Regional District of Central Kootenay (RDCK)

Johnsons Landing Landslide Hazard and Risk Assessment

May 16th 2013

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Prepared for:
Regional District of Central Kootenay

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Executive Summary

At 10:37 a.m. the morning of July 12th, 2012 a landslide occurred on the hillside approximately two km above the small community of Johnsons Landing, BC (Figure 1).

Approximately 320,000 m^3 of soil and rock travelled at speeds of up to 150 km/hr down the Gar Creek channel. Much of the landslide debris flowed out of the channel and onto the Johnsons Landing bench destroying three homes and causing the loss of four lives. Some debris continued down the channel destroying another house situated on the Gar Creek fan and removing three sections of public road. The landslide also resulted in the loss of the community water supply system and the long term evacuation of several residents.

This study was commissioned by the Regional District of Central Kootenay (RDCK) to determine the likelihood of further landslide activity and to determine the hazard to residents both over the short term (summer and winter of 2012) and the long term. The study was funded by Emergency Management British Columbia (EMBC).

A review of the landslide characteristics, local surficial and subsurface geology, and local weather conditions leading up to the event combined with the application of slope stability analyses, landslide run-out modelling, and judgement led to the following observations and conclusions:

- Record June rainfall and late snowmelt saturated the soils on the slope above the community and triggered the landslide.
- A landslide of similar size has not occurred in this area since deglaciation (last 12,000 years).
- Previous (before 2012) reviews and observations of the area:
    - The Gar Creek fan (lower landslide deposit adjacent to Kootenay Lake) was mapped as a potential debris flow area. The province provided the maps and files to the RDCK. The area is noted in the RDCK Floodplain Bylaw 2080 to have a Non Standard Flood and Erosion Rating.
    - Terrain mapping and site assessments in the Gar Creek drainage in 1983, 1994, 2001, and 2003 did not indicate the possible occurrence of a landslide large enough to travel onto the Johnsons Landing bench (Figure 2).

  - Local residents observed very high creek flows, high turbidity, changing flow patterns, high bed-load and debris blockages weeks and days before the landslide event.

- There is potential for future landslides in the Gar Creek drainage. The landslide likelihood estimates given below are approximate and could change in the future if more information on landslide movement becomes available.
  - The likelihood of a landslide and debris flow that is contained within the Gar Creek channel flowing over the Gar Creek fan and into Kootenay Lake is estimated at 1:10 per year.
  - The likelihood of a landslide of sufficient volume to travel onto and near the downslope end of the Johnsons Landing bench is estimated at 1:1,000 per year (see Figure 36).
  - The likelihood of a landslide of sufficient volume to travel onto the Johnsons Landing bench and continue to Kootenay Lake is estimated at 1:10,000 per year (see Figure 36).

The recommendations that follow are based on field reviews, numerical modelling, experience and judgement. The results of the landslide assessments and risk analyses indicate that some residents, users of the Argenta-Johnsons Landing and Houston Roads, users of the Community Hall, and users of the beach area are exposed to continued landslide and debris flow hazards.

The following is a list of site specific recommendations intended to reduce the risk of loss of life:

1. **Notify local residents of the estimated hazard and risk.** Some properties are large with portions of the properties straddling different hazard areas allowing for the potential to rebuild or relocate houses to safer areas.
2. **Restrict further land/house development in the areas identified as having a moderate, high, or very high hazard unless subsequent geotechnical investigations are conducted that supports the development, recommends protective works, and/or reduces the assessed hazard.** The investigations would need to consider the macro and micro topography, any updated landslide modelling and slope monitoring information, and any other new or existing information. It is likely that in areas identified as having a high or very high hazard that such an investigation and/or works would be cost prohibitive.
3. **Establish and maintain a minimum 5 m channel bottom to top of channel bank height at the 70° bend (elevation 750 m) in Gar Creek.** The landslide hazard map was

produced from modelling that included 4 m height differential at this bend and significant changes to this height (through creek deposition of sediments and debris) may extend landslide and snow avalanche hazard boundaries downslope. Upon review of the landslide run-out modelling and risk analyses it may be determined that it is advantageous to construct and maintain additional channel bank height. Any changes to the bank height, including the temporary berm, must consider private land ownership, berm maintenance, and downslope impacts.

