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Project No.: 2325001

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Senior Planner/Deputy Approving Officer
Development Services and Engineering Department
City of Nelson
Suite 101, 310 Ward Street
Nelson, BC V1L 5S4

Dear Ms. Andrijancic,

Re: Steep Creek Hazards Assessment – FINAL

1.0 INTRODUCTION

BGC Engineering Inc. (BGC) is pleased to provide the City of Nelson (the City, Nelson) with this letter report summarizing the outcomes of a steep creek hazard assessment. In this study, BGC focused on four creeks within the municipal boundary of Nelson that were previously identified as having potential impacts from steep creek (debris flood and debris flow) processes (BGC, March 31, 2019). The creeks, in order from east to west, are Anderson/Fell Creek[1], Ward Creek[2], Cottonwood Creek, and Smelter Creek (Drawing 01). Cottonwood Creek has main tributaries upstream of the City of Nelson municipal boundary (Giveout, Selous, and Gold creeks) that BGC also considered in this assessment as part of the Cottonwood Creek system. BGC did not include Five Mile Creek as it is outside of the municipal boundary; however, BGC understands that Five Mile Creek is a source of water for Nelson. BGC previously identified Five Mile Creek as debris-flood prone (BGC, March 31, 2019) and future work to assess the potential hazards to the water intake may be warranted.

The objective of this study is to provide the City of Nelson with updated, prioritized flood and steep creek hazard boundaries suitable for consideration in planning and decisions for further assessment. In support of this, BGC completed a desktop-level review of available aerial imagery (air photos, satellite imagery), review of previous reports and a history of events on the study creeks, and a one-day field reconnaissance visit to the fan areas of all four study creeks.

The deliverables of this study include:

- This report

[1] BGC refers to Anderson/Fell Creek as Anderson Creek throughout this report.
[2] Ward Creek was initially identified as an unnamed creek in BGC's proposal and has been updated to reflect the true name in the present study. The location is shown in Drawing 01.

- Updated hazard boundaries and compilation of exposed elements at risk (e.g., buildings, roads, etc.) provided to Nelson as a spatial data package and displayed online on BGC's web application Cambio (www.cambiocommunities.ca).
- Public presentation to Nelson residents planned for January 2023.

Based on the information reviewed in this study, BGC recommends additional assessment and consideration of risk-reduction measures on the study creeks. BGC recommends the following priority order for Nelson:

1. Anderson Creek
   - Highest priority of the study creeks from the perspective of economic risk.
2. Cottonwood Creek
   - Comprehensive study including tributaries. Giveout Creek is the highest priority of the study creeks from the perspective of life safety risk.
3. Smelter Creek
   - In advance of future residential development of the fan area
4. Ward Creek

BGC recognizes that the study creek watersheds extend beyond the City of Nelson municipal boundary and that further assessment, for example for the Cottonwood Creek system that includes Giveout, Selous, and Gold creeks, would likely require collaboration with other parties including the Regional District of Central Kootenay (RDCK) and First Nations. Nelson is in the traditional and unceded territory of the Sinixt, Syilx, and Ktunaxa Nations. Giveout Creek is identified as a priority creek here based on the potential life safety risk.

1.1. Steep Creek Hazards

Steep creek hazards include floods, debris floods, and debris flows that originate on creeks with slopes greater than 3° (5%). Details on these hazard processes are included for reference in Appendix A. In urban and semi-urban environments, such as the City of Nelson, there are unique considerations for hazard management of steep creek processes. These include:

- Creek runoff within the urban environment includes both the creek flow from the watershed area upstream of the urban interface, as well as storm and surface water directed towards the creek channel within the developed area. The resulting flows can be higher than natural flows.
- Creek channels are often narrowly constrained within constructed channels with limited areas to deposit sediment, migrate, or overtop the banks during high flows without impacting adjacent infrastructure.
- If a creek overtops its banks, the flow can intersect paved, or otherwise modified surfaces where water does not infiltrate and the amount of flow, flow velocity and distance travelled can be greater than on natural slopes. Urban features can redirect flows that might not pose life safety risk but can cause economic loss, such as where downward sloping driveways direct water and sediment towards garages and homes.
- Infrastructure to convey flows (culverts, bridges) and bank protection (riprap, berms, lined channels) can significantly influence the hazard. Standard practice has been to design

such infrastructure based on historical data and using statistical methods that did not include climate change or assume data stationarity (trend, mean, etc. of data stay constant over time). In a changing climate, urban conveyance and bank protection infrastructure can be insufficiently sized to manage future flows.

- Little was known about debris floods or debris flows in the past, which led to the designs of water conveyance structures that do not consider such processes.
- Risk transfer is an important consideration on steep creeks containing stormwater management infrastructure, such as where culvert replacement increases the chance of culvert blockage further downstream.

Within an urban or semi-urban environment, proactive management of steep creek hazards includes consideration of the specific nature of the hazards (Appendix A) along with the factors above. The influence of climate change on steep creek hazard processes is also of critical importance as changes in temperature and precipitation averages and hydroclimatic extremes influence the occurrence, size, and intensity of hazard processes (Prein et al. 2016, Fowler et al. 2021) as well as the likelihood of beetle infestations and wildfires (Sambaraju et al. 2012, Jones et al. 2020). The general trajectory of the above factors is an intensification of hazard processes that can be further accentuated by watershed-scale logging and future wildfires.

There are many examples of steep creeks hazards impacting communities in British Columbia, Alberta, and internationally. Two such examples are Canmore, AB in June 2013 and the District of North Vancouver (DNV), BC in November 2014. In Canmore, a multi-day rainstorm in June 2013 led to flooding, debris floods, and debris flows on multiple creeks within the Town of Canmore and adjacent Municipal District of Bighorn. The design and implementation of steep creek hazard mitigation works within these areas is ongoing in 2022. In the fall of 2014, heavy rainfall in the DNV led to full creek bed mobilization (Type 1 debris flood, after Church and Jakob, 2022) on multiple creeks. Video footage from the DNV events is publicly available[3]. These two cases are indicative of the potential impacts of steep creek hazards to communities.

2.0 SUMMARY OF DESKTOP REVIEW

2.1. Review of Previous Reports

BGC reviewed a selection of previous reports provided by the City of Nelson (Table 2-1). The purpose of the review was to familiarize BGC with past work on the creeks by Nelson and other consultants; BGC does not comment further on past work as part of the current project.

[3] Example videos: https://www.youtube.com/watch?v=KrK2zIA8ODs and https://www.youtube.com/watch?v=0RJJe5Vzk3I

Table 2-1. List of reports made available to BGC by the City of Nelson and other parties

Author	Year	Title
Urban Systems	2007	Anderson Creek Flood Protection Works 2007 Updated Budgetary Construction Cost Estimates (Urban Systems, July 16, 2007)
City of Nelson	August 27, 2007	Nelson City Council Committee of the Whole (The Corporation of the City of Nelson, August 27, 2007)
City of Nelson	2013	Section 4: Development Permit Area #3. National Environment and Hazardous Lands (The Corporation of the City of Nelson, 2013)
Columbia Basin Trust	March 1, 2018	Summary of Proceedings Nelson Community Climate Action Meeting (Columbia Basin Trust, March 1, 2018)
City of Nelson Emergency Management	Oct. 29, 2019	City of Nelson Hazard Risk and Vulnerability Analysis (MacCharles, October 29, 2019)
SNT Geotechnical Ltd.	Nov. 9, 2021	City of Nelson Creek Street Subdivisions (SNT Geotechnical, November 9, 2021)
City of Nelson	Nov. 18, 2021	Storm Sewer System Map (The Corporation of the City of Nelson, November 18, 2021)

In addition, BGC's review benefitted from input from Dr. Peter Jordan, P.Geo., a retired geomorphologist with extensive experience in the Nelson area, and Sarah Crookshanks, a Research Geomorphologist with Kootenay Resource Management Unit, including summaries of past events on the study creeks.

2.2. Air Photo Interpretation

BGC obtained and reviewed historical air photos archived by the National Air Photo Library and the British Columbia Base Map Online Store from 1946/1947, 1966, 1978, 1987, and 2005. Additionally, BGC reviewed recent satellite imagery available from ESRI. A summary of key observations that pertain to debris-flood and debris-flow hazards on Anderson, Cottonwood, and Smelter creeks are provided in Table 2-2. The objective of the review was to identify changes in the watershed that promote sediment availability (e.g., landslide activity, logging, and wildfires) and past steep creek hazard events (e.g., recent debris deposition). A more detailed review of aerial imagery could form part of future detailed assessments.

Table 2-2. Summary of key observations from aerial imagery review.

Creek	Aerial Imagery Year	Observations
Anderson Creek	1946	• Exposed sediment and point source failures present on the valley walls of both Anderson and Fell creeks • Logging cutblocks present in northwestern section of watershed
	1966	• Additional logging cutblocks present in western part of watershed
	1978	• Vegetation changes that may be indicative of slope failure present in upper watershed of Fell Creek • A bedrock feature is evident in upper watershed of Anderson Creek • Construction near watershed outlet
	1987	• Exposed sediment that may be associated with slope failures present in upper watershed of Fell Creek • Construction continued near the watershed outlet
	ESRI World Imagery (2021)	• Exposed sediment from slope failures is present along Anderson Creek • New logging cutblocks present in northwestern portion of watershed • Exposed sediment and sparse vegetation in upper watershed may be associated with natural disturbances (e.g., wildfire)
Cottonwood Creek	1946/1947	• Surface water and gully erosion present downslope of a road in the lower watershed • Sparse vegetation associated with previous slope failures is evident • Logging cutblocks present in western portion of watershed
	1966	• Additional logging cutblocks present in western part of watershed
	1978	• Construction of linear infrastructure occurred above and parallel to Cottonwood Creek • Additional logging cutblocks present in western portion of watershed
	1987	• A road was constructed across western part of watershed • Additional logging cutblocks present in western part of watershed in addition to near the watershed outlet
	2005	• Additional logging cutblocks present across a larger swath of the watershed
	ESRI World Imagery (2009, 2018, 2020, 2021)	• Exposed sediment and sparse vegetation in the upper watershed may be associated with natural disturbances (e.g., wildfire) • Additional logging cutblocks present across the watershed
Smelter Creek	1946	• Exposed sediment is present in the headwaters • Exposed material is present on the slopes in the upper watershed • Logging is present in the upper watershed
	1987	• A road was constructed across the centre of the watershed
	2005	• Logging cutblocks present in eastern section of watershed
	ESRI World Imagery (2018)	• Additional logging cutblocks present in upper watershed in addition to western section of watershed

2.3. Watershed and Fan Characteristics

BGC reviewed lidar dated 2017 and 2018 to identify study creek fan and watershed characteristics, as summarized in Table 2-3.

Table 2-3. Watershed and fan characteristics of the study creeks.

Characteristic	Anderson Creek	Ward Creek	Cottonwood Creek	Smelter Creek
Watershed area (km^2)	13.3	1.3	61.6	1.2
Maximum watershed elevation (m)[1]	2,020	1,700	2,210	1,680
Minimum watershed elevation (m)[1]	680	740	550	805
Watershed relief (m)[1]	1,340	960	1,660	875
Melton Ratio (km/km)[1]	0.37	0.84	0.21	0.80
Average channel gradient of mainstem above fan apex (%)	19	33	4	37
Fan area (km^2)	1.0	0.13	0.56	0.45
Average channel gradient on fan (%)	11	19 (3)	2	18
Average fan gradient (%)	11	18	6	21
Dominant Process Type(s)[4]	Mixed floods and debris floods	Debris floods	Mixed floods, debris floods.	Debris flows

Notes:

1. Watershed elevations are rounded to the nearest 10 m.
2. Melton ratio is watershed relief divided by the square root of the watershed area. It can be used to help characterize the dominant process type(s) in a watershed.
3. Ward Creek enters the municipal stormwater system through a culvert at Fort Sheppard Drive. This measurement is from the fan apex to Fort Sheppard Drive.
4. The dominant process type is determined based on the Melton Ratio and watershed stream length and supported by BGC field observations.

