm 24-hour PMP values of 294 to 376 mm and local storm 6-hour PMP values of 160 to 307 mm. Northwest Hydraulic Consultants (NHC, June 27, 2017) also estimated a 24-hour PMP value of 400 mm for the nearby Cougar Creek watershed. Koutsoyianiss (1999) has argued that the PMP has an associated return period of 60,000 years[4]. Extending the frequency analysis to a return period of 60,000 years, the GEV distributions yield 24-hour rainfall totals in excess of 500 mm, 420 mm is obtained with the LPIII, and 275 mm for PIII. These values suggest that the GEV distribution values are too high for the Kananaskis station, while the PIII distribution appears to underestimate higher return periods as indicated by

[4] It should be noted that others note even higher return periods for a PMP event.

its poor fit to the two highest storms recorded. Therefore, the LPIII distribution was chosen moving forward.

B.2.3. Hyetograph

Having chosen the magnitude of the storms to evaluate, the rainfall distribution (i.e. hyetograph) has to be selected. The SCS type (I, 1A, II and III) distributions are commonly used in North America. For the previous hazard assessment of Three Sisters Creek, BGC (December 31, 2014) used an SCS Type I distribution. To test this hypothesis, the distribution of the June 2013 storm was plotted with the SCS distributions (Figure B-5). That analysis suggests that a Type IA SCS storm may be more applicable for the snowmelt season, a period when a majority of recorded hydrogeomorphic events in the Bow Valley have occurred (BGC, May 1, 2018). Type I storms likely occur in the Canmore area but are expected later into the summer, when antecedent conditions are drier, and a lower CN value would apply.

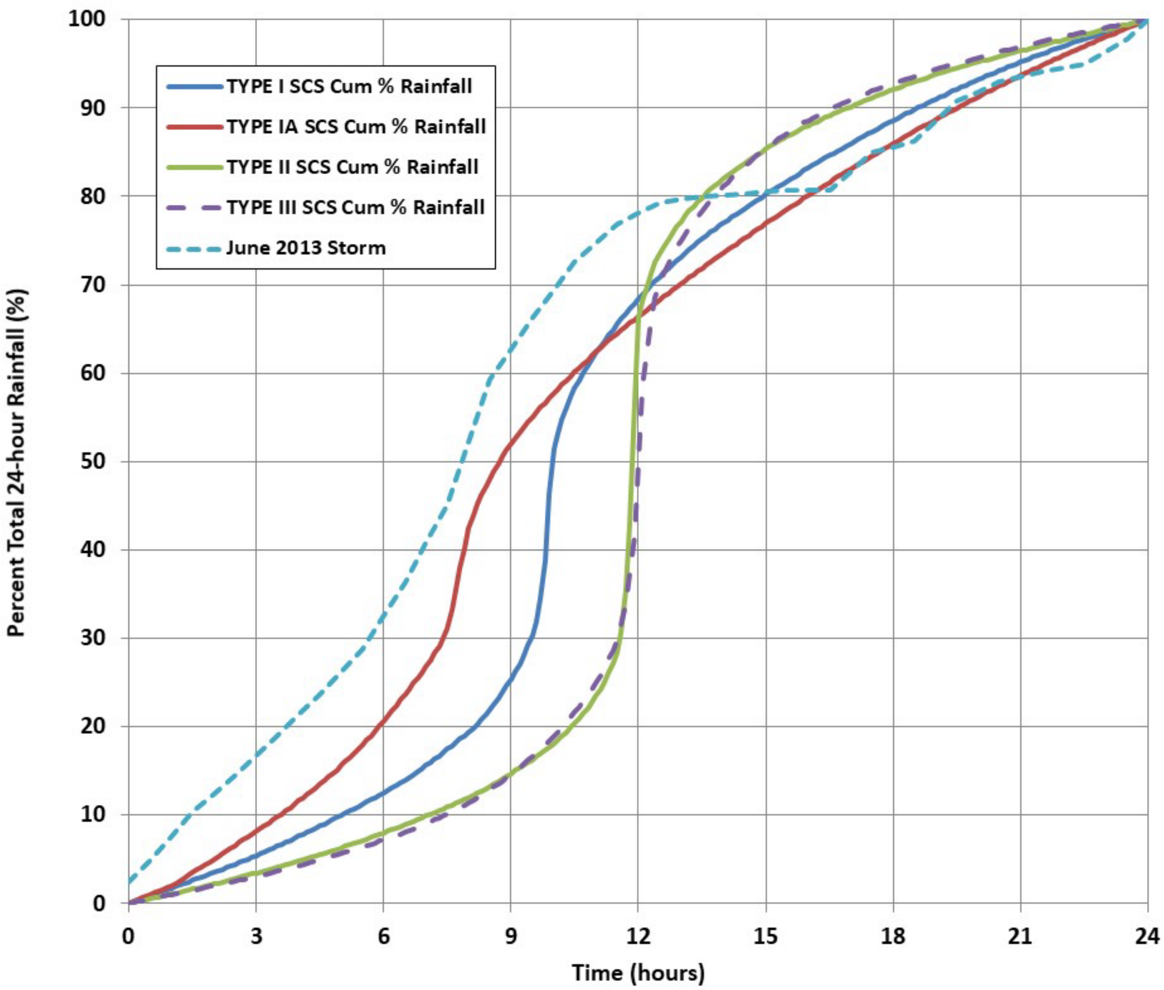

Figure B-5. SCS and June 2013 rainfall distributions.

B.2.4. Climate Change

Draft guidelines have been prepared for steep creek risk assessments in Alberta (BGC, September 4, 2015). Those guidelines stipulate that the qualified registered professional (QRP) consider projected climate change in steep creek assessments. Therefore, BGC also assessed the potential impacts of climate change on Three Sisters Creek peak flows.

The rainfall-runoff modeling was repeated for future conditions based on predicted changes to 24-hour rainfall amounts. While climate change is expected to alter temperatures and precipitation in the future, it is also expected to affect the magnitude and frequency of extreme precipitation events (Prein et al., 2017). The frequency of extremes predicted to increase approximately 2-fold in southwestern Alberta in June, July, and August (Figure B-6). The increase is due to a shift towards moister and warmer climatic conditions (Prein et al., 2017). Changes in short-term precipitation extremes contributes to the frequency and magnitude of debris floods and debris flows.

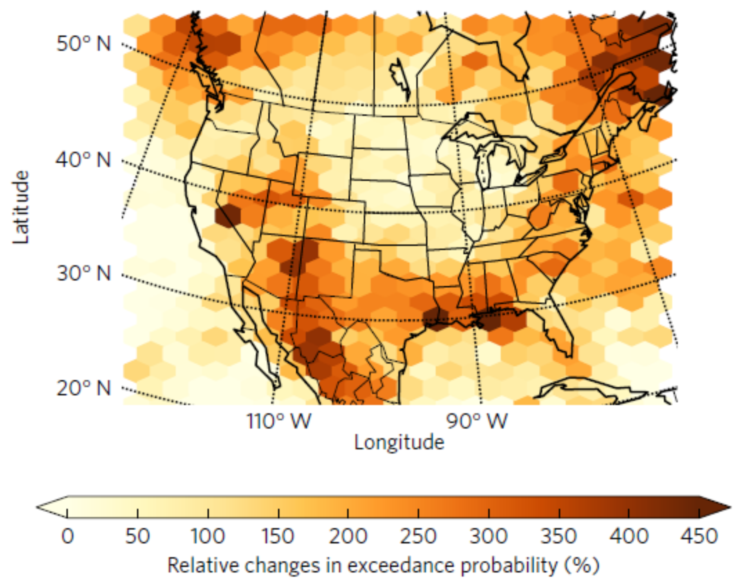

Figure B-6. Change in the exceedance probability of hourly precipitation intensities for June, July, and August (Prein et al, 2017).

BGC used the University of Western Ontario's IDF climate change tool (IDF_CC Tool 3.0) to evaluate the potential impacts of climate change on rainfall for a range of return periods. The tool was designed to analyze the effects of various Representative Carbon Pathway (RCP) scenarios on rainfall events based on GCM outputs.

The IDF_CC Tool allows for historical and climate change adjusted IDF data to be generated for gauged and ungauged sites at any location in Canada. The gauged Kananaskis climate station was selected within the tool and IDF data were generated using the model ensemble listed in Table B-3. As the IDF_CC Tool requires a minimum projection period of 50 years for climate change assessments, the period from 2021 to 2100 was selected along with Representative Concentration Pathway (RCP) 8.5 (i.e., emissions continue to rise in the 21st century, also known as the business-as-usual scenario). The results show an upward adjustment of 21% for the 100 year 24-hour rainfall depth compared to historical data. These results are also consistent with the projections of Zhang et al. (2019), who assessed potential climate change impacts on temperature and precipitation across Canada.