4. **Establish a simple landslide monitoring program.** Landslide monitoring and further site observations over the next several years will provide additional information on the hazard and may allow for a refinement or modification to the estimated likelihood of landslide occurrence. Monitoring and site observations may include the collection of information related to slope movements, rainfall and snowpack accumulation and melt, inventory of and changes to the location and volume of springs and seeps, and appearance of any new tension cracks, shear zones, scarps or the extension of existing scarps. The degree to which monitoring will be implemented will ultimately depend on land use decisions.

5. **Establish communication plans and protocols to update residents and visitors of local conditions during periods of potential increased landslide hazard.** While some local residents are familiar with the signs of increased landslide hazard (example: high creek turbidity), the recognition of landslide early warning signs should be communicated in a formal manner to all those present or accessing the area (including visitors).

6. **Establish a watershed plan for resource management and development on crown land within the Gar Creek watershed.** The plan may outline allowable and restricted watershed activities such as the harvesting of timber or road construction.

7. **The Ministry of Transportation and Infrastructure should evaluate opportunities to reduce landslide risk to the travelling public in areas potentially impacted by future landslide events in the Johnsons Landing area.**

8. **To document lessons learned from this tragic event, Government agencies should review the following suggestions intended to improve public safety relating to landslide events:**

    a. **Increase public awareness of when and how to report signs of unusual creek activity and slope instability.** There were signs of unusual creek activity (high flows, high turbidity, and small debris/erosion events) in the days before the Johnsons

Landing 2012 landslide event that did not get reported to the local government or EMBC.

b. **Enhance the accessibility of landslide hazard maps and reports to regulatory bodies, qualified professionals, property owners and the public.** A map identifying the Gar Creek fan as a potentially hazardous area was available in 1998. However, some residents, with property on the fan, were not aware that this information existed. There were other landslide hazard maps and reports available but were not easily accessible. There are other areas in the Kootenays where landslide hazards have been identified and the general public and landowners may not be aware of this information (mainly in the form of maps appended to the RDCK Floodplain Management Bylaw and MFLNRO Flood Hazard Maps). Residents and the general public should be made aware of and/or understand how to access existing landslide hazard information, new landslide reports and new landslide hazard maps.

c. **Raise awareness of the benefits of LIDAR (Light Detection and Ranging) for professionals, government agencies, and private companies in areas of known or expected landslide hazard located above areas with significant values.** The use of LIDAR mapping at Johnsons Landing provided a better definition of the previous landslide activity that was not evident in air photos or on the ground.

d. **Establish uniform and consistent landslide risk tolerance/acceptability criteria to be applied throughout the Regional District for assessment of landslide risk relating to land development, building permitting, and existing residences.** The criteria will help avoid potential confusion with respect to what is considered "safe".

e. **Maintain robust emergency communications with consistent protocols for all emergency response personnel responding to landslide events.** The second landslide that occurred on the morning of July 13th, 2012, came very close to impacting several people in the area. It is important that during post landslide response that adequate consideration be given to the potential of secondary landslide activities. Rapid geotechnical assessments are often required with ongoing spotting requirements and attention to precipitation and snowmelt levels in order to minimize hazards to responders.

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1. Introduction

On July 12th and July 13th, 2012, landslides occurred within the Gar Creek drainage at Johnsons Landing, B.C. (Figure 1 and Figure 2), resulting in four fatalities and considerable property damage.