2.4. Infrastructure and Development

The study creek fans intersect developed areas within the municipal boundary or infrastructure essential to city operations. In a risk assessment, the people, infrastructure, and assets that may potentially be impacted by a hazard are collectively called “Elements at Risk”. BGC compiled elements at risk for each of the study fans including:

- Total population (2016 census)
- Number of parcels within fan areas and total improvement value (BC Assessment)
- Number of businesses and annual revenue
- Lifelines (e.g., roads, railways, utilities)
- Environmentally sensitive habitat (e.g., agricultural, fisheries, ecosystems at risk)

This information is presented in Cambio Communities and Table 2-4 provides a summary of select key metrics that support BGC's prioritization. Note that the population statistics are estimated from the 2016 Census and exclude non-residential properties.

Table 2-4. Summary of key elements at risk data for study creeks.

	Anderson Creek	Ward Creek	Cottonwood Creek[4]	Smelter Creek
Population[1]	2,000	300	12	149
Number of Parcels	1,551	237	113	29
Total Improvement Value[2]	$687.3 Million	$79.1 Million	$65.6 Million	$12.9 Million
Number of Businesses	79	3	55	6
Business Activity[3] (Annual Revenue)	>$100 Million annual revenue	$100k to $1 Million annual revenue or 2-5 businesses.	>$100 Million annual revenue	$1 to $10 Million or 6-10 businesses

Notes:

1. Total population based on 2016 census. Population is rounded to nearest 100.
2. Total improvement value from BC Assessment (received February 2022). Improvement value rounded to nearest $100,000.
3. Business activity is expressed as total annual revenue or number of businesses. Annual revenue from Geografx (received February 2022).
4. Elements at risk are presented for Cottonwood Creek fan only and do not include the tributaries.

Nelson staff also provided BGC with information on critical infrastructure for the city. Anderson Creek, and to a smaller extent Fell Creek, is a primary water source for Nelson that contributes 8-15% of the city's water supply depending on the season (email from Scott Eagleson, personal communication, November 11, 2022). In addition to residential and commercial development on the Anderson Creek fan, there is a 75 ft (22.8 m) wide concrete dam with spillway and intake stilling well, a chlorination building, and a three-story treated water reservoir that are all critical infrastructure for Nelson (email from Scott Eagleson, personal communication, November 11, 2022). Nelson also indicated that a smaller intake structure is located on Selous Creek within the Cottonwood Creek watershed. As previously noted, Five Mile Creek located approximately 4.5 km northwest of the municipal boundary is a key water source for Nelson. It was outside of the scope of the present scope as it does not intersect the City of Nelson municipal boundary and may warrant future assessment. Cottonwood Creek fan is largely non-residential and contains several lifelines and critical facilities including the Nelson Airfield, Nelson Public Works, and the office of the Regional District of Central Kootenay.

3.0 SUMMARY OF FIELD OBSERVATIONS

3.1. Introduction

The following sections summarize BGC's field observations from a site visit on June 12, 2022. The site visit was completed by Dr. Matthias Jakob, P.Geo., P.L.Eng. and Lauren Hutchinson, M.Sc., P.Eng. The interpretations presented are supported by BGC's review of previous reports, aerial imagery, and desktop-level assessment of watershed and fan characteristics (Section 0).

3.2. Anderson Creek

Anderson Creek drains a watershed of 13.3 km^2. It has an average steepness of 19% (11°) and is interpreted to be susceptible to floods and debris floods (Table 2-3). The total watershed relief is approximately 1,500 m, ranging from almost 2,020 m in the headwaters to approximately 530 m at Kootenay Lake. Fell Creek (watershed area of 4.6 km^2) is a tributary of Anderson Creek, confluent at approximately elevation 700 m. BGC classifies Anderson Creek as subject to floods and debris floods (Table 2-3).

The Anderson Creek watershed is underlain by Jurassic volcanic rocks on the south side and Jurassic plutonic (igneous intrusive, granitic) rock on the north side. Fell Creek is situated entirely within plutonic rock (Paradis and Underhill, 2009). Anderson Creek follows roughly the transition between the volcanic and intrusive rocks which may have been responsible for the creek's location. Typically, volcanic rocks are more friable than igneous rocks and weather into smaller-grained sediment that may influence the bulk density of a debris flood. Bedrock is overlain by a blanket of till of unknown thickness[4].

The watershed is treed to ridge top with little recent logging confined to the westernmost ridges of the watershed. Few active debris sources exist in the watershed.

The Anderson Creek fan includes a paleofan[5] on the northern fan portion that BGC interprets to have developed against the receding trunk valley glacier during early deglaciation. Once the glacier had retreated, Anderson Creek flowed towards the North where it carved a notch into the paleofan given the change in base-level then and present Kootenay Lake. Eventually a new channel formed that eroded and obliterated the steep escarpment of the southern paleofan with debris (Figure 3-1). This sequence of events is important to understand the hazard potential of Anderson Creek. Avulsions to the north are now very unlikely as the creek has incised near the fan apex likely due to waning sediment supply such that events with sufficient discharge are unlikely to jump the channel to the north.

[4] Although the thickness is unknown, the term "blanket" is generally used to describe material thickness greater than 2 m which is consistent with BGC's interpretation in this instance.

[5] Paleofan refers to a portion of a fan that developed during a different climate, base level, or sediment transport regime and which will not be affected by contemporary geomorphic processes (debris flows, debris floods, floods) affecting the active fan surface.

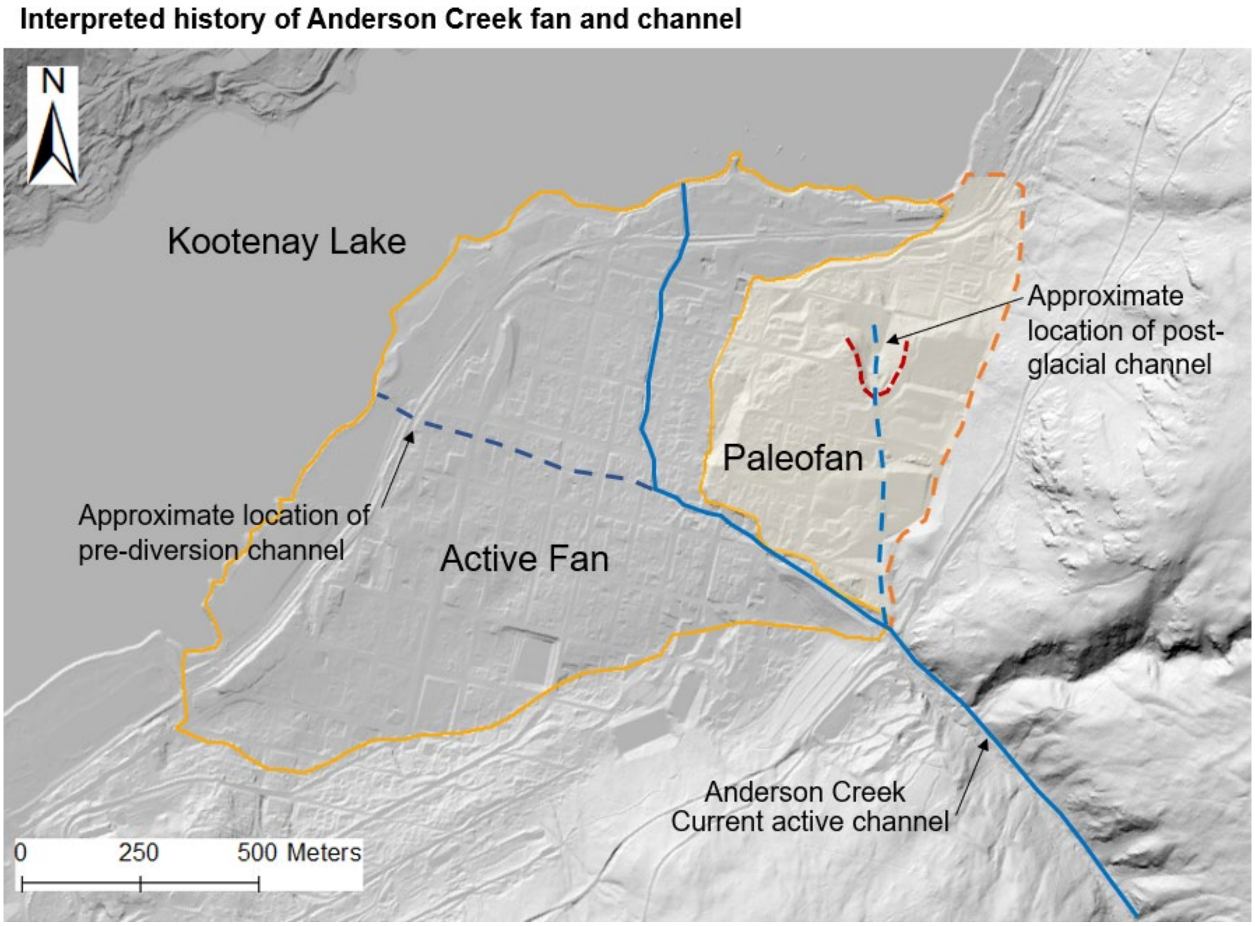

Figure 3-1. Anderson Creek fan area showing active fan (orange), paleofan surface (yellow shading), current channel (blue), interpreted historic channel locations (blue dash), and eroded notch in paleofan (red dash). The active fan has been modified by development on the fan.

At the fan apex, Anderson Creek passes below a trestle bridge (Figure 3-2). The wooden trestles are vulnerable to damage from debris-flood impact. Immediately downstream of the fan apex near Svoboda Rd, a new water facility has recently (2022) been constructed. During BGC's site visit, an existing deflection berm/flooding dike to the south appeared to have been removed to grant access (Figure 3-3A). BGC noted that this could allow an avulsion towards the South into a residential neighbourhood near Davies Park. BGC informed the City of this issue (email on June 15, 2022) and replacement of the berm was completed (Figure 3-3B). BGC has not visited the site since the berm replacement and cannot comment further on the design or condition of the structure.

Figure 3-2. Trestle bridge over Anderson Creek near the fan apex. Wooden trestles would likely suffer major damage during a debris flood. Photo: BGC, June 12, 2022.

Figure 3-3. Anderson Creek near the fan apex. A) The left (west) lateral berm appeared to have been removed adjacent to the new water facility. Photo: BGC June 12, 2022. B) The left (west) lateral berm was replaced. Photo: Nelson, December 13, 2022.

Downstream of the water facility, Anderson Creek is relatively poorly confined through the reach to Elwyn Drive, increasing the potential for the creek to overtop the banks and flood adjacent areas (Figure 3-4). At Elwyn Drive, an engineered trash rack has been constructed to catch organic debris and larger boulders before they can enter the Elwyn Creek culvert which has been equipped with an overflow culvert (Figure 3-5). At the time of BGC's site visit, water flow was too high to measure the main culvert or overflow culvert dimensions. This location has experienced previous flooding, for example in 2020 (Figure 3-6).

The channel downstream is entirely developed. At road crossings, the creek is confined within culverts or spanned by bridges. There are eight crossings downstream of the fan apex until the creek's confluence with Kootenay Lake where a delta has formed north of 4th Street. Adjacent arc-shaped deltas suggest that the outlet of the creek has shifted over time. According to a presentation to Nelson City Council on August 27, 2007 (The Corporation of the City of Nelson, 2007), the creek was artificially diverted around 1930 to 1940 from its former course along Kootenay Avenue and via Lakeside Park into Kootenay Lake to its present alignment (Figure 3-1).

Within the developed sections, the creek is highly confined with property lines going right to the creek's boundary. Because of the confinement and the creek's steepness it flows fast and exerts high erosive forces against its bed and banks. This has prompted landowners to mitigate in various forms from well-stacked angular riprap to improvised protection measures (Figure 3-7).

Should flood or debris-flood discharges exceed the design discharge of the conveyance of bank protection infrastructure, and an avulsion occurs, water and debris would flow down grade, preferentially following roads due to lower flow resistance. Downward sloping driveways could direct water and sediment towards garages and homes.