Table B-3. GCM ensembles used by BGC for the IDF_CC Tool.

University of Western Ontario IDF_CC Tool
CNRM-CM5
CanESM2
CSIRO-Mk3-6-0
CCSM4
MIROC5
MPI-ESM-LR
MRI-CGCM3
GFDL-ESM2G
HadGEM2-ES

BGC also evaluated an ensemble of 9 different bias-corrected GCMs from the Pacific Climate Impacts Consortium[5] (PCIC) for the time period from 2050 to 2100. Two RCP scenarios were considered: the RCP 4.5 scenario and the RCP 8.5 scenario. RCP 4.5 is a reasonably optimistic scenario that represents reaching a radiative forcing[6] of 4.5 W/m^2 between now and 2100, accompanied by an increase in annual global temperature of 2°C over pre-industrial levels. Both RCP scenarios project 24-hour rainfall increasing by approximately 30%.

For this study, an increase in the 24-hour rainfall depths of 30% was adopted for conservatism.

5 The Pacific Climate Impacts Consortium (PCIC) is a climate service center out of the University of Victoria. PCIC focuses on climate studies and the impacts of a changing climate for the BC and Yukon regions.

6 Radiative forcing is the net radiative flux on the Earth's atmosphere. It is expressed as power per area (Watts per square meter). Net radiative flux is the amount of energy absorbed by the Earth compared to the amount of energy redirected to space.

B.2.5. Rainfall Summary

Table B-4 summarizes the 24-hour rainfall estimates adopted for the HEC-HMS modelling.

Table B-4. Summary of 24-hour rainfall estimates for the Kananaskis (3053600) climate station using data from 1940 to 2019 and LPIII distribution.

24-hour Rainfall (mm)	Return Period (Years)						
	10	30	100	300	1000	3000	PMP
Existing Conditions	75	100	132	167	213	263	300-400
Climate Change (2050-2100)	100	130	170	215	275	340	

B.3. HEC-HMS MODELLING

The 24-hour rainfall values were input to the HEC-HMS model to determine the peak discharge for a given return period both for existing conditions and under climate change. The resulting peak discharge values are summarized in Table B-5.

Table B-1. Estimated peak discharge for Three Sisters Creek based on historical rainfall at the Kananaskis climate station and under possible climate change conditions.

	Units	Return Period (Years)					
		10	30	100	300	1000	3000
BGC (October 31, 2014)	m^3/s	10	-	19	29	42	54
BGC, 2020	m^3/s	2	6	15	27	45	66
2050-2100 RCP 8.5	m^3/s	5	14	30	48	73	102

As noted earlier, the 2013 storm had an estimated peak discharge in the range of 20 to 25 m^3/s. Based on Table B-5, the associated return period would be 100 to 300 years. This return period is consistent with work on Cougar Creek where BGC (December 11, 2013) estimated that the return period of the 2013 flood could be between 200 and 350 years, while nhc (June 27, 2017) estimated a return period of approximately 200 years. The 1000-year return period peak flow (Q_{1000}) estimate of 45 m^3/s is also consistent with rainfall-runoff modelling conducted by nhc (June 27, 2017). nhc estimated that the Q_{1000} on Cougar Creek was 180 m^3/s. Scaling by drainage area and using an exponent of 0.8, a Q_{1000} value of 53 m^3/s is estimated for Three Sisters Creek.

Of note is that the significant increase in peaks for the climate change scenario. This increase is a result of the increased rainfall contributing directly to runoff, rather than a portion going into soil storage.

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APPENDIX C
BANK EROSION ANALYSIS

APPENDIX C – BANK EROSION ANALYSIS

C.1. INTRODUCTION

Debris floods exert high shear stresses on stream channel bed and banks. As a result, debris floods may cause damage not only by inundating fan areas with water and debris, but also through bank erosion. In the Bow Valley, steep creek banks on fans consist predominantly of unconsolidated, loose and non-cohesive sandy gravels. At Three Sisters Creek, there are also few trees adjacent to the creek along Middle Fan as a result of past development and the golf course construction. The combination of non-cohesive bank material with little root strength makes the banks of Three Sisters Creek particularly susceptible to bank erosion, as evidenced by the extensive erosion that occurred during the June 2013 debris flood.

C.2. HISTORICAL IMAGERY ANALYSIS

Several years of air photos and satellite imagery, dating from 1947 to 2015, were georeferenced in a geographic information system (GIS) and used to identify changes in the size and location of the Three Sisters Creek channel over time. Potential error or uncertainty in these measurements can be introduced by shadows from vegetation, poor image quality, distortion during rectification, or errors in georeferencing; BGC estimates the cumulative error associated with these factors is approximately 5 m at Three Sisters Creek. Depending on the resolution, quality, and recurrence frequency of the photos and the thickness of the vegetation, it is also possible to observe changes to the fan surface such as fresh debris lobes or channels, or recent breaks in vegetation cover. Table C-1 summarizes the observations from the available imagery.

Table C-1. Air photo and satellite imagery descriptions.

Year	Roll	Photo No.	Scale	Observations
1947	A10908	109, 110	1:40,000	Black and white grainy photograph covering the entire fan area. Partially vegetated avulsion channels are present to the east of the main channel, extending into the Lower Fan. Recent landslides appear to have occurred on the west side of the valley, immediately upstream of the fan apex, and there is abundant exposed sediment within the main channel.
1949	AS 0168	136	1:40,000	Black and white photograph covering the full fan area. Additional vegetation is present within the main channel, producing channel narrowing in the Upper Fan and Middle Fan. A 20 m wide right-of-way (RoW) was constructed across the northernmost extent of the Middle Fan, oriented northwest to southeast.
1962	AS 0830	51, 52	1:31,600	Black and white photo covering the full fan extent. Further narrowing has occurred through the Upper and Middle Fan reaches relative to the 1949 photo, and vegetation density has increased within the avulsion channels. The powerline RoW was widened to 60 m in the Middle Fan, and the main channel appears to have been engineered at the RoW (as well as upstream).
1972	AS 1185	5, 6	1:21,120	Black and white photo blurry photo covering the entire fan area. The photo quality is poor, but vegetation encroachment and channel narrowing appear to have continued since the previous photo.
1975	AS 1383	105, 106, 153-155	1:12,000	Small scale black and white photos each covering a portion of the fan area. The channel appears to have widened slightly in the Middle Fan, upstream of the RoW, but the apparent change may reflect differences in the air photo quality.
1984	AS 3085	39, 40, 73, 74	1:20,000	Colour photo covering the entire fan area. Vegetation has grown across much of the channel bed in the Upper Fan, narrowing the channel, and the historical avulsion channels on the east side of the fan are well vegetated. A gravel mine is now present at the downstream end of the Middle Fan (crossing the RoW) and will later become the golf course pond. Extensive exposed gravel is present within the pit.
1997	AS 4824	42, 43, 62, 63	1:15,000	Colour photo covering the entire fan area. The main channel has widened relative to the 1984 photo in the reach upstream of the gravel pit. The gravel pit appears to have narrowed. The avulsion channels to the east of the main channel are densely vegetated and becoming difficult to distinguish from the surrounding forest.

Year	Roll	Photo No.	Scale	Observations
2008	AS 5450	217, 240	1:30,000	Colour photo covering the full fan extent. Extensive development has occurred, including the construction of a golf course in the Middle Fan, and construction of a subdivision within the Middle and Lower Fan to the east of the main channel. The golf course pond – at the location of the gravel pit – is inundated, and extensive riprap is present for over 200 m upstream of the pond. A pedestrian bridge has been added at the downstream end of the pond. Vegetation has densified within the Upper Fan and is now also present throughout much of the channel bed upstream of the engineered segment in the Middle Fan. The historical avulsion paths have been developed and are no longer visible, and a berm is present at the upstream (south) end of the avulsion channels.
2013	Orthophoto	-	-	Colour orthophoto covering the full fan extent. Dramatic channel widening has occurred throughout the Upper and Middle Fan reaches. The golf course pond has been infilled with sediment, and the channel engineering upstream of the golf course pond is no longer visible. Erosion is also visible at the outlet of the golf course pond, downstream of the Lower Bridge, and downstream of Three Sisters Parkway.
2015	ESRI World Imagery	-	-	Colour satellite imagery. Mitigation measures are visible throughout the channel and include channelization and regrading throughout the Upper and Middle Fan reaches and sediment removal from the golf course pond. Riprap has been placed at the outlet of the golf course pond, in the reach extending from the Lower Bridge to Three Sisters Parkway, and for a stream length of nearly 100 m downstream of Three Sisters Parkway.