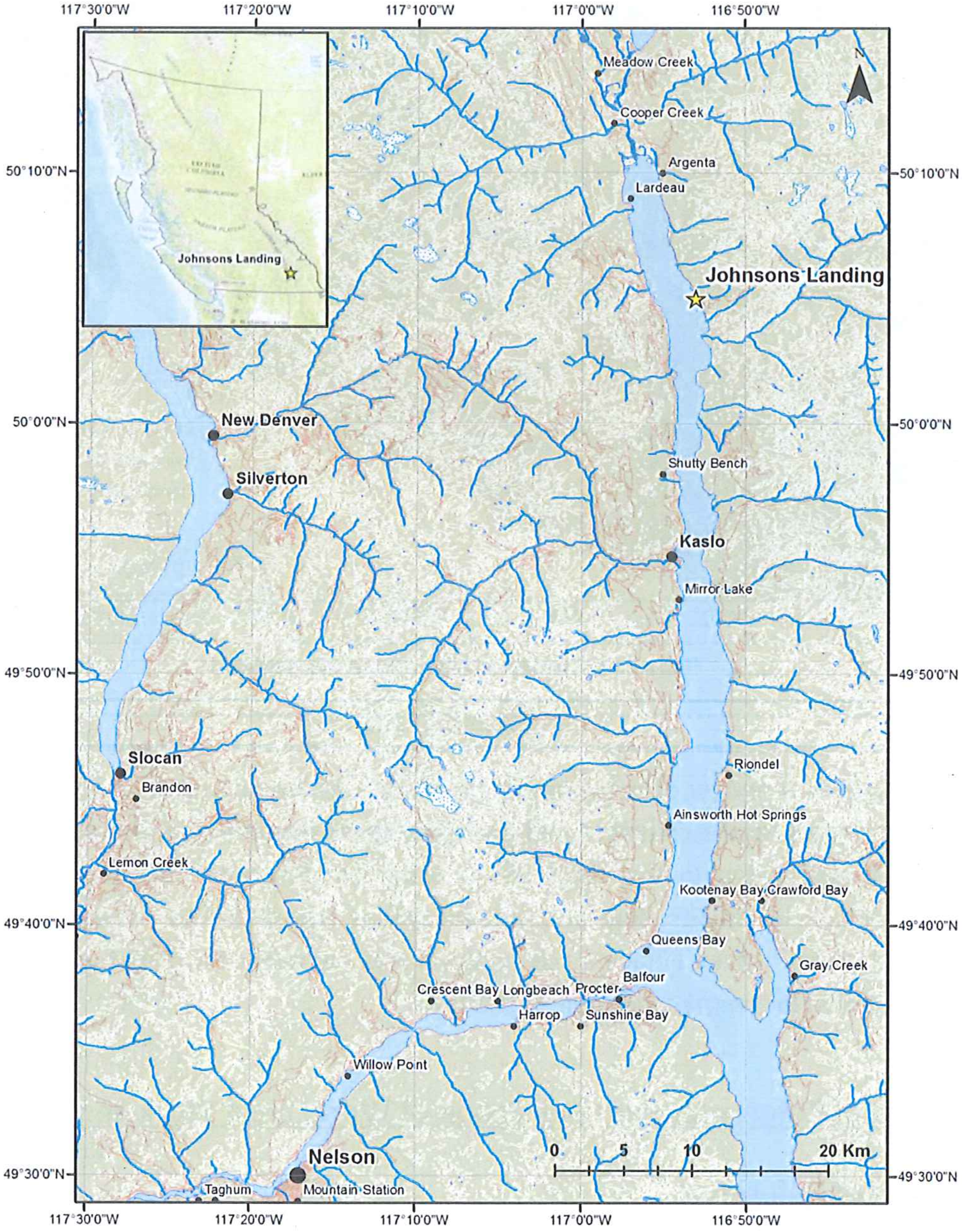

Figure 1: Johnsons Landing site location

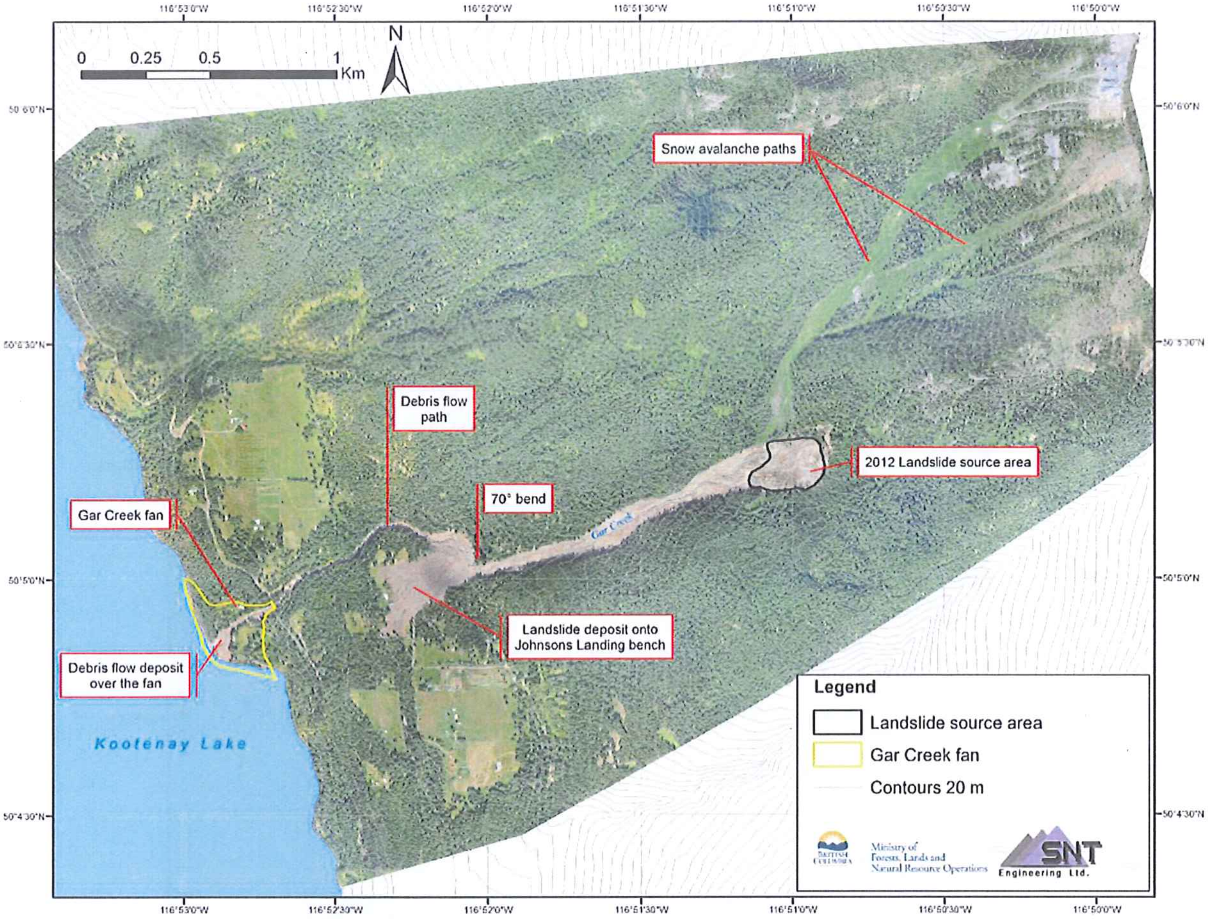

Figure 2: Orthophoto of Johnsons Landing landslide

(see Appendix B Map 1)

This report includes a review of meteorological conditions leading up to the landslide event, a review of the surface and subsurface soil and geological conditions and a review of previous technical work completed in the drainage in order to determine the landslide cause and potential for future landslides. Run-out modelling was completed to assess where potential future landslides may travel. Finally a risk analysis was completed to assist local residents and local government(s) in the management of the risk.