Figure 3-4. Anderson Creek during high flows between the new water facility and Elwyn Drive. The creek is relatively unconfined in this section. Photo: BGC, June 12, 2022.

Figure 3-5. High flows at the upper culvert on Elway Drive with an engineered trash rack to avoid organic debris and large boulders from entering the culvert. Photo: BGC, June 12, 2022.

Figure 3-6. Overflowing culvert at Anderson Creek (June 2nd, 2020, Photo: Nelson Star)

Figure 3-7. Anderson Creek between Gordon and Fell St. Note the make-shift mitigation works on the right (d/s looking) channel bank in the form of a jersey barrier. Photo: BGC, June 12, 2022.

Based on meeting minutes from a City of Nelson Council meeting in 2007, BGC understands that residents have alerted the City to concerns with Anderson Creek due to a series of floods that have damaged adjacent properties. BGC also understands the City has made efforts to resolve the concerns and mitigate the risks. However, the City is limited in some areas as many of the properties do not have statutory rights of way or public access for staff to inspect or make improvements to the area. BGC understands this is particularly true downstream (west) of Ninth Street.

BGC understands that the following studies have been conducted on Anderson Creek:

- The City of Nelson Capital Work Plan (1997)
- Urban Systems (1999): Anderson Creek Flood Protection Study

It is outside BGC's current scope to review Urban System's Anderson Creek Flood Protection Study. However, BGC is unaware of any additional plans to comprehensively manage flood hazard on Anderson Creek that goes beyond repairing or improving specific weak points along the creek.

3.3. Ward Creek

Ward Creek is a well-incised creek in the uplands east of Nelson (Drawing 01). It drains from an elevation of approximately 1,700 m, enters the city limits at around 740 m, and has a watershed area of approximately 1.3 km^2 measured upstream of the Nelson Rail Trail. West of the Rail Trail, the creek runs above ground until it reaches the vicinity of Fort Sheppard Drive from where it disappears underground and is funneled through the City's underground drainage network (Figure 3-8). BGC understands that eventually, it drains beneath Highway 6 and into Cottonwood Creek.

Bedrock in the Ward Creek watershed is part of the Jurassic Rossland Group consisting of basaltic flows, flow breccias, and subvolcanic intrusions (all volcanic rocks). Based on the information reviewed to date, BGC cannot confirm if the bedrock geology prevailing in Ward Creek contributes to sediment loading or if most sediment is derived from late Pleistocene sediments.

The fan of Ward Creek is poorly visible on aerial images as it has been substantially altered by urban development. BGC delineated the fan using lidar imagery with narrowly spaced contours (Figure 3-8). The fan has an approximate slope of 10° (18%), which is indicative of debris-flow transport. However, in this case, this may be misleading as the natural slopes nearby (in absence of fans) have a slope of 8 to 9°. This implies that the processes that created the Ward Creek fan only steepened it by about 1 to 2°, which does not allow an interpretation of process.

The creek is deeply incised in till as evidenced by some road cuts (Figure 3-9). As BGC did not traverse the length of the creek during this reconnaissance study, it is unknown if bedrock is encountered in the creek's base, though BGC considers this likely given the extent of incision. In places the till may be masked by overlying colluvium (Figure 3-10).

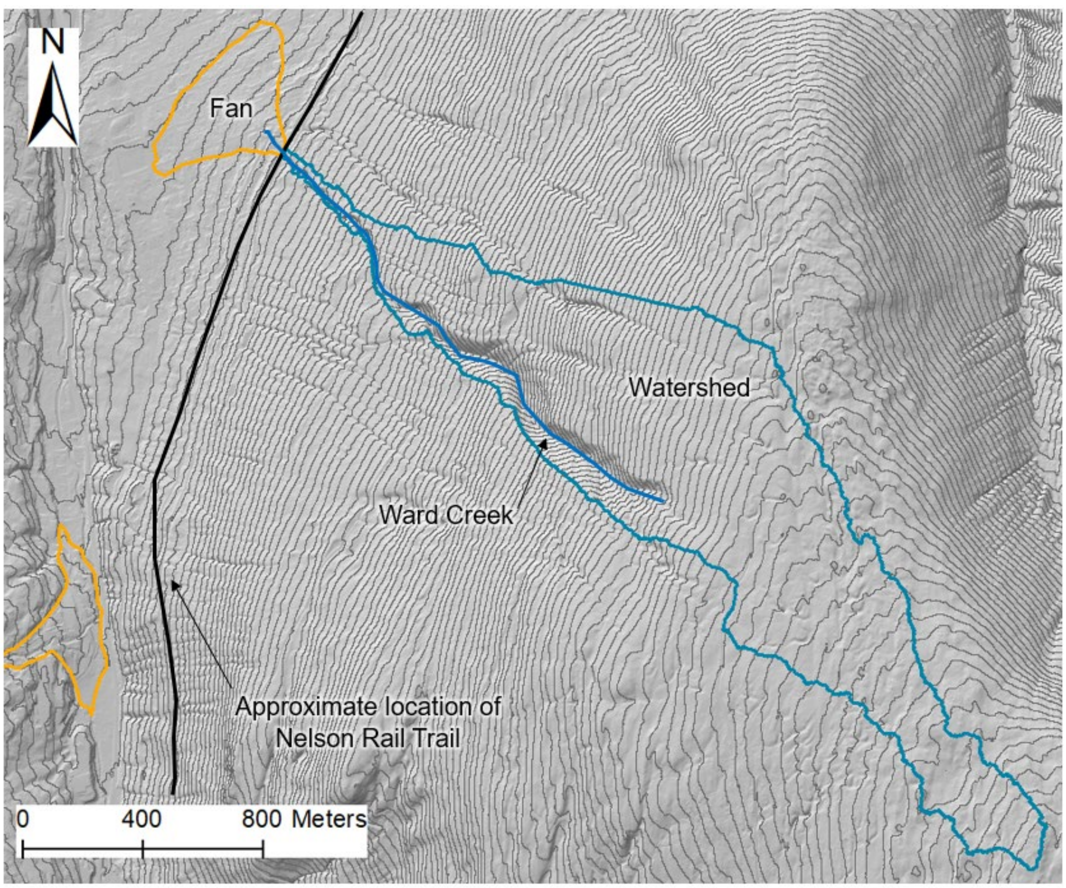

Figure 3-8. Ward Creek drainage with some key features. Contour interval is 10 m.

Figure 3-9. Till exposure along a property access road at approximately elevation 820 m near the Ward Creek drainage. Photo: BGC, June 12, 2022.

Figure 3-10. Ward Creek at approximately elevation 940 m. The creek is incised in till. No bedrock was encountered during the reconnaissance field investigation. Photo: BGC, June 12, 2022.

BGC did not encounter signs of either debris flows or debris floods during the field visit. BGC expects that debris floods are possible on this creek given the erodible creek bottom sediments and the size of the watershed. BGC has worked on similar creeks within the DNV which experienced debris floods in November 2014 (Section 1.1). BGC believes that the DNV creeks are reasonable analogues to what could occur at Ward Creek in Nelson. BGC notes that the damaging 2014 events in the DNV occurred on creeks with only moderate life safety risk (i.e., not the highest risk creeks in the District from a life safety perspective). This finding influenced changes in DNV's risk management process to consider both life safety and economic risk in a 10-year risk management plan (Holm et al., 2017).

Sediment mobilization, even in relatively small volumes, could block the culverts at the Nelson Rail Trail and subsequent downstream culverts (for example, at Fort Sheppard Drive Figure 3-11). In the event of a culvert becoming clogged, BGC assessed that the following could occur:

- The Nelson Rail Trail embankment could become saturated, overtop, and then rapidly incise. Piping or collapse of the embankment could also occur in areas adjacent to Ward Creek where water is directed along the ditch on the upslope side of the Rail Trail.
- Water may not re-enter the channel and uncontrolled overland flow could impact residents' backyards.
- Given the general steepness of terrain in the vicinity of Fort Sheppard Drive, localized slumps could occur, erosion and deposition of sediment. While it is unlikely that these processes will result in life loss, they could lead to significant economic damage.

Based on the evidence reviewed to date BGC considers the potential for debris flows to be low and that the FLOW-R modelling (BGC, March 31, 2019) overestimates runout extents because of the coarse topography used for the FLOW-R modelling. Detailed modelling based on lidar DEM would provide more accurate inundation extents.

Figure 3-11. Culvert on Ward Creek at Fort Sheppard Drive. Photo: BGC, June 12, 2022.

3.4. Cottonwood and Giveout Creeks

Cottonwood Creek has a watershed area of 61.6 km^2 and elevations ranging from approximately 530 m at Kootenay Lake to approximately 2,210 m at Toad Mountain (Table 2-3). Cottonwood Creek has three main tributary channels upstream of the City of Nelson:

- Giveout Creek (watershed area: 15.2 km^2)
- Selous Creek (watershed area: 15.5 km^2)
- Gold Creek (watershed area: 4.6 km^2).

The locations of the tributary channels and mapped fan areas are available through BGC's web platform Cambio Communities (communities.bgcengineering.ca). BGC visited the confluence of each of the tributary creeks with Cottonwood Creek and reviewed aerial imagery of the full Cottonwood Creek watershed to identify potential impacts to downstream hazards within the City of Nelson. As an example of the interconnected nature of tributary creeks, Dr. Peter Jordan described a debris slide-debris flow on Gold Creek that resulted in increased sediment concentration in Cottonwood Creek, to the extent that Kootenay Lake at the mouth of Cottonwood Creek turned muddy (email from Peter Jordan, personal communication, July 8, 2022).

In this section, BGC describes field observations on Cottonwood and Giveout creeks. BGC visited the Giveout Creek fan in addition to the confluence, as was done for Selous and Gold creeks, as desktop- and field-observations suggested elevated hazard and risk from debris flows. Cottonwood Creek is subject to debris floods, and Giveout Creek is subject to debris flows (Table 2-3).

The Cottonwood and Giveout creek watersheds are underlain by basaltic volcanic rocks in the southern and eastern portions and by granodioritic intrusive rocks in the northern and western portions (Hoy et al, 1994). These rock types generally produce coarse fragments in debris floods and flows.

3.4.1. Cottonwood Creek

Cottonwood Creek is crossed by several bridges to access private property from Highway 6 upstream of the City of Nelson. Within the City, Cottonwood Creek has a weir and an organic debris barrier situated approximately 60 m upstream of the main culverts where Vancouver Street meets Mines Road (Figure 3-12). The barrier consists of double-T-bars embedded in the concrete weir crown. Some appear to have been displaced (bent). This barrier may be successful in capturing some organic debris, however, in a major runoff event, BGC expects that substantial amounts of logs and woody debris could overtop the structure.

Figure 3-12. Debris barrier across Cottonwood Creek approximately 60 m upstream of culvert below Highway 6. Photo: BGC, June 12, 2022.

Downstream, Cottonwood Falls is located immediately north of the Highway 6 crossing. From here, the creek runs alongside Highway 3A. Downstream of Observatory Street a large flume conveys flow for approximately 300 m to where it daylights and is directed into a spillway. Another flume under Nelson Highway daylights at Cottonwood Creek falls. Additional culverts exist at Baker Street and across the railways north of the Nelson Visitor Centre. The last 450 m Cottonwood Creek flows at a gentle gradient to Kootenay Lake just south of the Nelson air strip.

BGC understands that Cottonwood Creek has a long history of damaging floods as per Table 3-1.

Table 3-1. Notable floods or debris floods on Cottonwood Creek.