BGC delineated the channel bank location for eight of the photo years. Unvegetated avulsion channels were also delineated if present. Drawing 02 shows the channel position within the fan for several years of imagery, as well as the delineated channel centerline in 1947 and 2015. BGC also delineated the channel banks for several intervening years to evaluate changes in channel width (Table C-2).

From the air photo analysis, it appears that a large event (Class 4) occurred sometime before 1947 producing an avulsion on the eastern floodplain. The channel then narrowed from 1947 to 1962 as vegetation established on sediment deposited during the earlier event. Following a slight widening on the 1975 air photo, the channel again narrowed in the 1984 and 1997 imagery, before widening a second time in 1997. This suggests that in addition to the large event prior to 1947, smaller events also occurred in the period from 1962 to 1975 and from 1984 to 1997. The largest debris flood occurred in 2013 (Drawing 03), producing dramatic widening throughout the Upper Fan and Middle Fan (Table C-2).

Table C-2. Summary of changes in channel width in the Upper, Middle, and Lower Fan over time.

Imagery Year	Upper Fan Average Width (m)	Middle Fan Average Width (m)	Lower Fan Average Width (m)
1949	18	25	-
1962	21	21	5
1975	**24**	**28**	**4**
1984	11	9	5
1997	**10**	**24**	**5**
2008	8	16	4
2013	**36**	**37**	**6**
2015[1]	39	45	7

Note:

1. Increased width from 2013 to 2015 is attributable to in-stream mitigation works (e.g., channelization upstream of the GCP) rather than a debris flood event.

C.3. PROBABILISTIC NUMERICAL MODELING

BGC used a probabilistic, physically based model to predict the extent of bank erosion that could occur during a single event. The model builds upon recent work conducted at the Mountain Channel Hydraulic Experimental Laboratory at the University of British Columbia (e.g., Eaton, MacKenzie, Jakob, & Weatherly, 2017; Mackenzie, Eaton, & Church, 2018), as well as numerical modeling conducted by Davidson and Eaton (2018).

The model relies on the following assumptions:

- Bank erosion occurs when the coarse material on the channel bed is fully mobilized, as the bed destabilizes leading to undercutting the banks and rapid retreat.
- The threshold for erosion can be defined in terms of the critical shear stress, τ_c required to fully mobilize the coarse fraction (D_{84}) of the bed material.
- Erosion occurs rapidly during a single flood event and proceeds until the flow depth reaches the critical value, leading to re-stabilization of the D_{84} and prevent further widening (Figure C-1). As a result, the magnitude of bank erosion can be predicted based on flood discharge.

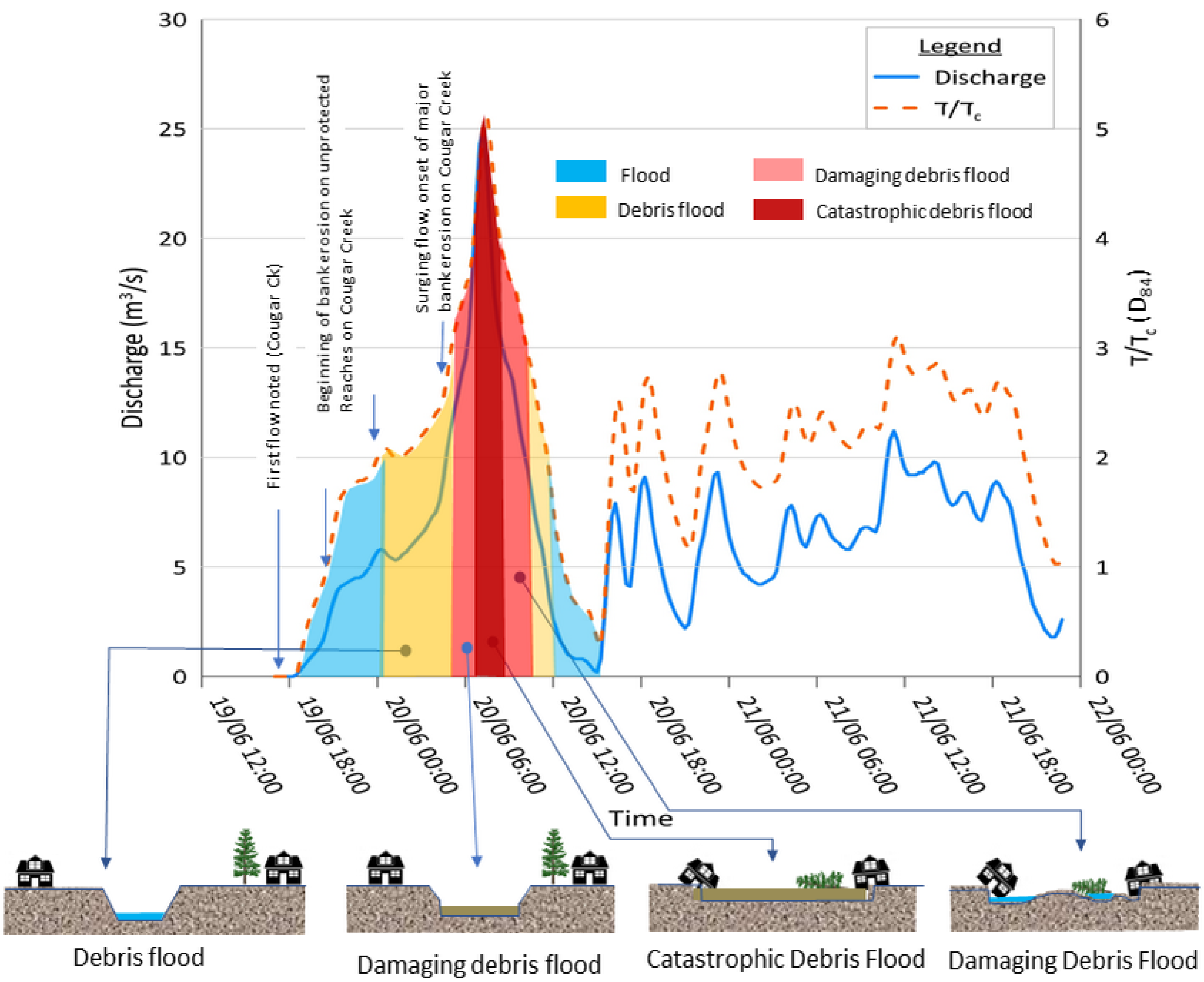

Figure C-1. Hydrograph and shear stress ratio during the June 19-31 debris flood on Three Sisters Creek. Debris flood stages are indexed by the shear stress ratio.

The governing equation to determine the amount of erosion (E) for each return period flood (Q_i) is given by:

$$E = 0.85W_0\left(\frac{Q_i}{Q_c} - 1\right) \quad \text{[Eq. C-1]}$$

where W_0 is the pre-flood channel width and Q_c is the critical discharge at which erosion initiates.

The critical discharge (Q_c) is a function of the shear stress needed to mobilize the coarse particles on the channel bed (D_{84}), which control the overall bed stability. It is calculated according to Eq. C-2:

$$Q_c = \frac{2 \cdot D_{84} \cdot \theta_c \cdot (\rho_S - \rho_{cwb})}{\rho_{cwb} S} \quad \text{[Eq. C-2]}$$

where θ_c is the dimensionless critical shear stress (Shields number) required to entrain the D_{84}, S is the channel slope, ρ_S is the density of sediment, and ρ_{cwb} is the bulked water density[1].

Dimensionless critical shear stress has been shown to increase with gradient in steep creeks, such that grains of the same size will be more stable on the Three Sisters Creek fan (9% average gradient) than they would be in a lower gradient setting (Lamb, Dietrich, & Venditti, 2008; Prancevic & Lamb, 2015). As the Shields number is difficult to characterize in the absence of sediment transport observations, BGC adjusted this parameter to calibrate the model to match the measured erosion as a result of the approximate 300-year return period event in 2013. The resulting value of 0.07 is reasonable given the stream gradient and the use of the the D_{84} in the model and not the D_{50}; larger particles are more exposed to the flow and will therefore be entrained at lower shear stresses than the median particle size.

BGC then used a Monte Carlo modeling approach to predict future erosion at Three Sisters Creek based on the current channel configuration, for both current and future climate conditions. This stochastic model explicitly incorporates variability in model inputs, such as grain size (D_{95}), channel geometry (e.g., S, W_0) and dimensionless critical shear stress (θ_c). Unlike deterministic models, which provide a single prediction for each event, this modeling approach provides a probabilistic distribution of bank erosion estimates for each return period. For example, while a deterministic model might predict 10 m of erosion during a 100-year event, the stochastic model could show that while the event has a 50% probability of erosion exceeding 10 m, it has only a 5% probability of exceeding 20 m.