2. Terms of Reference, Purpose, Scope of Work, Field Work and Methods

2.1 Terms of Reference

SNT Engineering Ltd. was requested by the Emergency Operations Centre, Regional District of Central Kootenay (RDCK), to carry out a study to determine the likelihood of further landslide activity originating near the 2012 landslide source area and to determine the landslide hazard to residents both over the short term (summer and winter of 2012) and the long term. SNT presented a proposal that included a multi-agency collaborative effort involving the BC Ministry of Forests, Lands, and Natural Resource Operations (MFLNRO) and the BC Ministry of Transportation and Infrastructure (MoTI). During the days immediately following the landslide event, experts from these Ministries and SNT were involved with the search and recovery efforts, the re-establishment of select road access, and the establishment of spotter locations and safe entry procedures.

Funding for the project was provided by Emergency Management British Columbia (EMBC).

2.2 Purpose and Scope of Work

The purpose of this work was to determine the trigger and cause of the 2012 landslide, to provide advice with respect to safe access, and to delineate hazard areas with respect to future possible landslides.

The scope of work included five general components:

1) Safe Access – Determine safety conditions relating to temporary access for local residents to remove household possessions and for the safe access requirements for agencies (example MoTI and utility companies). This work would include the development of procedures for safe entry, spotting, and temporary road construction (for removal of possessions).
2) Evacuation Order Area – Develop an interim hazard map to outline an interim zone of low hazard (until the completion of the final report), whereby residents within the interim low hazard area could return to their homes. Rapid damage safety assessments were conducted by the RDCK building inspectors of all houses impacted by the landslide.
3) Field Investigation/Modelling/Mapping – Conduct field investigations, slope stability assessments, and landslide run-out modelling to produce mapping that identifies the likely limits of future landslides and debris flows. Information acquired and reviewed would include LIDAR, orthophotos, photogrammetry, and soil sampling. Modelling would include slope stability and landslide run-out analyses. The results of the data collection and analyses would be used to zone potential landslide deposition areas into hazard classes that could then be used by the RDCK for zoning purposes and by local landowners for site awareness.

4) Snow Avalanche – Conduct a review of the snow avalanche hazard to determine if post landslide conditions have resulted in elevated potential snow avalanche hazard and snow avalanche run-out distances. The results to include a snow avalanche hazard map.

5) Landslide Cause and Recommendations – Review the pre-slide terrain conditions, hazard mapping, and early warning signs and determine the likely cause of the 2012 landslide. Assess the potential for future landslides in this location, and determine whether there are lessons learned that can be transferred to other developed areas in the Kootenays.

2.3 Available Information

Data and information available for the study included local previous studies and reports, mapping and assessments, historical air photos, orthophotos, and LIDAR (acquired for this study). Previously published information includes the following:

- Topographic maps - 1:20,000 TRIM contour maps, and 1:10,000 contour maps;
- Soil, terrain, and ecosystem mapping (Kutenai Nature Investigations Ltd., 1983, terrain mapping revised 1998);
- Reports accompanying the soil and terrain mapping (Kutenai Nature Investigations Ltd., 1983; Salway, 1983);
- Watershed assessment for the Argenta-Johnsons Landing area (EBA Engineering, 2003);
- Terrain Stability Inventory Alluvial and Debris Torrent Fans Kootenay Region (Klohn-Crippen 1998);
- Corridor hazard mapping (Jordan 1994) and local site review (Jordan 2001);
- Regional District of Central Kootenay Alluvial Fan Boundary Mapping (Carol Wallace Consulting, 2001);
- Flood Hazard Maps (MFLNRO);
- Floodplain Management Bylaw (RDCK); and
- Airphotos:
    - 2006, 30BCC06067: 3-6, 34-37
    - 2004, 15BCC04014:201-203, 115-117
    - 2000, 30BCC0070:210-212, 207-209
    - 1997, 30BCB97109: 124-126
    - 1993, 30BCB 91123: 10-12
    - 1945, A7660-87,88,91,92,95,96,99,112,113,116,117, 120, 121,124
    - 1939, BC172:1,2,104,105,106,107

Information obtained for this study includes:

- Post landslide digital elevation model (DEM) from LIDAR
- Pre landslide DEM, from photogrammetry and field observations
- An orthophoto obtained by the RDCK in late July 2012 (resolution 1 pixel = 30 cm)
- LIDAR bare earth models and low elevation orthophotos
- Photographs and video of the landslide and 2003 and 2012 snow avalanches
- Laboratory tests of soil samples and water samples; and
- Local eyewitness accounts

2.4 Field Work and Methods

Field work and the collection of data began immediately following the landslide events as part of the search and rescue efforts, the re-establishment of road access and the determination of a safe area for temporary evacuation. Field work was conducted shortly after the landslide event to prepare a hazard map for the RDCK to use to declare a state of emergency and issue evacuation orders. On July 17th the main scarp and upper scarp were reviewed on the ground; however, the site was not deemed safe for extensive field reviews until early September.