Year	Month/Day	Process	Source	Description
1954	May	Flood	BC Archives	Cottonwood Creek threatened homes and caused erosion of back yards along the creek. A temporary shear dyke was constructed to protect homes. The creek avulsed from its course and flowed across a road off the main highway.
1956	June	Flood	BC Archives	Heavy rains followed three weeks of unseasonably warm weather. A severe thunderstorm and heavy rain caused Cottonwood Creek to flood the CPR tracks and yard.
1968	June 3	Flood	Septer (2007)	Nelson was the hardest hit when Cottonwood Creek flooded a number of homes and a service station.
1980	April	Debris Flood	BC Archives	Cottonwood Creek flooded and threatened homes along its banks.
1999	June	Flood	Septer (2007)	Cottonwood Creek eroded the shoulder of Highway 6 between Salmo-Nelson, north of the Perrier Road intersection. Cost to backfill with rockfill was $3,000. The Slocan River flooded and eroded 10 m along shoulder of Highway 6, 0.84 km north of Passmore. Cost to backfill with rock fill was $3,000

As shown in Table 3-1, there have been at least five significant (damaging) floods on Cottonwood Creek in the last 68 years. This implies a frequency of damaging floods/debris floods of approximately 1:14 years and confirms that Cottonwood Creek is highly flood-prone.

3.4.2. Giveout Creek

Giveout Creek is susceptible to debris flows as evidenced by large boulder lobes and levees on the fan surface observed by BGC during the field visit on June 12, 2022. The watershed has been extensively logged and numerous trails and logging and mining roads crisscross the watershed (Figure 3-13). The state of road and trail maintenance and abandonment is unknown to BGC.

Several debris flows and instabilities associated with logging have been observed in Giveout Creek (pers. communication, Peter Jordan and Sarah Crookshanks, June 16, 2022) and summarized in Table 3-2.

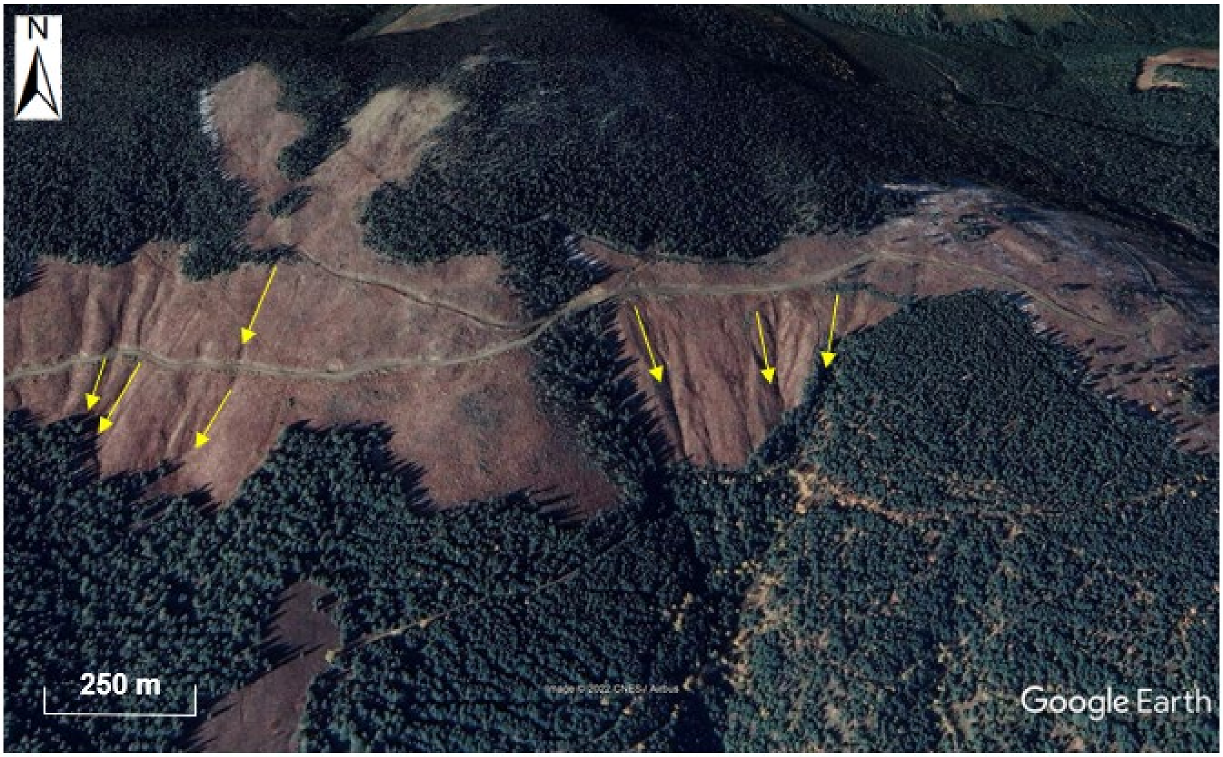

Figure 3-13. Detail of recent clearcutting in steep terrain the upper Giveout Creek watershed. Oblique Google Earth image. Areas particularly susceptible to debris-flow initiation are shown with yellow arrows. Image: Google Earth 10-18-2021.

Table 3-2. Notable instabilities in Giveout Creek watershed.

Year	Month/Day	Process	Description
1988	May 8	Debris slide	Debris slide into the creek from a mining road (based on hand-written notes and photos).
1997	May	Landslide	Landslide into a creek from an old logging road
2002	May 22	Debris slide	Water was diverted onto the road from private land logging (skid roads) above. The cutbank sloughed causing the ditch to be plugged. This redirected water onto the road fill causing the embankment material to slump. Giveout Creek FSR @ 5.5 km. It is unclear if this made it to the creek or not. Event reported by Atco Lumber.
2003	Spring	Debris slide	Natural slide noted from overview flight, originally thought to be caused by water diversion of an old skid road. Closer inspection revealed no cause. Assumed to be natural causes after being reviewed on the ground by Atco staff (Craig Stemmler). Non-status road on mineral claim within DL4148.

The Giveout Creek fan is inhabited with a combination of mobile and manufactured homes and other residences (Figure 3-14). Mobile and manufactured homes are more vulnerable to the impact forces associated with debris flows than other building construction types. In BGC's field reconnaissance, BGC noted multiple locations where Giveout Creek is poorly confined to the creek channel and avulsion potential exists (Figure 3-15). Cottonwood Creek flows northward along the base of the Giveout Creek fan immediately adjacent to Highway 6 (Figure 3-16).

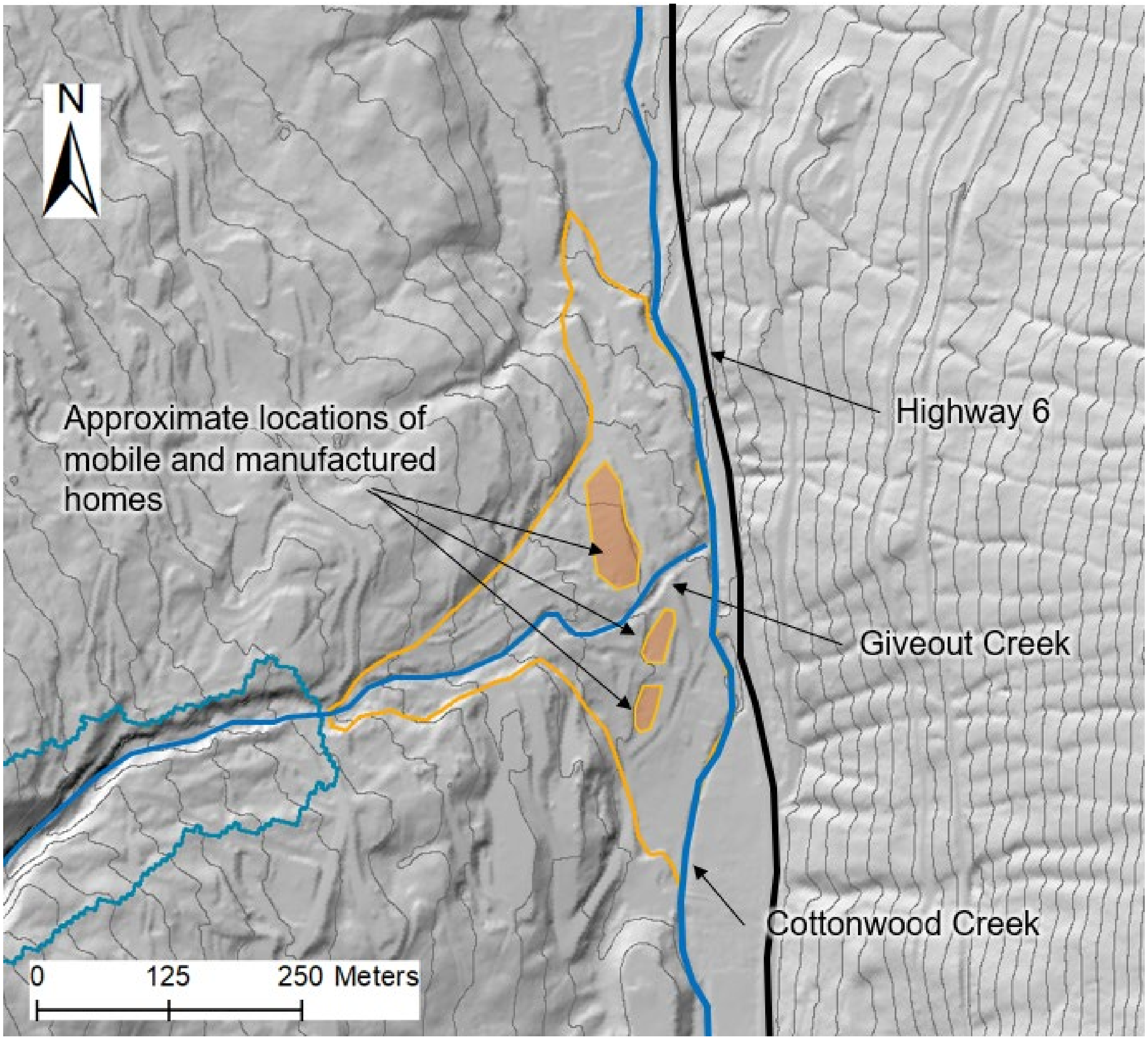

Figure 3-14. Giveout Creek fan (orange outline) and watershed (teal outline) with the approximate location of mobile and manufactured homes (shaded orange). Other buildings and homes are located on the fan but not shown here. Contour interval is 10 m.

Figure 3-15. Giveout Creek through a poorly confined section of its fan. Numerous water intakes were noted with abundant pipes and other infrastructure in the flow path. Photo: BGC, June 12, 2022.

Figure 3-16. Giveout Creek at the confluence with Cottonwood Creek photographed from across Cottonwood Creek at Highway 6. Photo: BGC, June 12, 2022.

Debris flows on Giveout Creek could result in:

1. Impacts to residences on the fan surface (approximately 20 on the fan)
2. Damming of Cottonwood Creek.

In the latter scenario, Cottonwood Creek would flood upstream of the debris-flow dam and likely heavily erode the Highway 6 south-bound embankment with possible highway loss. A debris-flow dam would rapidly be overtopped and could cause an outbreak flood with high sediment concentration. Further study would be required to estimate the degree of attenuation before such a sediment pulse enters the City boundary. Higher density flows create more buoyancy and allow larger boulders to be entrained. The result is higher bank erosion potential downstream of the Giveout-Cottonwood creek confluence with the potential for banks to be undermined and create log jams with associated flow constrictions.

Considering the watershed characteristics, ongoing and former logging and mining activities, a dense network of trails and roads, and the observed signs of former debris flows on the fan, BGC considers Giveout Creek as being subject to a high debris-flow hazard. This sentiment is shared by Dr. Peter Jordan, P.Geo. who served as the regional geomorphologist for the Ministry of Forests for almost 30 years (Jordan, pers. comm. 2022). BGC communicated this assessment to the City of Nelson by email on June 17th, 2022 and understands that this communication was shared with the Regional District of Central Kootenay (RDCK) and BC Ministry of Transportation and Infrastructure (MoTI).

3.5. Smelter Creek

Smelter Creek has a watershed area of approximately 1.2 km^2 above the fan apex. Its relief ranges from approximately 530 m at Kootenay Lake to approximately 1,680 m along the ridgeline that separates Smelter Creek from Giveout Creek. The average stream channel between the fan apex and the visible upper portion of the creek is 20° (37 %).