C.4. SUMMARY

Table C-1 summarizes the erosion estimates for floods with return periods ranging from 30 years to 3000 years under the current (i.e., historical) climate conditions. Erosion was only modeled for the Upper Fan and Middle Fan, extending from the fan apex to the GCP. Erosion was not modeled for the lower fan as it is bounded partially by bedrock and dense till which are much less erodible than alluvium. Since bedrock and till has not been mapped, it is not possible to reliably model

[1] The bulked water density is a function of the concentration of sediment in the water.

bank erosion in this channel reach. Future bank erosion will occur preferentially in channel sections with a cap of fan alluvium and minor (centimeter to less than a metre) erosion expected in bedrock and dense till sections.

Table C-1. Summary of predicted erosion for the current (i.e., historical) hydrological conditions.

Return Period (Years)	Bulked Peak Discharge (m^3/s)	Predicted Erosion (m)				
		5%[1]	25%	50% (Median)	75%	95%
10-30	6	0	0	0	0	0
30-100	16	3	5	6	8	11
100-300	28	17	21	25	29	36
300-1000	50	52	61	69	78	92
1000-3000	73	73	84	94	105	124

Note:

1. The percentages represent the probability of non-exceedance. For example, there is a 5% probability that erosion will not exceed the 5% predicted erosion and a 95% probability that it will exceed this value.

The modeling was repeated for the RCP 8.5 climate change scenario which is presented in detail in Appendix B. The results for the time frame 2050-2100 are summarized in Table C-2.

Table C-2. Summary of predicted erosion for the year 2050 to 2100 under the RCP 8.5 climate change scenario.

Return Period (Years)	Peak Discharge (m^3/s)	Predicted Erosion (m)				
		5%[1]	25%	50% (Median)	75%	95%
10-30	15	2	4	6	8	11
30-100	32	20	25	29	34	41
100-300	50	40	49	55	62	74
300-1000	80	84	98	110	122	143
1000-3000	112	121	141	156	173	202

Note:

1. The columns represent the probability of exceedance. For example, there is a 5% probability that erosion will not exceed the 5% predicted erosion and a 95% probability that it will exceed this value.

Bank erosion is predicted to increase substantially in the future (2050 to 2100) relative to the current conditions. Under the future conditions, BGC predicts that erosion will occur for all return period events, including the 10-30-year return period which is predicted to remain stable under the current conditions. The increase in bank erosion is driven by increases in the peak discharge for a given return period, with large proportional increases for more frequent events. BGC predicts that the median erosion will increase by nearly 400% for the 30-100-year event in response to a doubling of peak discharge. For the largest event (1000-3000-year return period), BGC predicts that the median erosion will increase by 65% as a result of a 55% increase in peak discharge.

BGC used the current channel geometry to model erosion under the future climate conditions in 2050 to 2100. In rivers with erodible banks (and without bank protection), channel size is likely to increase over time in response to larger formative flows resulting in a wider channel geometry (e.g., Wilhere, Atha, Quinn, Helbrecht, & Tohver, 2016). Given that the modeling was conducted using the current channel width, erosion may be over-predicted in the future period if the channel is able to adjust in size over the coming decades, as the shear stress associated with a given flood is lower in a wider channel.

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APPENDIX D
NUMERICAL MODELING

APPENDIX D - NUMERICAL MODELING

D.1. INTRODUCTION

This appendix describes the approach used to develop numerical models to represent the 10 to 3000-year debris flood events. Modelling allows the estimation of the corresponding flood extent for each return period. The following sections detail the methodology followed to develop the models including the development of Digital Elevation Models (DEM) for the channel and floodplain, and the development of the hydraulic model. A review of modelling limitations is also included.

Hydrodynamic modelling was completed using FLO-2D Version 19.07.21, a two-dimensional, volume conservation hydrodynamic model. It is a Federal Emergency Management Agency (FEMA) approved model which lends additional legitimacy of the model. Comparisons between FLO-2D and other debris flow models (i.e., RAMMS or DAN 3D), have shown that it yields reasonable results once calibrated with known events (Cesca & D'Agostino, 2008; Moase, Strouth, & Mitchell, 2018).

In FLO-2D, 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 2D 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.

D.2. INITIAL SETUP

The model domain was selected to include the entire fan extent as well as the proposed Three Sisters Mountain Village to ensure that all flooding, including avulsions were included. Detailed topographic data of the floodplain are available from high-resolution lidar datasets obtained by the Town of Canmore through multiple providers. Lidar of the Bow Valley was flown in 2009, 2013 and 2015. Only the 2013 and 2015 lidar sets were used for modelling. Additionally, the golf course pond as-built plans were used in place of bathymetry data to create a pond bottom rather than the water surface that lidar captures. Models were run on a grid generated from a DEM constructed from the lidar-generated topography. Grid spacing was set to 4 m, as the number of cells in the model should not exceed about 30,000 cells to ensure reasonable processing times for the models. Elevation is averaged for each cell from the DEM.

Appropriate boundaries and boundary conditions were selected to best show how the flows would interact with the topography and development. Individual buildings were not included, instead the model domain was designed to cover the main development on the fan. Manning's *n* values were input for all cells depending on whether the cell was in the channel, on a main road, or on the fan. FLO-2D overrides the specified Manning's n input value as required by the limiting Froude constraint (FLO-2D Software Inc., 2017). For all creeks a limiting Froude number of 1.1 was specified, as supercritical flow is rare for fan reaches with moderate gradients, especially for lower return period flows (Grant,1997). A Manning's *n* value of 0.04 was chosen for the main channel, golf course and developed areas, 0.03 for Three Sisters Parkway and 0.08 for forested areas.

Infiltration parameters were not used in the analysis, as it is challenging to predict the groundwater level. This means that the model results are somewhat conservative as they assume no fan infiltration which may not be the case for short (minutes to an hour or so) duration convective storms but would be likely for a multi-day storm with high groundwater levels.

A hydrograph for the inflow cell at the fan apex was specified depending on the modeled return period. The peak discharge of the hydrograph is changed between model scenarios to model different event sediment concentrations and peak discharges. Debris-flood input hydrographs used a scaled hydrograph shape based on the 2013 event storm hydrograph (BGC, August 1, 2014).

2.1. Model Runs

Table D-1 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.

Table D-1. Summary of FLO-2D modeling scenarios. Aggradation scenarios are based on the lidar digital elevation model that was generated within days of the June 19-21, 2013 events and reflect the net channel changes prior to major sediment removals.

Scenario ID	Return Period (years)	Bulking Factor	Bulked Peak Flow (m^3/s)	Scenario Description
1a	10-30	1.05	15	Current channel, no blockage, no aggradation (2015 lidar)
1b				Aggraded channel, some sediment infilling (2013 lidar)
2a	30-100	1.05	32	Current channel, no blockage, no aggradation (2015 lidar)
2b				Aggraded channel, some sediment infilling (2013 lidar)
3a	100-300	1.05	50	Current channel, no blockage, no aggradation (2015 lidar)
3b				Aggraded channel, some sediment infilling (2013 lidar)
4a	300-1000	1.1	80	Current channel, no blockage, no aggradation (2015 lidar)
4b				Aggraded channel, some sediment infilling (2013 lidar)
4c				Main channel blocked, simulating an avulsion (2015 lidar, with blockage)
5a	1000-3000	1.1	112	Current channel, no blockage, no aggradation (2015 lidar)

5b				Aggraded channel, some sediment infilling (2013 lidar)
5c				Main channel blocked, simulating an avulsion (2015 lidar, with blockage)

Of note in Table D-1 is that the discharge selected for the given return period range represents the upper bound of the range. These outputs are shown as individual modelling results and also combined into a composite hazard map. To combine multiple scenarios for each return period class, each scenario was assigned a probability of occurrence. These probabilities are shown in Table D-2 and were developed using professional judgement. The sensitivity of the composite hazard map to the below scenario probabilities was tested by varying the probabilities by +/- 20%. This changed the hazard rating of the modeled inundation area by up to 1.5%, demonstrating that altering the scenario probabilities is unlikely to change the composite hazard rating. Therefore minor (10-20%) changes in the ratio of probabilities for specific scenarios have little bearing on the composite hazard map results.

Table D-2. Scenario probabilities.

Scenario ID	Return Period (years)	Scenario Description	Scenario Probability (%)
1a	10-30	Current, no blockage, no aggradation (2015 lidar)	70
1b		Aggradation (2013 lidar)	30
2a	30-100	Current, no blockage, no aggradation (2015 lidar)	50
2b		Aggradation (2013 lidar)	50
3a	100-300	Current, no blockage, no aggradation (2015 lidar)	40
3b		Aggradation (2013 lidar)	60
4a	300-1000	Current, no blockage, no aggradation (2015 lidar)	20
4b		Aggradation (2013 lidar)	70
4c		Blockage (2015 lidar, with blockage)	10
5a	1000-3000	Current, no blockage, no aggradation (2015 lidar)	20
5b		Aggradation (2013 lidar)	60
5c		Blockage (2015 lidar, with blockage)	20

2.2. Uncertainties

Debris floods involve complex and dynamic physical processes that are variable in space and time. No two debris floods, even with identical volumes, are expected to result 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.

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-flood volumes, peak flows, and hydrograph shapes (e.g., those uncertainties described in the preceding sections), model uncertainties include the following:

- 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 as the module of FLO-2D used does not allow for morphodynamic changes to the input topography (possibly significant, especially if knickpoints develop)
- Sediment transport and deposition processes as FLO-2D does not accurately model sediment at concentrations of <20% and therefore only clearwater inflow as used in the modelling (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 Three Sisters Creek fan. However, by conducting multiple models runs with differing assumptions of bank erosion and channel aggradation, 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 flood outcomes.

Auxiliary hazards are not reflected in the modeling. For example, water flowing uncontrolled over Three Sisters Parkway in case of a debris flood exceeding the culvert capacity at the Parkway, are likely to erode into the northern road embankment leading to gullying, retrogressive erosion and possible severance of the Parkway with a deep (several metres) gully connecting the upstream Parkway ditch with the confluence of the overflow with the lower Three Sisters Creek. Such auxiliary hazards need to be accounted for in the option analysis which will be presented under separate cover.

REFERENCES

BGC Engineering Inc. (2014, August 1). *Cougar Creek Forensic Analysis – Hydroclimatic Analysis of the June 2013 Storm* [Report]. Prepared for Town of Canmore.

Cesca, M., & D'Agostino, V. (2008). Comparison between FLO-2D and RAMMS in debris-flow modelling: a case study in the Dolomites. *Monitoring, Simulation, Prevention and Remediation of Dense Debris Flows II*. https://doi.org/10.2495/deb080201

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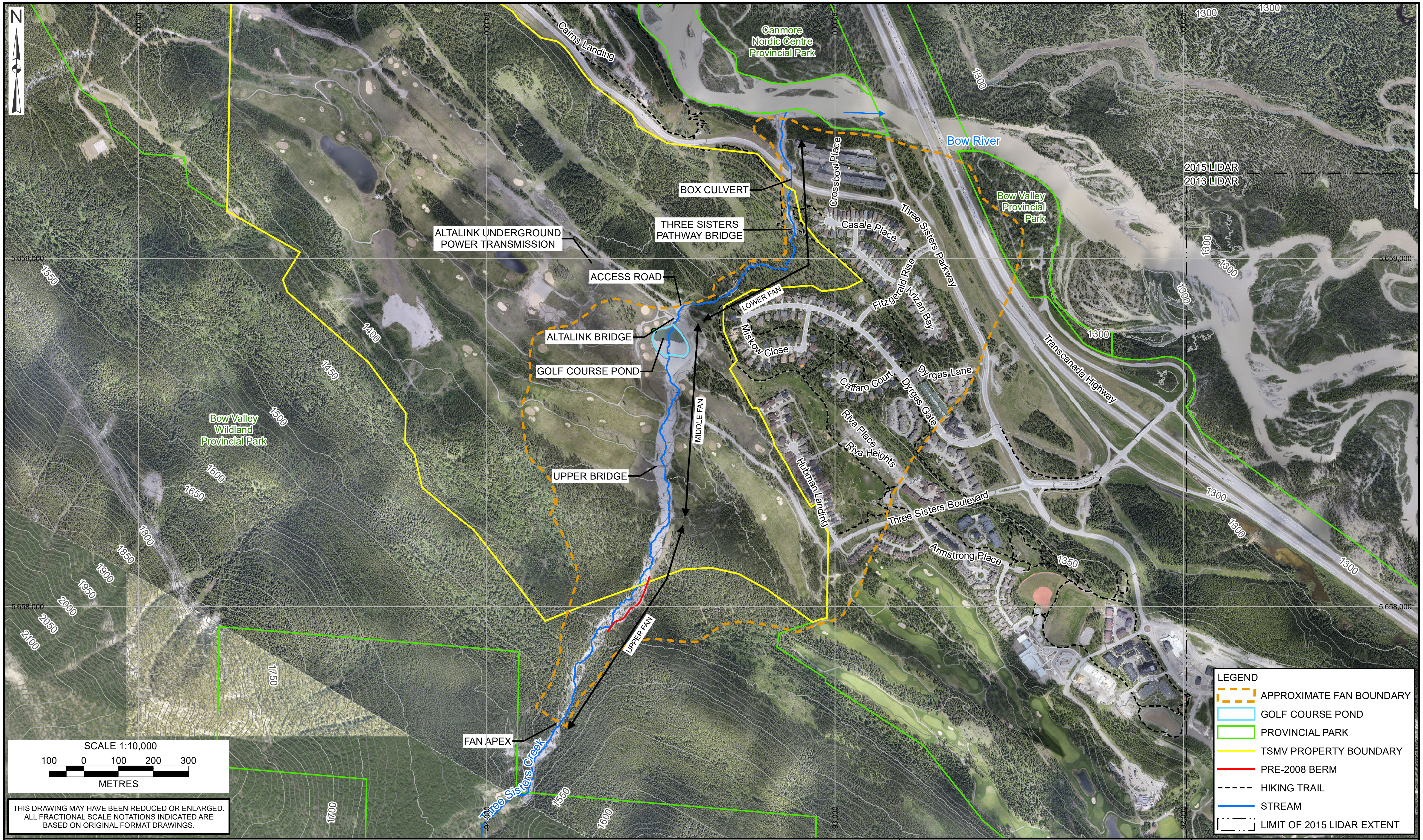
Grant, G. (1997). Critical flow constrains flow hydraulics in mobile-bed streams: a new hypothesis. *Water Resources Research, 33*(2), 349-358. https://doi.org/10.1029/96WR03134

Moase, E., Strouth, A., & Mitchell, A. (2018). A comparison of different approaches for modeling a fine-grained debris flow. Paper presented at Second JTC1 Workshop on Triggering and Propagation of Rapid Flow-like Landslides, Hong Kong, Seton Portage, BC.

DRAWINGS



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DATE:	OCT 2020
DRAWN:	BMB, LL
CHECKED:	SD, BCP
APPROVED:	MJ

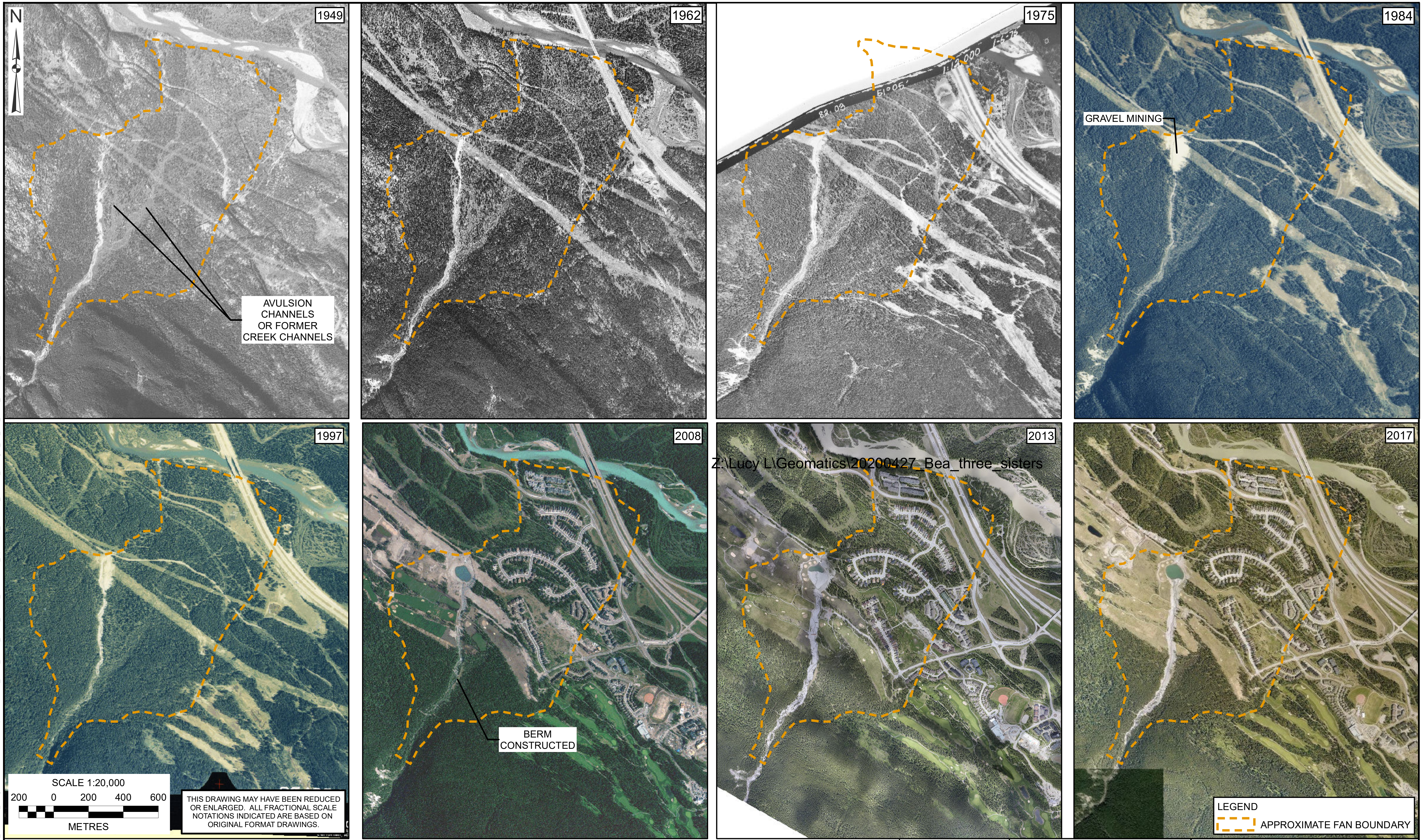
BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: THREE SISTERS mountain village