The Smelter Creek watershed is located almost entirely (up to an elevation of approximately 1300 m) within the Jurassic Nelson Intrusions consisting of granodiorite. As the creek was not ascended during this reconnaissance fieldwork, it is unknown to what extent bedrock supplies sediment to the channel, the geotechnical characteristics of bedrock and if bedrock failures are possible.

The watershed has been logged at times and is at different levels of vegetative recovery (Table 2-2). A major logging road traverses the creek and the upper watershed at approximately elevation 1,220 m. The watershed is entirely vegetated with a conifer forest mixed with occasional small clusters of aspens.

Smelter Creek is deeply incised into the surrounding uplands, signaling a strong history of erosion from the watershed. A notable area of high erosion activity can be seen on lidar imagery (Figure 3-17). The reason why it is more active than areas upstream or downstream is unknown.

Its fan has an approximate area of 0.45 km^2, slopes ranging from 6 to 15° (11% to 27%), and a diffuse outline where it merges into the adjacent till or glaciofluvial surficial sediments. Near the fan apex, the creek turns sharply to the northwest and flows on the far northwestern margin of its fan. Such behaviour is not uncommon but can quickly be reversed by a debris flow depositing near the fan apex and directing flows into a different fan sector.

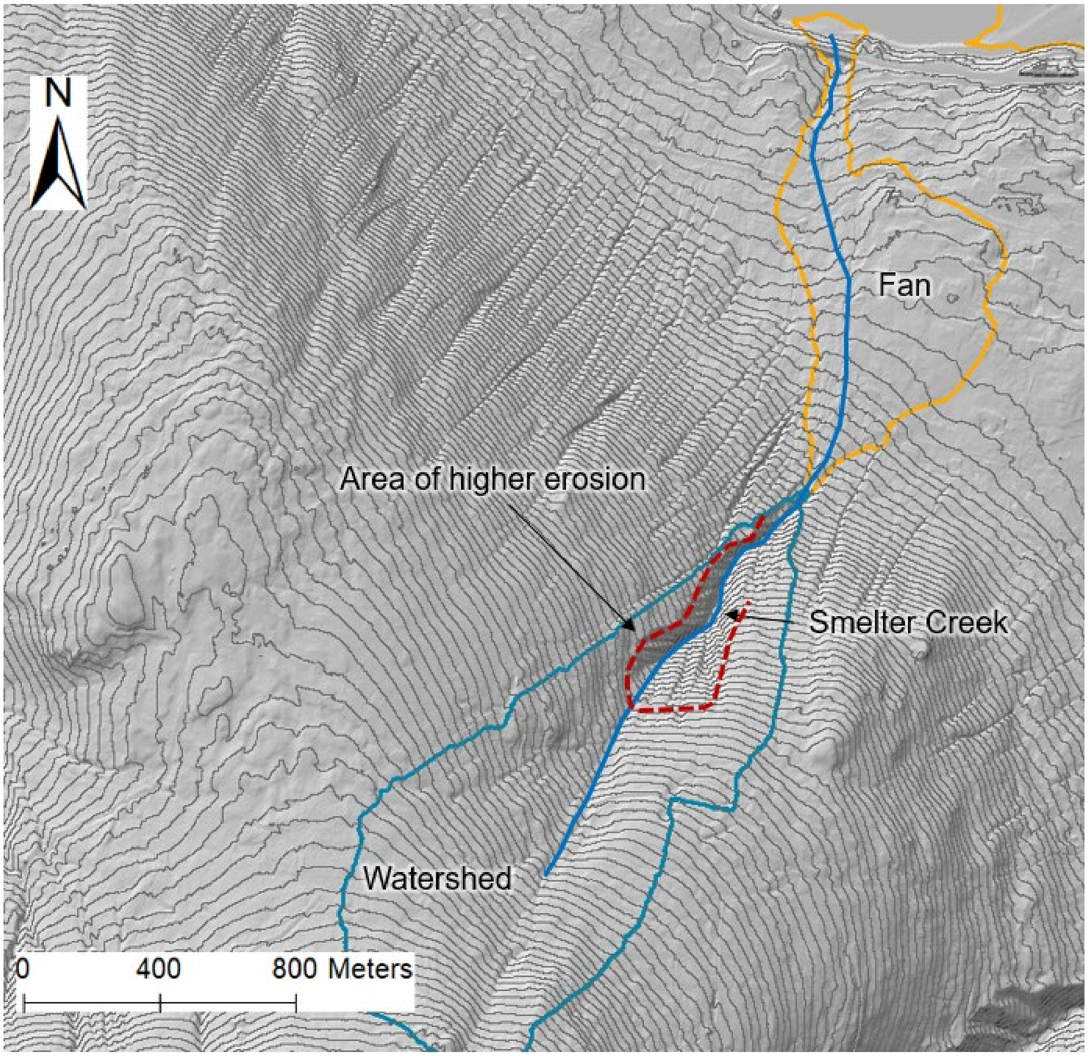

Figure 3-17. Smelter Creek watershed (teal) and fan (orange). Outlined in red is an area of particularly high erosion that should be investigated in the field. Contour interval is 10 m.

Recent excavations on the upper fan appear to be associated with housing development plans and golf course expansion. The subsurface consists of large boulders with up to 1 m diameter which is typical for debris-flow fans. A small water retention pond and some water works (presumably for golf course irrigation) were noted at an elevation of approximately 730 m (Figure 3-18).

Figure 3-18. Small water retention pond and water diversion works on Smelter Creek, looking east. In the background recent ground disturbance associated with possible housing development and golf course expansion. Photo: BGC, June 12, 2022.

The creek then flows west of the Granite Point Golf Club through urban areas where it traverses Golf Links Road, Knox Road, Granite Road and Highway 6 before discharging into Kootenay Lake.

Given the watershed size and steepness as well as the fan morphology and soil characteristics, Smelter Creek appears to be prone to debris flows. A cursory examination of the channel upstream of the fan apex suggests that such events are rare (several decade return period) but potentially of high magnitude. BGC recommends that any development on the fan should consider this hazard and be supported by a detailed hazard assessment.

4.0 SUMMARY AND CONCLUSIONS

The City of Nelson requested that BGC provide a preliminary assessment of four creeks (Anderson Creek, Ward Creek, Cottonwood Creek, and Smelter Creek) within the municipal boundaries of Nelson with the objective to evaluate which ones of those creeks should be designated for further study.

BGC completed a high-level, desktop review of previous reports, aerial imagery, and lidar on the study creeks along with a one-day site visit on June 12, 2022, in which the fan areas of all four creeks were visited. On Cottonwood Creek, BGC also visited the fan area of Giveout Creek, and the confluence of Selous and Gold creeks with Cottonwood Creek to evaluate potential impacts to downstream hazard and risk within the City of Nelson. A summary of BGC's observations and recommendations is provided in Table 4-1.

Based on the information reviewed to date, BGC interprets Giveout Creek to have the highest life loss potential and therefore highest safety risk. Anderson Creek likely has the highest economic loss potential (highest economic risk), closely followed by Cottonwood Creek. Uncontrolled flows on Cottonwood Creek also have the potential to damage or close Highway 6, a major traffic artery to the south.

Table 4-1. Summary of study outcomes and recommendations for further assessment.

Study Creek	Dominant Hazard Process(es)	Secondary Hazard Process(es)	Key Observations	Recommendation(s) for Additional Assessment
Anderson / Fell Creek	Debris flood	• Avulsion potential • Bank erosion • Undercutting of buildings • Development of scour holes • Damage to road crossings and linear infrastructure at road crossings • Water and sediment inundation • Basement and first floor flooding.	• Anderson Creek is poorly confined (has shallow banks) immediately downstream of the fan apex and potential to avulse (leave the main channel) downstream of the water utility building and inundate areas south of the existing berm. • The creek follows a narrow artificially confined channel through the entire developed area. In multiple locations, the channel has limited available freeboard, insufficient erosion protection, and/or culverts with insufficient capacity to convey debris floods (all to be confirmed in a detailed study). • Should an avulsion occur during a major flood or debris flood, very high economic damages, in the order of millions, can be expected in the residential areas. • Current FLOW-R modeling (accessible via Cambio Communities) does not accurately portray the extent of inundation in case of an avulsion.	Additional detailed hazard assessment warranted. Hazard assessment should include definition of various hazard scenarios and detailed numerical modeling with a two-dimensional runout model.
Ward Creek	Clearwater flood	• Building flooding • Nelson Rail Trail embankment slump or failure if flow is redirected along embankment ditch	• Ward Creek drains the northwest facing slopes above Nelson Rail Trail. The channel is one of multiple parallel channels directing surface water downstream into the stormwater system. • BGC did not identify any evidence of past debris flows or destructive debris floods on the creek during the field reconnaissance or in the aerial imagery. • Should culvert blockages occur, inundation would be classified as nuisance flooding with a very low chance of life loss or injury. • Wildfires along the slopes would substantially change the runoff regime in this creek.	Debris flood assessment warranted. Ongoing maintenance activities consistent with municipal stormwater management. Climate change assessment should identify if, when, and by how much culvert capacities are likely to be exceeded.
Cottonwood Creek	Debris flood <u>Tributary creeks:</u> Giveout Creek: debris flow Selous Creek: debris-flood[1] Gold Creek: debris flood[1]	• Various hazard chains feasible. Bank erosion, Cottonwood Creek impoundment, road washouts, log jams at bridges and bridge isolation or washout, building undercutting by bank erosion, log jam flooding at Cottonwood Lake, especially after forest fires or landslides into the lake.	• Cottonwood Creek originates at Cottonwood Lake and parallels Highway 6 downstream into Nelson and Kootenay Lake. The highway is within a narrow valley. Residential and commercial buildings are situated along the floodplain. The highway is susceptible to being undercut by Cottonwood Creek from bank erosion during debris floods. • Giveout Creek is susceptible to debris flows. There is limited to no protection from debris flows to existing development on the fan area, especially to an existing mobile home park. Giveout Creek meets Cottonwood Creek at a 90° angle from the west with limited to no available debris storage. If a debris flow occurs, there is potential for Cottonwood Creek channel aggradation and channel blockage with subsequent outbreak flood and washout (erosion) of Highway 6. • Selous Creek meets Cottonwood Creek at an oblique angle on the east side and approximately 1.9 km upstream (south) of Giveout Creek. BGC's regional prioritization of steep creek hazards within the RDCK identified this creek as debris-flood prone (BGC, March 31, 2019). Debris floods on Selous Creek have the potential to increase the flow and sediment volumes in Cottonwood Creek. • Gold Creek meets Cottonwood Creek at an almost 90-degree angle on the west side and approximately 1.8 km upstream (south) of Selous Creek. BGC categorized it as debris-flood prone (BGC, March 31, 2019). As with Selous Creek, debris floods on Gold Creek could increase peak discharge and sediment volumes in Cottonwood Creek.	Additional study recommended on Cottonwood and tributary creeks. Assessment should include bank erosion for different return period debris floods on Cottonwood Creek and an in-depth assessment of debris-flow hazards and life loss risks on Giveout Creek. The two assessments should be conducted in conjunction as Giveout Creek influences the behaviour of Cottonwood Creek. Risk assessment, if completed, should consider the function during an emergency of critical facilities located on Cottonwood Creek fan.
Smelter Creek	Debris Flow	• Direct impact to future buildings • Flooding and sedimentation of the golf course • Channel avulsions • Downstream avulsions near Golf Links Road.	• Smelter Creek fan area is heavily disturbed by land clearing for either golf course expansion or residential properties. Evidence of historic steep creek processes is difficult to discern from anthropogenic activities at a cursory field visit level. • The fan area is upstream of the channel outlet and to the northwest of the Granite Point Golf Club. There is no existing development, but ongoing works suggest future development in this area. • The creek channel upstream of the fan apex is well incised with a relatively small watershed in relation to the size of the fan area suggesting a zone of geological weakness (fault, or otherwise weak rock). Near the fan apex, the channel is poorly incised suggesting avulsion potential and channel instability.	The need for additional assessment will be governed by the intended land use on the fan area. If the proposed land use includes residential development additional detailed hazard and risk assessment is required according to current EGBC Guidelines[2]. If the proposed land use does not include residential uses, the need for hazard and risk assessment is less and should be discussed with the City. The logging road crossing and all forest road-related drainage issues should be reviewed. Any future logging should be scrutinized considering potential downstream consequences.

Notes:

1. BGC visited the confluence of Selous Creek and Gold Creeks with Cottonwood Creek but did not hike on the fans during the June 12, 2022 field visit.
2. Engineers and Geoscientists British Columbia (EGBC) Professional Practice Guidelines for Landslide Hazard Assessments (EGBC, 2022).

5.0 RECOMMENDATIONS

Based on the information reviewed as part of this study, BGC recommends additional assessment and consideration of risk-reduction measures on the study creeks in the following priority order:

1. Anderson Creek
    - Highest priority of the study creeks from the perspective of economic risk.
2. Cottonwood Creek
    - Comprehensive study including tributaries. Giveout Creek is the highest priority of the study creeks from the perspective of life safety risk.
3. Smelter Creek
    - In advance of future residential development of the fan area
4. Ward Creek

BGC's recommendations are summarized in Table 5-1.

Table 5-1. Summary of study recommendations.

Site	Recommended Action(s)	Intended Outcomes / Deliverables	Comments
Giveout Creek	• Develop risk communication and emergency response plan. • Complete detailed steep creek hazard and risk assessment. • Develop watershed management plan.	• Communication plan and materials regarding existing life safety risk; response procedures that may be taken by residents or authorities. • Hazard map(s) for debris-flow impact. • Regulatory maps (Composite Steep Creek Hazard Map, Life-Safety Risk Map)	As a pro bono service, BGC has developed infographics about steep creek hazards and risk that we can provide without cost to the City or RDCK, as appropriate.
Cottonwood Creek	• Updated, detailed flood and debris-flood hazard and risk assessment according to current guidelines.	• Hazard maps for inundation and bank erosion. • Regulatory maps (Flood Construction Levels, Composite Steep Creek Hazard Map).	BGC suggests: • Inclusion of landslide dam as a potential flood mechanism. • Consideration of climate change effects on both the mainstem creek and tributaries subject to steep creek processes. • For risk assessment, consider the function during an emergency of critical facilities located on Cottonwood Creek fan.
Anderson Creek	• Updated, detailed flood and debris-flood hazard and risk assessment according to current guidelines.	• Hazard maps for inundation and bank erosion. • Regulatory map (Composite Steep Creek Hazard Map).	BGC anticipates that economic risk is likely the controlling factor for decision making. For risk assessment, consider factors relevant to emergency response such as access and egress and critical facilities.
Ward Creek	• Urban interface debris hazard assessment.	• Basis to consider debris hazard at urban development interface and through stormwater management infrastructure on Ward Creek.	BGC completed comparable work for the DNV in support of stormwater management planning that Nelson may wish to review.
Smelter Creek	• Detailed hazard and risk assessment, in advance of future development	• Hazard and risk basis on which to make land use and development decisions.	Work as may be required by Nelson as part of a development approval process. Such assessment would reference the most recent EGBC landslide guidelines (September 29, 2022).

6.0 CLOSURE

BGC Engineering Inc. (BGC) prepared this document for the account of City of Nelson. The material in it reflects the judgment of BGC staff in light of the information available to BGC at the time of document preparation. Any use which a third party makes of this document or any reliance on decisions to be based on it is the responsibility of such third parties. BGC accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this document.

The final version of this report was completed after the untimely passing of Dr. Matthias Jakob in October 2022. Dr. Jakob was an international leading expert on steep creek hazard and risk. The full assessment except for the final report benefitted from Dr. Jakob's contributions and review.

Yours sincerely,

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LCH/KH/mjp/sjk

Attachment(s): Appendix A
Drawings

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APPENDIX A
STEEP CREEK HAZARDS

A.1. INTRODUCTION

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

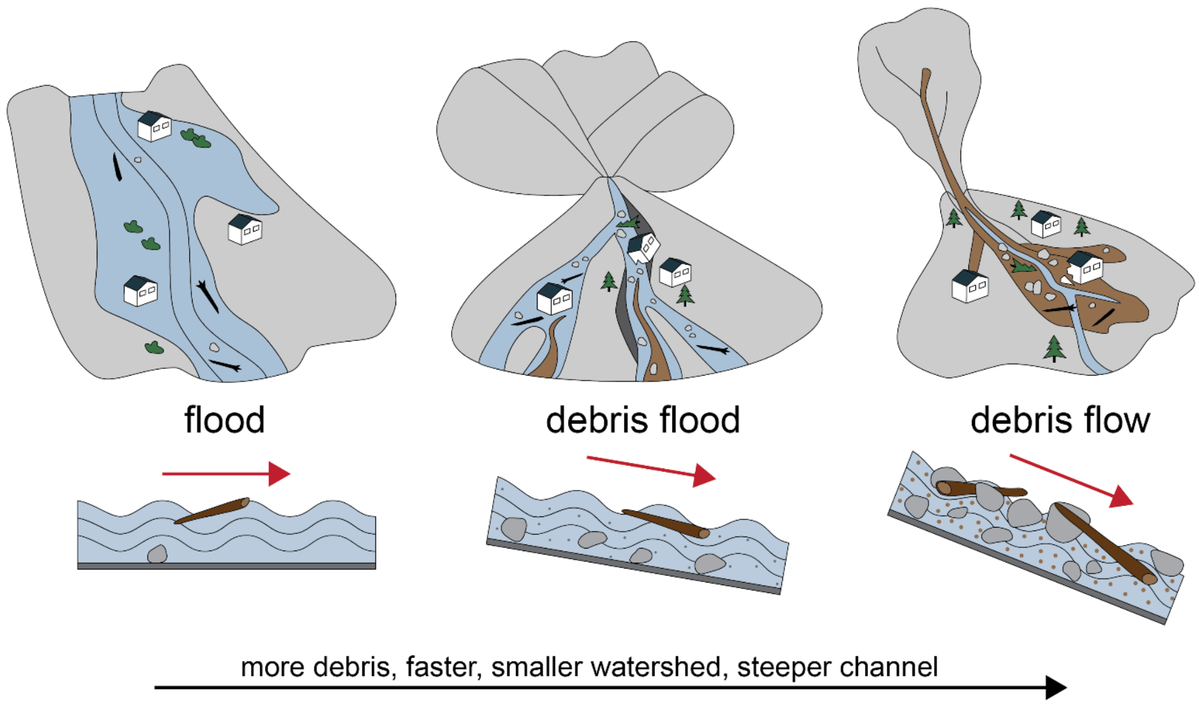


Figure A-1. Simplified illustration summarizing the hazards associated with each hydrogeomorphic process. BGC-created figure.

Clearwater floods do transport bedload and other sediments; they are not completely clear. The transition of a flood into a debris flood occurs when most of the channel bed is mobilized except possibly the largest clasts (Church and Jakob, 2020). As more and more fines (clays, silts and fine sands) are incorporated into the flow, hyperconcentrated flows may develop (not of relevance to the City of Nelson study creeks). Debris flows are typically triggered by side slope landslides or progressive bulking with erodible sediment in particularly steep (>15°) channels. Debris flows are more prevalent following wildfires of moderate to high burn severity when there is ample surface sediment 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-2 summarizes the different hydrogeomorphic processes by their appearance in plan form, velocity, and sediment concentration

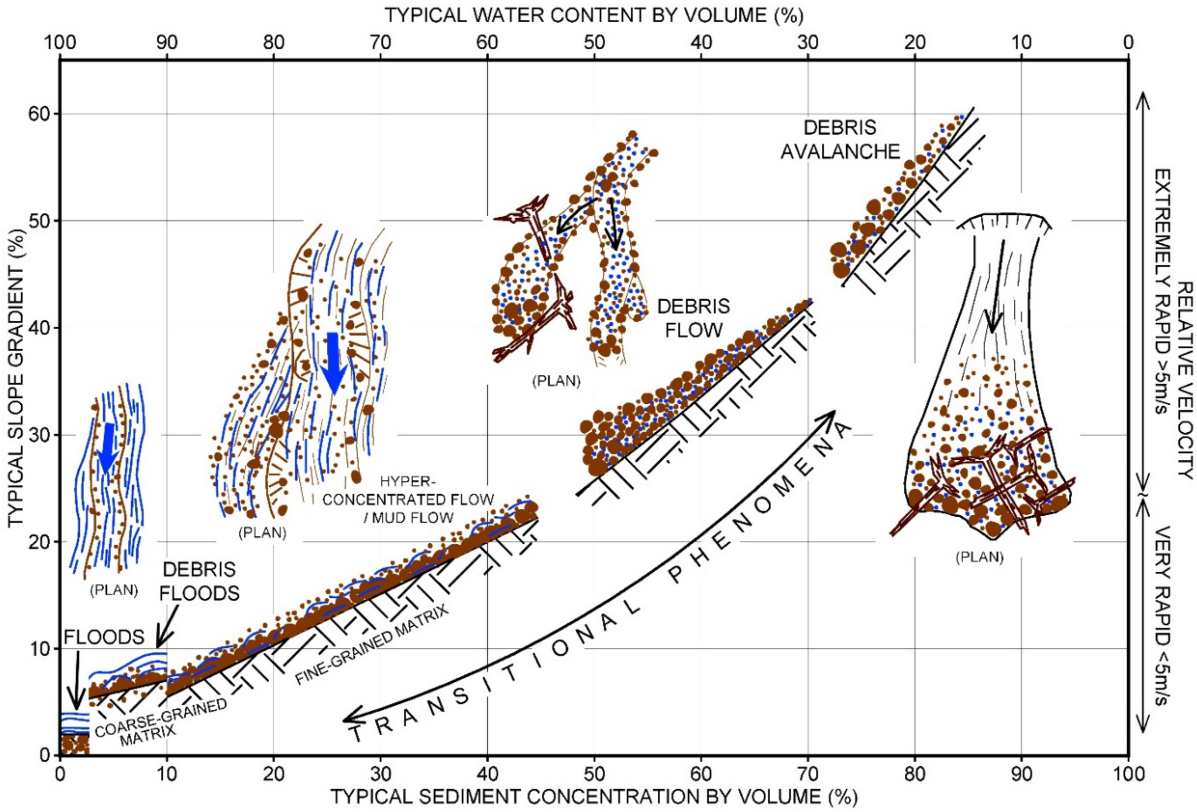


Figure A-2. Hydrogeomorphic process classification by sediment concentration, slope velocity and planform appearance. BGC-created figure.

A.1.1. Debris Floods

Debris floods typically occur on creeks with channel gradients between 5 and 30% (3-17°), but in contrast to common belief, can also occur on lower gradient gravel bed rivers. Debris floods occur when large volumes of water in a creek or river entrain the gravel, cobbles and boulders on the channel bed; this is known as “full bed mobilization”. The peak discharges are often very similar to those of clearwater floods, but the flow is more heavily charged with debris and sediment. Debris floods are known for their ability to cause extensive and rapid bank erosion (Church and Jakob, 2020; Jakob et al. 2022), scour, and aggrade channel beds increasing the risk of channel avulsion (Hungr et al., 2014). Cycles of scour and aggradation can occur in different phases throughout a debris flood.

Church and Jakob (2020) developed a three-fold typology for debris floods, which had previously not been defined well. This typology is summarized in Table A-1. Identifying the correct debris-flood type is important in understanding the sediment concentration the debris flood may carry and the changes to peak discharge, both of which feed into the frequency-magnitude relationship. Type 1 debris floods are initiated from rainfall or snowmelt generated streamflow that is sufficiently powerful to fully mobilize the channel bed. Type 2 debris floods are generated from diluted debris flows. Type 3 are generated by natural or man-made dam breaches.