PROJECT: THREE SISTERS CREEK HAZARD ASSESSMENT UPDATE

TITLE: 2013 ORTHOPHOTO OF THREE SISTERS CREEK FAN

PROJECT No.:	DWG No.:
1531 003	01



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4. 1949, 1962, 1984, 1997, 2008 AIR PHOTOS PROVIDED BY THE ALBERTA AIR PHOTO LIBRARY AND THE NATIONAL AIR PHOTO LIBRARY. 2013 ORTHOPHOTO PROVIDED BY THE TOWN OF CANMORE. 2017 IMAGERY FROM WORLD_IMAGERY_BASEMAP.
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APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: THREE SISTERS mountain village

PROJECT: THREE SISTERS CREEK HAZARD ASSESSMENT UPDATE

TITLE: HISTORICAL CHANNEL CHANGES ON THE THREE SISTERS CREEK FAN

PROJECT No.: 1531 003

DWG No.: 02

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THIS DRAWING MAY HAVE BEEN REDUCED OR ENLARGED. ALL FRACTIONAL SCALE NOTATIONS INDICATED ARE BASED ON ORIGINAL FORMAT DRAWINGS.

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CHECKED:	BCP
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: THREE SISTERS mountain village

PROJECT: THREE SISTERS CREEK HAZARD ASSESSMENT UPDATE

TITLE: THREE SISTERS CREEK CHANNEL CHANGES FROM 2008 TO 2017

PROJECT No.: 1531 003

DWG No.: 03

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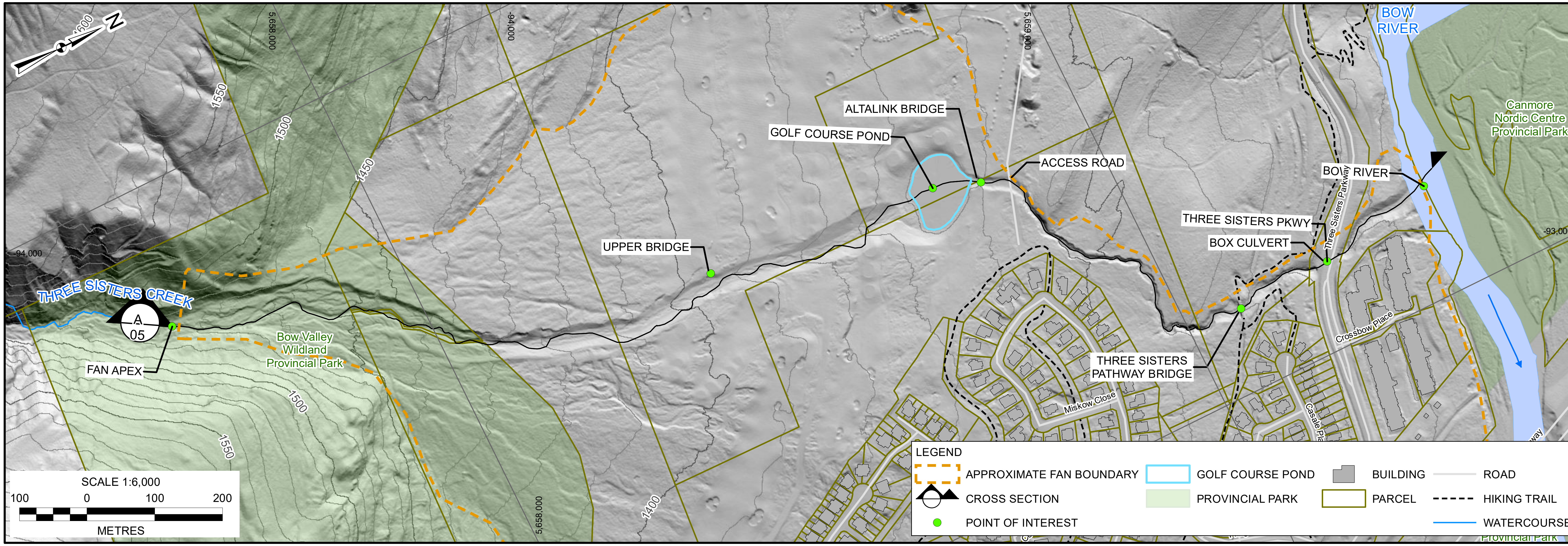

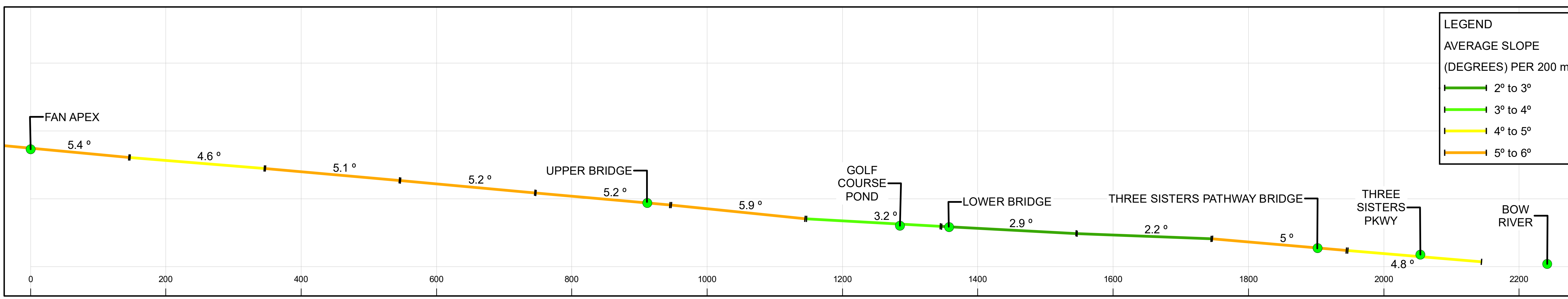

SCALE 1:6,000

100 0 100 200

METRES

DISTANCE (m)