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

Term	Definition	Typical sediment concentration by volume (%)	Typical factor applied to clearwater peak discharge	Typical impacts
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	1.02 to 1.2 (depending on the proximity of major debris sources to the fan apex as well as organic debris loading)	Widespread bank erosion, avulsions, alternating reaches of bed aggradation and degradation, blocked culverts, scoured bridge abutments, damaged buried infrastructure particularly in channel reaches u/s of fans.
Type 2 (Debris flow to debris flood dilution)	Substantially higher sediment concentration compared to a Type 1 debris flood and can transport larger volumes of sediment. All grain sizes are mobilized, except those from lag deposits (big glacial or rock fall boulders)	< 50	Up to 1.5 depending on the distance of the debris-flow transition to the area of interest. If the debris flow tributary is immediately upstream of the fan apex, the bulking factor may be higher.	
Type 3 (Outbreak floods)	Outbreak flood in channels that are not steep enough for debris-flow generation. The critical shear stress for debris-flood initiation is exceeded abruptly due to sharp hydrograph associated with the outbreak flood. All grains are mobilized in the channel bed and non-cohesive banks.	< 10 (except immediately downstream of the outbreak)	Up to 100 depending on size of dam and distance to dam failure. Peak discharges should be calculated through dam breach analyses and flood routing	Vast bank erosion, avulsions, substantial bed degradation along channels and aggradation on fans, destroyed culverts, outflanked or overwhelmed bridges, damaged buried infrastructure on channels and fans.

A.1.2. Debris Flows

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 as the flow moves down a confined gully or channel. Post-wildfire 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 a debris flow.

Coarse granular debris flows require a channel gradient of at least 27% (15°) for transport over significant distances (Takahashi, 1991) and have volumetric sediment concentrations greater than 50% (i.e., there is more debris and sediment than there is water). Transport is possible at gradients as low as 20% (11°), although some 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.

Flow velocities typically range from 1 to 10 m/s leading to peak discharges during debris flows that are at least an order of magnitude larger than those of clearwater floods of comparable return period floods and can be 50 times larger or more (Jakob & Jordan, 2001; Jakob et al., 2016).

Debris flows are more than 50% sediment by volume and typically transport large boulders and woody debris meaning the flow is quite dense. The dense flow travels at high speeds meaning it can have very high impact forces and can cause extensive damage to structures, infrastructure, and cause life loss.

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 can be crushed and debris may enter the building, leading to extensive damage to the interior of the structure (Jakob et al., 2012). Similarly, linear infrastructure such as roads and railways can be 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 avulsions are likely in poorly confined channel sections (particularly on the outside of 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.1.3. Peak Discharge Estimation

Clear-water flood, debris-flood, and debris-flow processes can differ widely in terms of peak discharge. The peak discharge of a debris flood is typically 1 to 1.2 times that of a clear-water flood in the same creek but could be much greater for Type 2 and 3 debris floods. If the creek is subject to debris flows, the peak flow may be much higher (as much as 50 times) than the flood peak discharge (Jakob & Jordan, 2001). Figure A-3 shows a hypothetical cross-section of a steep creeks, including:

- Peak flow for the 2-year return period (Q_2)
- Peak flow for the 200-year return period flood (Q_{200})
- Peak flow for Type 1 debris flood (Q_{max} full bed mobilization)
- Peak flow for Type 3 debris flood (Q_{max} outburst flood)
- Peak flow for debris flow (Q_{max} debris flow).

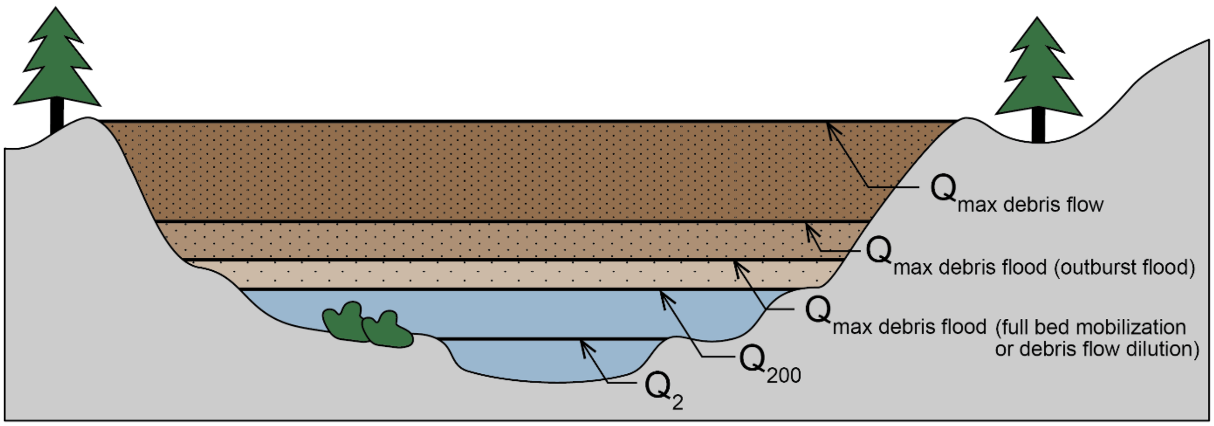


Figure A-3. Steep creek flood profile showing schematically peak flow levels for different events.

A.1.4. Avulsions

An avulsion occurs when a watercourse jumps out of its main channel into a new course across its fan or floodplain. This can happen because the main channel cannot convey the flood discharge and simply overflows, or because the momentum of a flow allows overtopping on the outside of a channel bend. Finally, an avulsion can occur because a log jam or blocked bridge redirects flow away from the present channel. The channel an avulsion flow travels down is referred to as an avulsion channel. An avulsion channel can be a new flow path that forms during a flooding event or a channel that was previously occupied.

In Figure A-4, a schematic of a steep creek and fan is shown where the creek avulses on either side of the main channel. The avulsion channels are shown as dashed blue lines as avulsions only occur during severe floods (i.e., rarely). On high resolution topographic maps generated from Lidar, avulsion channels are generally visible and are tell-tale signs of past and potential future avulsions.

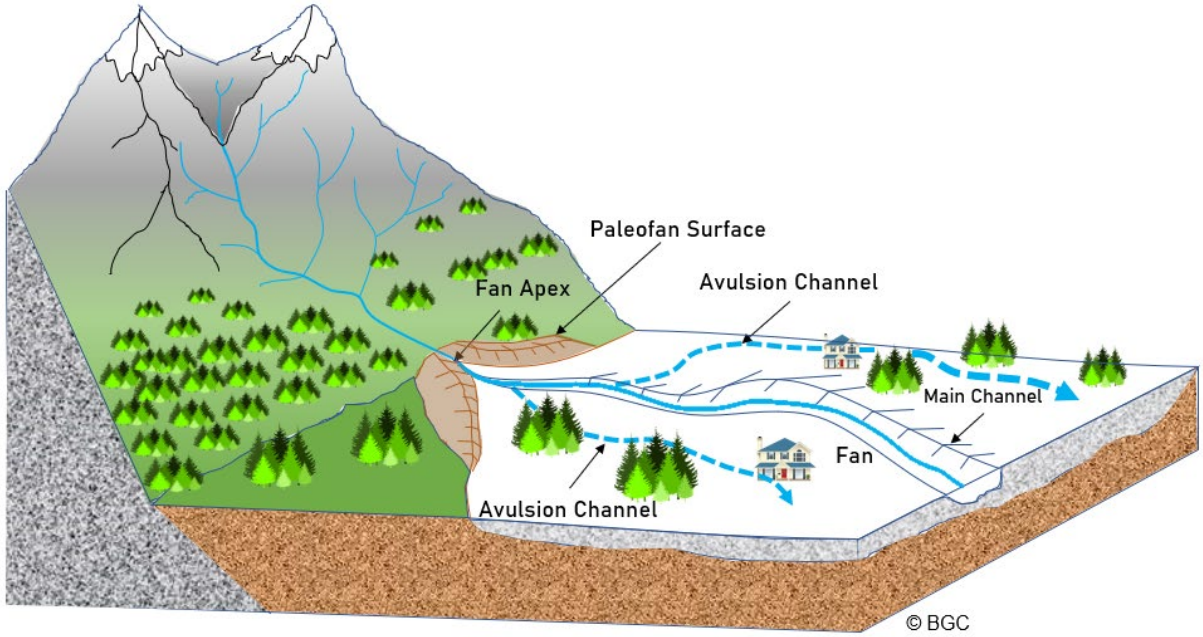
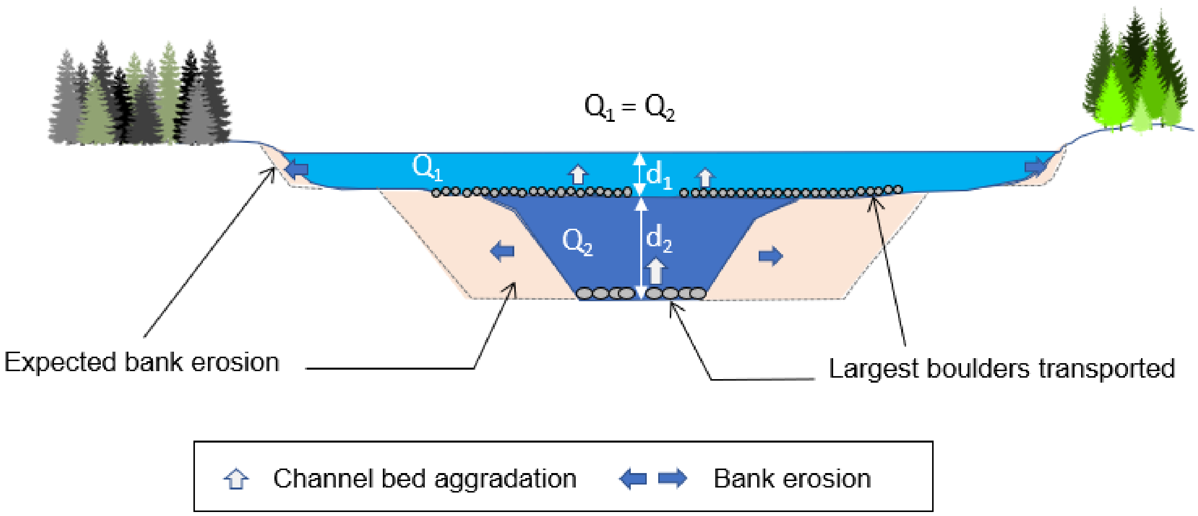


Figure A-4. Schematic of a steep creek channel with avulsions downstream of the fan apex. Artwork by BGC.

A.1.5. Bank Erosion

Floods and debris floods exert high shear stresses on channel banks which can lead to bank erosion. Alluvial fans may be particularly susceptible to bank erosion as channel bed armouring limits the erodibility of the bed relative to the channel banks, which are often composed of non-cohesive materials such as sands and gravels. In contrast, rivers that typically experience overbank flooding and deposition of fine sediment during clearwater floods are likely to have cohesive banks composed of silt and clay, which are relatively strong compared to the channel bed.

Bank erosion along steep creeks is not considered in standard hydraulic models, and therefore needs to be assessed separately. Bank erosion is a self-limiting process as channel widening lowers the flow depth and shear stress associated with a given flood magnitude (Figure A-5).



Channel configuration	Flow characteristics and bank erosion potential
Wide channel and floodplain (light blue)	• Low flow depth (d_1) and velocity lead to low shear stresses exerted on channel banks. • Lower bank erosion potential and smaller grain sizes transported. • Lesser erosion protection and channel maintenance requirements.
Narrow channel (dark blue)	• High flow depth (d_2) and velocity lead to high shear stresses exerted on channel banks. • Higher bank erosion potential and larger grain sizes transported. • Greater erosion protection and channel maintenance requirements.

Figure A-5. Schematic of channel configuration and associated bank erosion potential.

A.2. CLIMATE CHANGE

Climate change is expected to impact steep creek geohazards both directly and indirectly through complex feedback mechanisms. Given that hydrological and mass movement processes are higher order effects of air temperature increases, their prediction is highly complex and often site-specific.

Regional climate change projections indicate that there will be an increase in winter rainfall (PCIC, 2012), an increase in the hourly intensity of extreme rainfall and increase in frequency of events (Prein et al., 2017). Changes to short duration (one hour and less) rainfall intensities are particularly relevant for post-fire situations in debris-flow generating watersheds. Within the year to a few years after a wildfire affecting large portions of a given watershed, short duration and high intensity rainfall events are much more likely to trigger debris flows or debris floods, than prior to a wildfire event.