CROSS SECTION A/05

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APPROVED:	MJ

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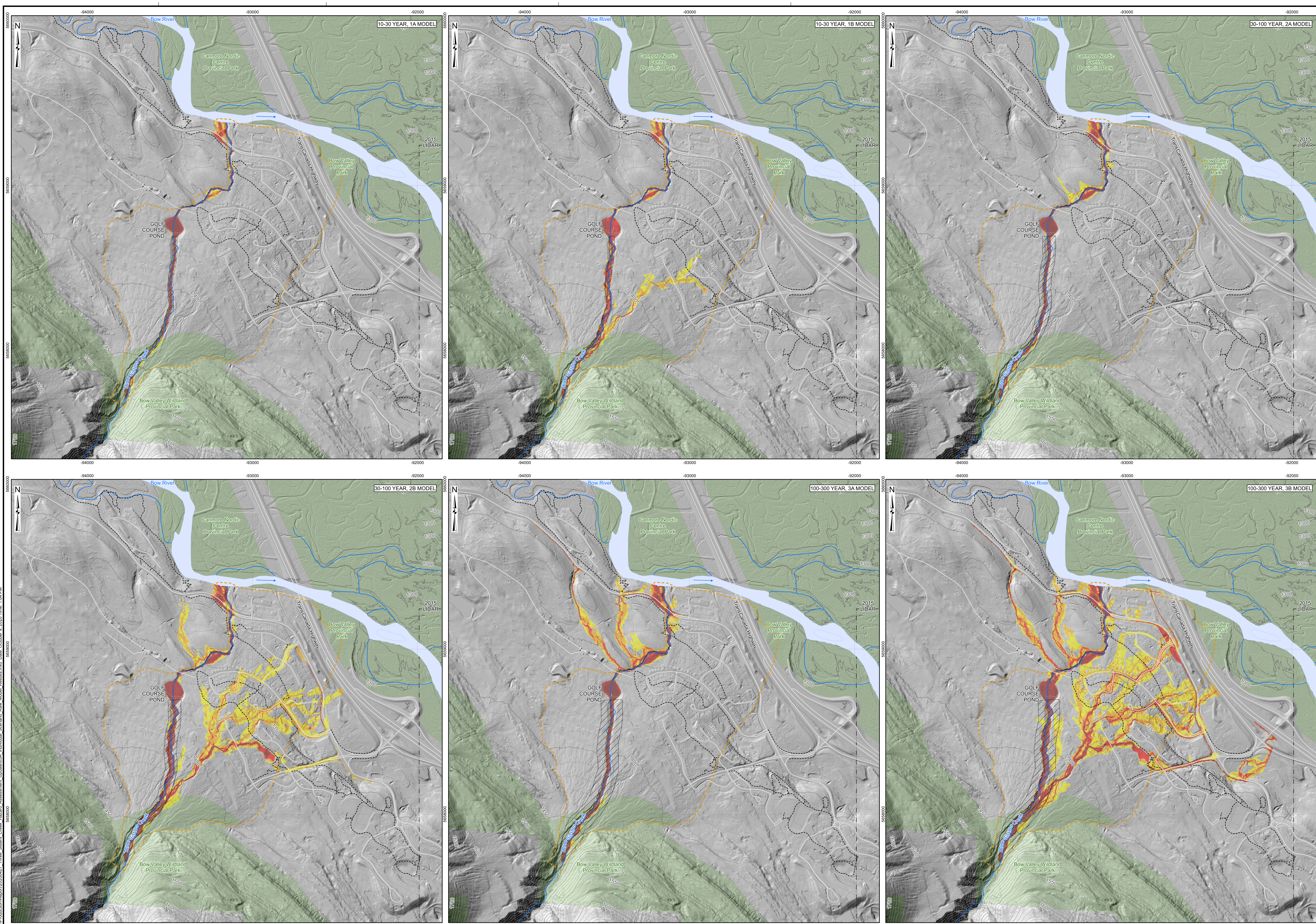
CLIENT: THREE SISTERS mountain village

PROJECT: THREE SISTERS CREEK HAZARD ASSESSMENT UPDATE

TITLE: THREE SISTERS CREEK PROFILE

PROJECT No.: 1531 003 | 04



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METRES

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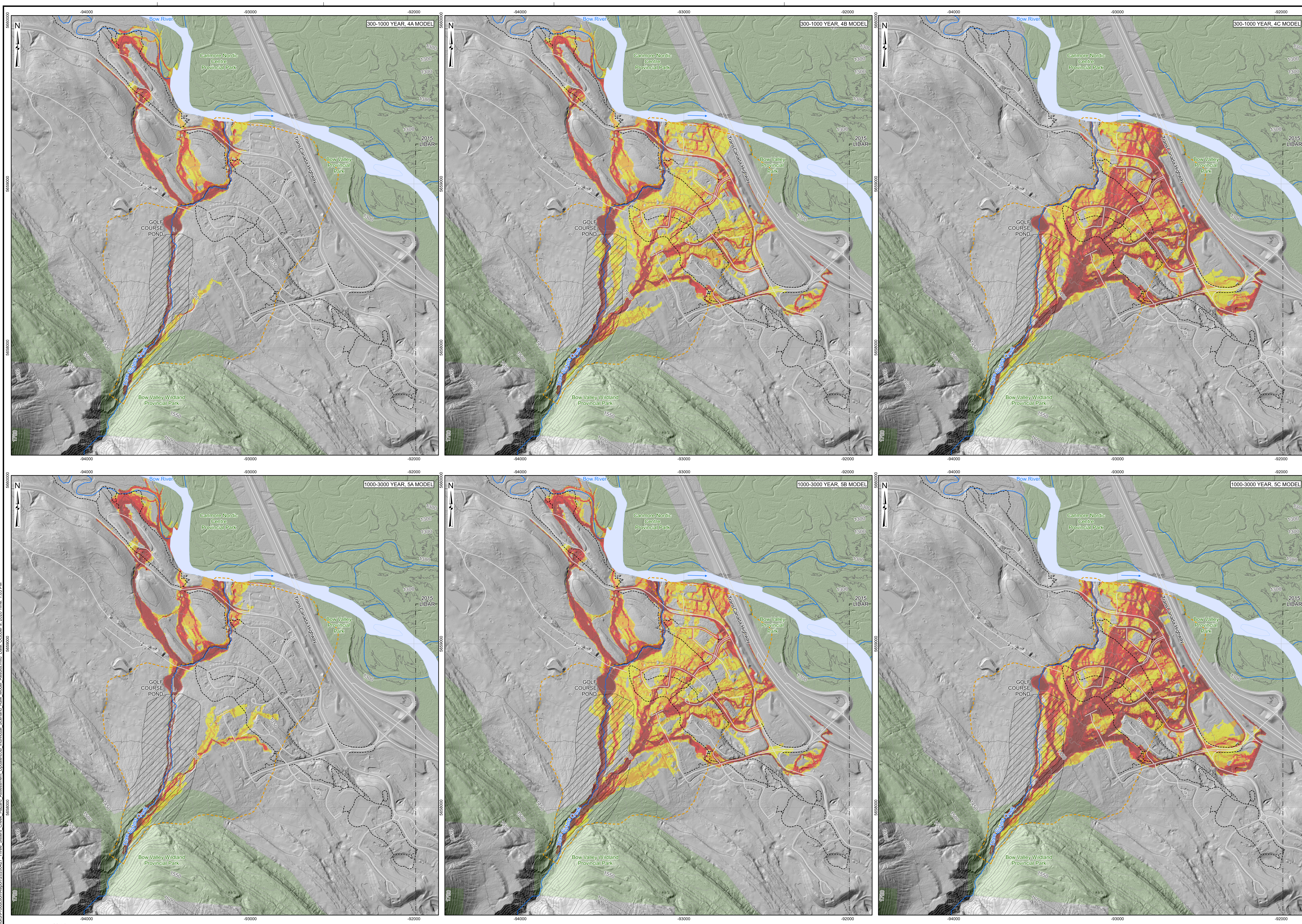
LEGEND
- APPROXIMATE FAN BOUNDARY
- CORRESPONDING BANK EROSION CORRIDOR (50TH PERCENTILE)
- PROVINCIAL PARK
- ROAD
- HIKING TRAIL
- STREAM
- WATERBODY
- LIMIT OF 2015 LIDAR EXTENT

IMPACT FORCE (kN/m)
- < 1
- 1 to 10
- 10 to 100
- 100 to 1000
- > 1000

SCALE: 1:7,500	BGC ENGINEERING INC. AN APPLIED EARTH SCIENCES COMPANY	PROJECT: THREE SISTERS CREEK HAZARD ASSESSMENT UPDATE	
DATE: OCT 2020		TITLE: INDIVIDUAL SCENARIO MODEL RESULTS (10-300 YEAR)	
DRAWN: MIB, LL	CLIENT: THREE SISTERS mountain village		
CHECKED: BCP, LCH		PROJECT No.: 1531003	DWG No.: 05A
APPROVED: MJ			

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



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- CORRESPONDING BANK EROSION CORRIDOR (50TH PERCENTILE)
- PROVINCIAL PARK
- ROAD
- HIKING TRAIL
- STREAM
- WATERBODY
- LIMIT OF 2015 LIDAR EXTENT

IMPACT FORCE (kN/m)
- < 1
- 1 to 10
- 10 to 100
- 100 to 1000
- > 1000

SCALE:	1:7,500
DATE:	OCT 2020
DRAWN:	MIB, LL
CHECKED:	BCP, LCH
APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT: THREE SISTERS mountain village

PROJECT: THREE SISTERS CREEK HAZARD ASSESSMENT UPDATE

TITLE: INDIVIDUAL SCENARIO MODEL RESULTS (300-3000 YEAR)