Steep creek basins can be generally categorized as being either:

- Supply-limited: meaning that debris available for transport is a limiting factor on the magnitude and frequency of steep creek events. In other words, once debris in the source zone and transport zone has been depleted by a debris flow or debris flood, another event even with the same hydro-climatic trigger will be of lesser magnitude; or,

- Supply-unlimited: meaning that debris available for transport is not a limiting factor on the magnitude and frequency of steep creek events, and another factor (such as precipitation frequency/magnitude) is the limiting factor. In other words, there is always an abundance of debris along a channel and in source areas so that whenever a critical hydro-climatic threshold is exceeded, an event will occur. The more severe the hydro-climatic event, the higher the resulting magnitude of the debris flow or debris flood.

Further subdivisions into channel supply-limited and unlimited and basin supply-limited and unlimited are possible but not considered herein.

The sensitivity of the two basic types of basins to increases in rainfall (intensity and frequency increases) differ (Figure A-6):

- Supply-limited basins would likely see a decrease in individual geohazard event magnitude, but an increase in their frequency as smaller amounts of debris that remain in the channel are easily mobilized (i.e., more, but smaller events).
- Supply-unlimited basins would likely see an increase in hazard magnitude and a greater increase in frequency (i.e., significantly more, and larger events).

Supply-limited basins can transition into supply-unlimited due to landscape changes. For example, sediment supply could be increased by wildfires, landslide occurrence, or human activity (e.g., related to road building or resource extraction). In the case of wildfires, the impact on debris supply is greatest immediately after the wildfire, with its impact diminishing over time as vegetation regrows (see Section A.2.1). Wildfires are known to both increase the sediment supply and lower the precipitation threshold for steep creek events to occur.

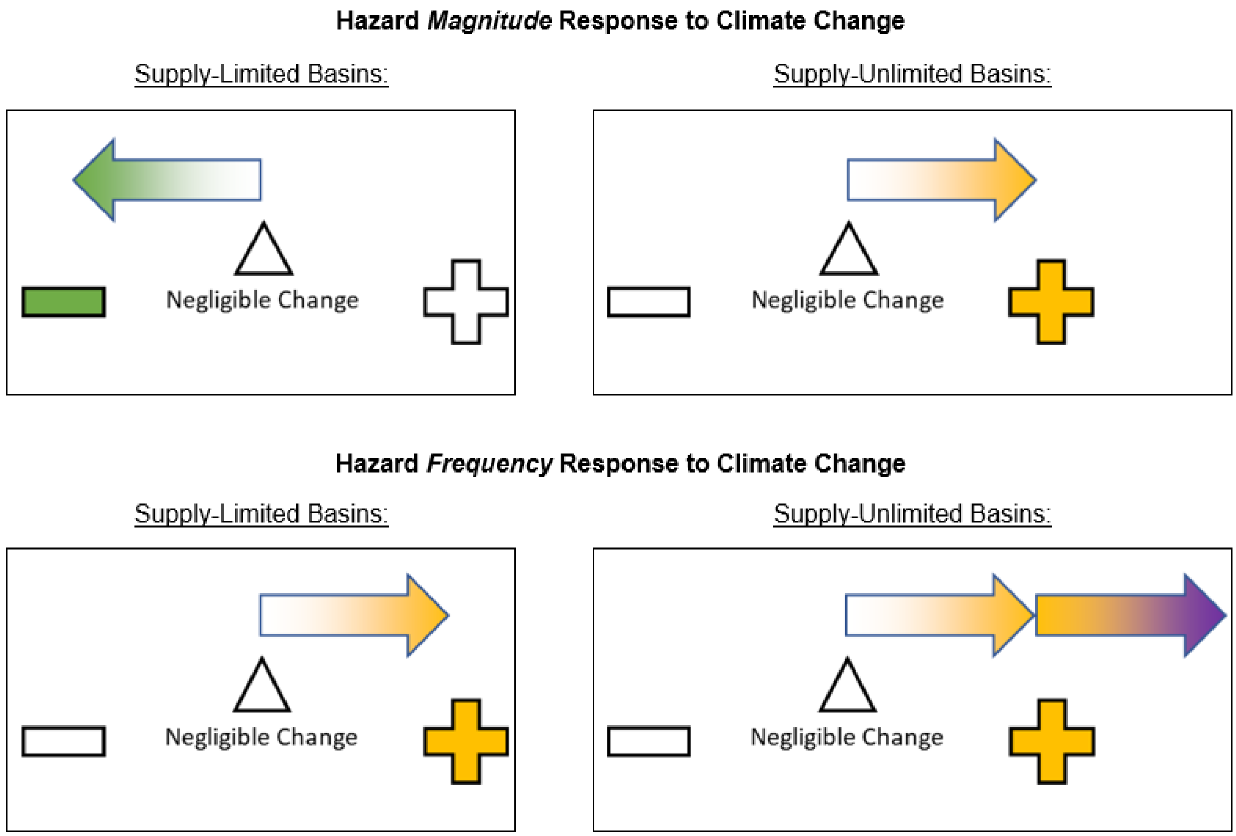


Figure A-6. Steep creek hazard sensitivity to climate change – supply-limited and supply unlimited basins.

A.2.1. Wildfires

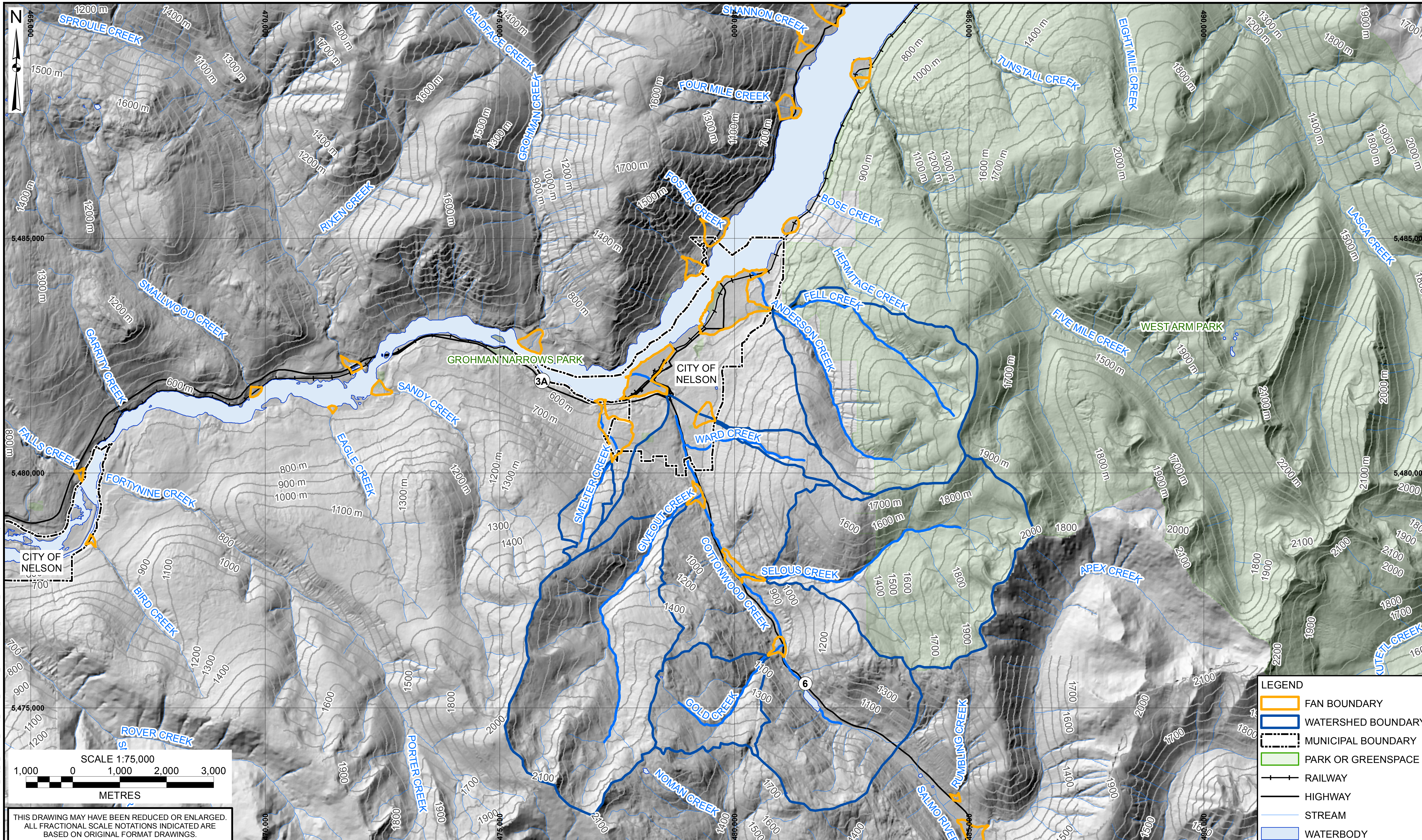
Wildfires in steep mountainous terrain are often followed by a temporary period of increased geohazard activity. This period is most pronounced within the first three to five years after the fire (Cannon & Gartner, 2005; DeGraff et al., 2015). After about three to five years, vegetation can reestablish on hillslopes and loose, unconsolidated sediment mantling hillslopes and channels may have been eroded and deposited downstream. A second period of post-fire debris-flow activity is possible about ten years following a fire, when long duration storms with high rainfall totals or rain-on-snow events cause landslides that more easily mobilize due to a loss of cohesion caused by tree root decay (DeGraff et al., 2015; Klock & Helvey, 1976; Sidle, 1991; 2005). This second period of heightened debris-flow activity is rare.

A.2.2. Landslide Dam Outbreak Flood Potential

Some steep creek watersheds are prone to LDOFs, which could trigger flooding, debris floods, or debris flows with larger magnitudes than "typical" hazards. An example of this hazard in the Squamish Lillooet Regional District is landslides in the Mount Meager volcanic complex, which have generated several landslide dams along Meager Creek and Lillooet River (Figure A-7; Bovis & Jakob, 2000; Guthrie et al., 2012). Review of LDOF potential on the City of Nelson study creeks has not been undertaken.

Figure A-7. Landslide dam on Meager Creek from the August 6, 2010 rockslide-debris flow from Capricorn Creek. The dam impounded Meager Creek for some time. Photo by D. Steers.

DRAWINGS



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NOTES:
1. ALL DIMENSIONS ARE IN METRES UNLESS OTHERWISE NOTED.
2. THIS DRAWING MUST BE READ IN CONJUNCTION WITH BGC'S REPORT TITLED "CITY OF NELSON STEEP CREEK HAZARDS ASSESSMENT", AND DATED JANUARY 2023.
3. BASE TOPOGRAPHIC DATA BASED ON LIDAR DATED 2017 AND 2018. CONTOUR INTERVAL IS 100 m. BASE IMAGERY FROM WORLD_IMAGERY_BASEMAP, DATED JULY 2018.
4. FAN AND WATERSHED BOUNDARIES DELINEATED BY BGC BASED ON LIDAR DATED 2017 AND 2018. FAN BOUNDARIES SHOULD NOT BE CONSTRUED AS A HAZARD MAP, NOR DO THEY SHOW THE SPATIAL EXTENT OF POTENTIAL FLOODING.
5. RAILWAY DATA FROM GEOBASE NATIONAL RAILWAY NETWORK, DATED 2013. ROADS DATA FROM BC DIGITAL ROAD ATLAS. WATERCOURSE AND WATERBODY DATA FROM CANVEC.
6. COORDINATE SYSTEM IS NAD 1983 UTM ZONE 11N. VERTICAL DATUM IS CGVD28.
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APPROVED:	LCH

CLIENT: CITY OF NELSON

BGC

PROJECT: CITY OF NELSON STEEP CREEK HAZARDS ASSESSMENT

TITLE: LOCATION MAP

PROJECT No.:	DWG No:
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