PROJECT No.: 1531003

DWG No.: 05B

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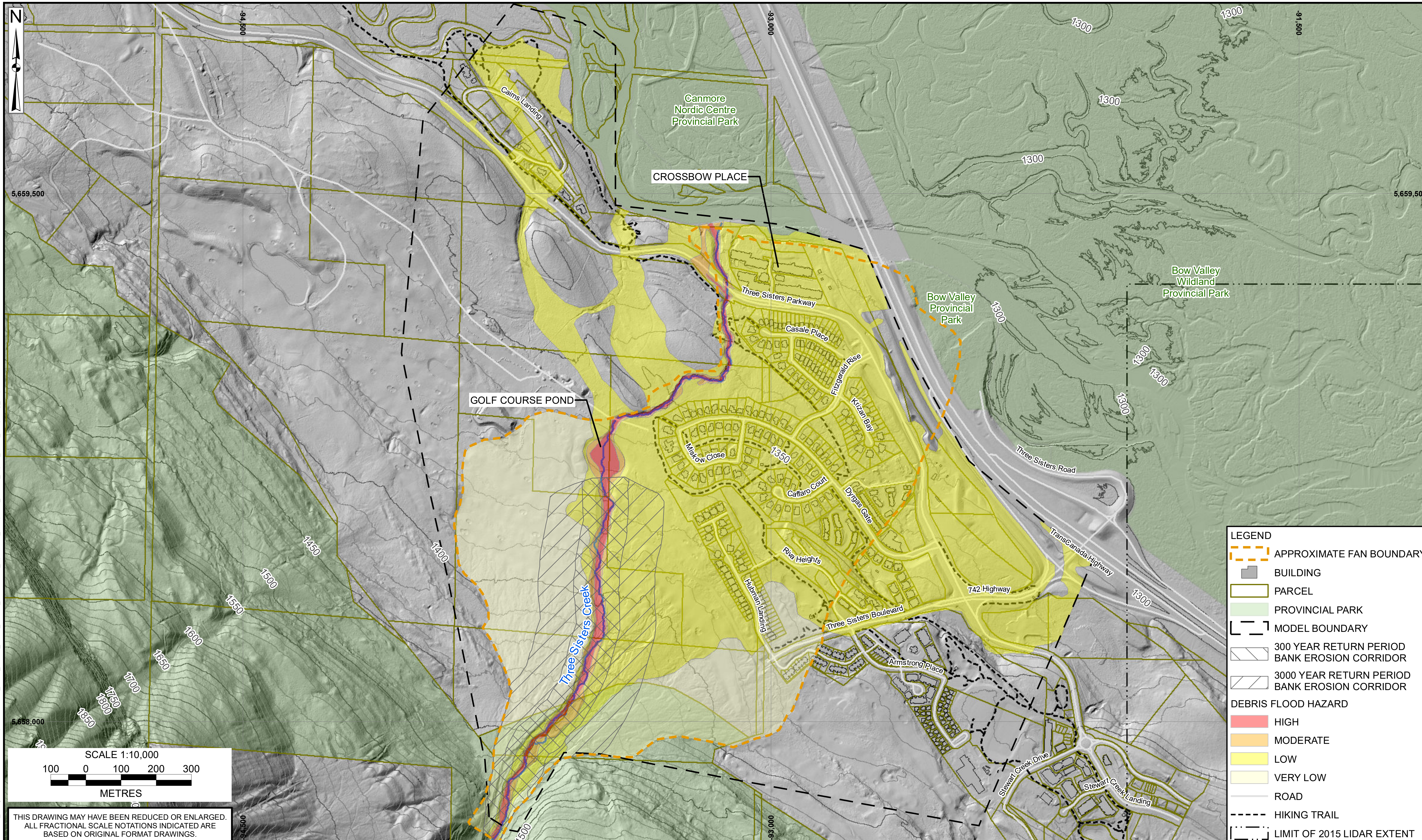

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APPROVED:	MJ

BGC ENGINEERING INC.
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CLIENT: THREE SISTERS mountain village

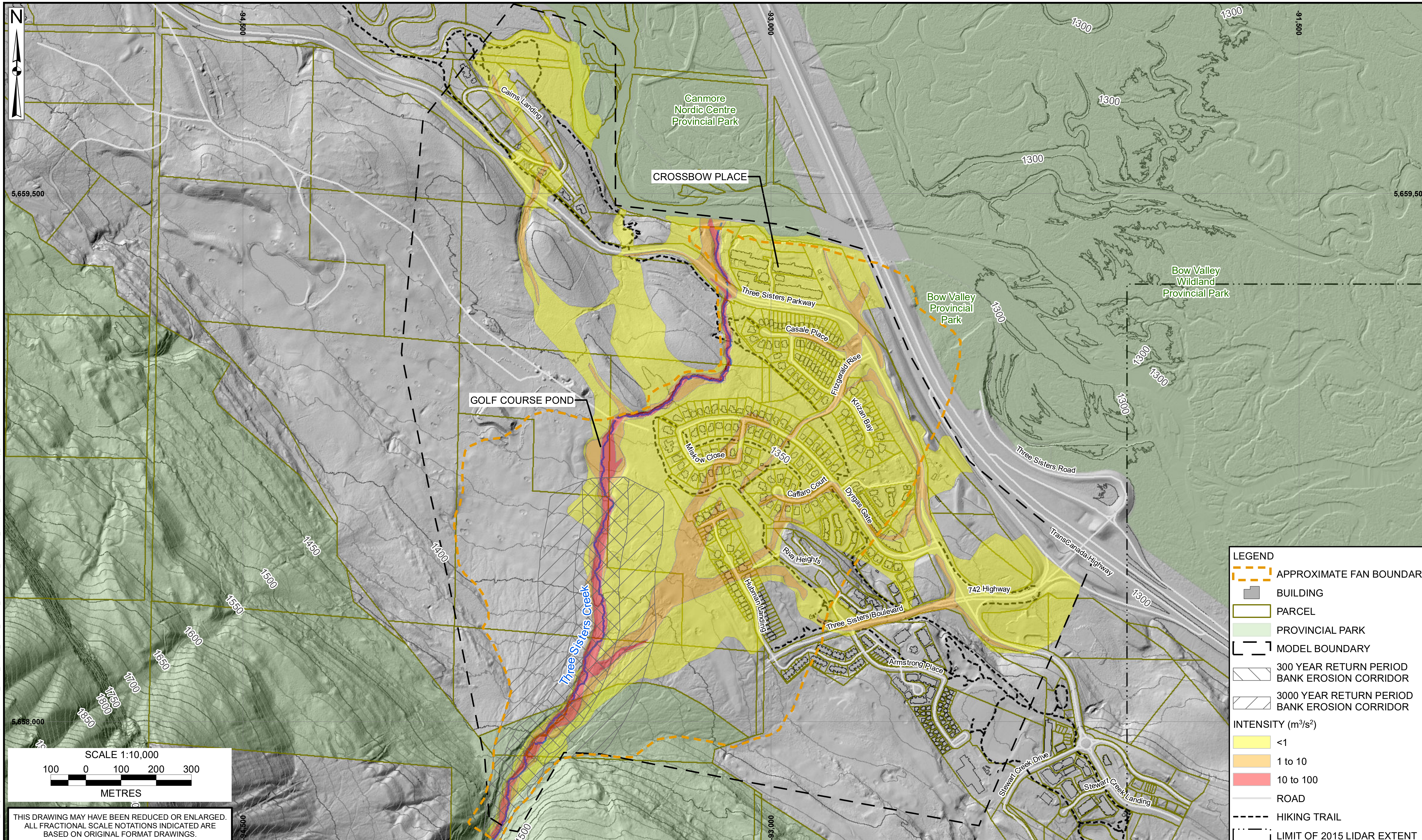
PROJECT: THREE SISTERS CREEK HAZARD ASSESSMENT UPDATE

TITLE: COMPOSITE HAZARD IMPACT FORCE FREQUENCY MAP

PROJECT No.: 1531 003

DWG No: 06

X:\Projects\1531_Three_Sisters_Mountain_Village\003\GIS\Production\Report\20200427_Three_Sisters_Creek_Hazard_Assessment_Update\06_Composite_Hazard_Impact_Force_Frequency_Map.mxd Date: October 9, 2020 Time: 1:01 PM



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APPROVED:	MJ

BGC ENGINEERING INC.
AN APPLIED EARTH SCIENCES COMPANY

CLIENT:
THREE SISTERS mountain village

PROJECT: THREE SISTERS CREEK HAZARD ASSESSMENT UPDATE

TITLE: COMPOSITE HAZARD INTENSITY MAP

PROJECT No.: 1531 003

DWG No: 07

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