LIDAR imagery was acquired for the landslide and adjacent area, including the watersheds of Gar Creek and Gardner Creek (to the north), in early August. A detailed orthophoto was also acquired as part of this project. For field work, hillshade images of the bare earth model, 1 m contour maps, and orthophoto prints were prepared at a scale of 1:2000.

Field work was largely conducted on Sept 4th to 7th, with the field party consisting of D Nicol, P Jordan, D Boyer, M Deschênes, and T Giles. This field work included traverses on the landslide deposit and adjacent areas of the Johnsons Landing bench, traverses of the main scarp and upslope areas, and field delineation of areas subject to potential debris flows below the landslide deposit and on the Gar Creek fan. A significant component of this field trip was the investigation of bedrock landslide areas in the south fork of the Gar Creek, which were identified on the LIDAR images. All traverses were mapped using GPS waypoints and tracks, and plotted on the contour and hillshade maps.

Additional field work took place on Oct 2nd and 3rd. The area of tension cracks above the landslide scarp was traversed and mapped, test pits were dug on the deposit and nearby areas, and data were collected to aid in run-out modeling (see Section 12). A total of 12 pits were dug with an excavator, with depths ranging from 2.5 m to 12 m, and over forty soil samples were collected. Water samples were collected from seven springs on and near the landslide main scarp. Textural analyses of the soil samples were performed at the MFLNRO lab at Kootenay Lake Forest District, to attempt to distinguish soil of landslide and glacial origin. Water samples were analysed to aid in investigation of the possible origin of groundwater. The results of the test pitting and water sample testing are located in Appendices D and M respectively.

Several additional one day field trips were made in October and November by members of the study team to collect additional data and to place measurement stakes along the upper cracks above the landslide main scarp. During the field work period, local residents were interviewed to obtain eyewitness accounts of the landslide event and any relevant background information.

3. Johnsons Landing Landslide

3.1 The July 12th-13th 2012 Events

The main Johnsons Landing landslide occurred on the morning of July 12th 2012, at 10:37 a.m. The landslide originated in deep glacial till and colluvium at an elevation of 1050 m to 1250 m (Figure 3 and Figure 4). The estimated landslide volume was approximately 320,000 m^3 (see Photos 1 to 6 Appendix A). The initial event comprising most of the volume is classified as a rapid debris avalanche (Hungr et al 2001). It descended the channel of Gar Creek, a steep narrow valley which occasionally carries small debris flows and snow avalanches. Approximately 50% of the debris (169,000 m^3) left the creek channel at a 70° bend in the creek 1400 m from the initiation area, travelled up and over a low ridge at 750 m elevation, and spread out approximately 250 m wide by 300 m long with an average thickness of 2.6 m on a gently sloping bench (Johnsons Landing bench) which was occupied by forest, cultivated land, and houses. Three houses were destroyed on the Johnsons Landing bench and two additional houses were severely damaged. Four lives were lost. A portion (less than 5%) of the debris continued flowing down the narrow creek channel as a debris flow, destroying three creek crossings of the Argenta-Johnsons Landing Road, and inundating a portion of the fan area at the lake damaging a house (see Photos 7 and 8 Appendix A). The total area impacted by the landslide is 30.8 hectares (ha), of which the source area is 7.5 ha. The source area is the area from which the landslide material originated. Landslide debris covered an area of 6.5 hectares on the Johnsons Landing bench and affected 16.8 hectares in the channel and fan.

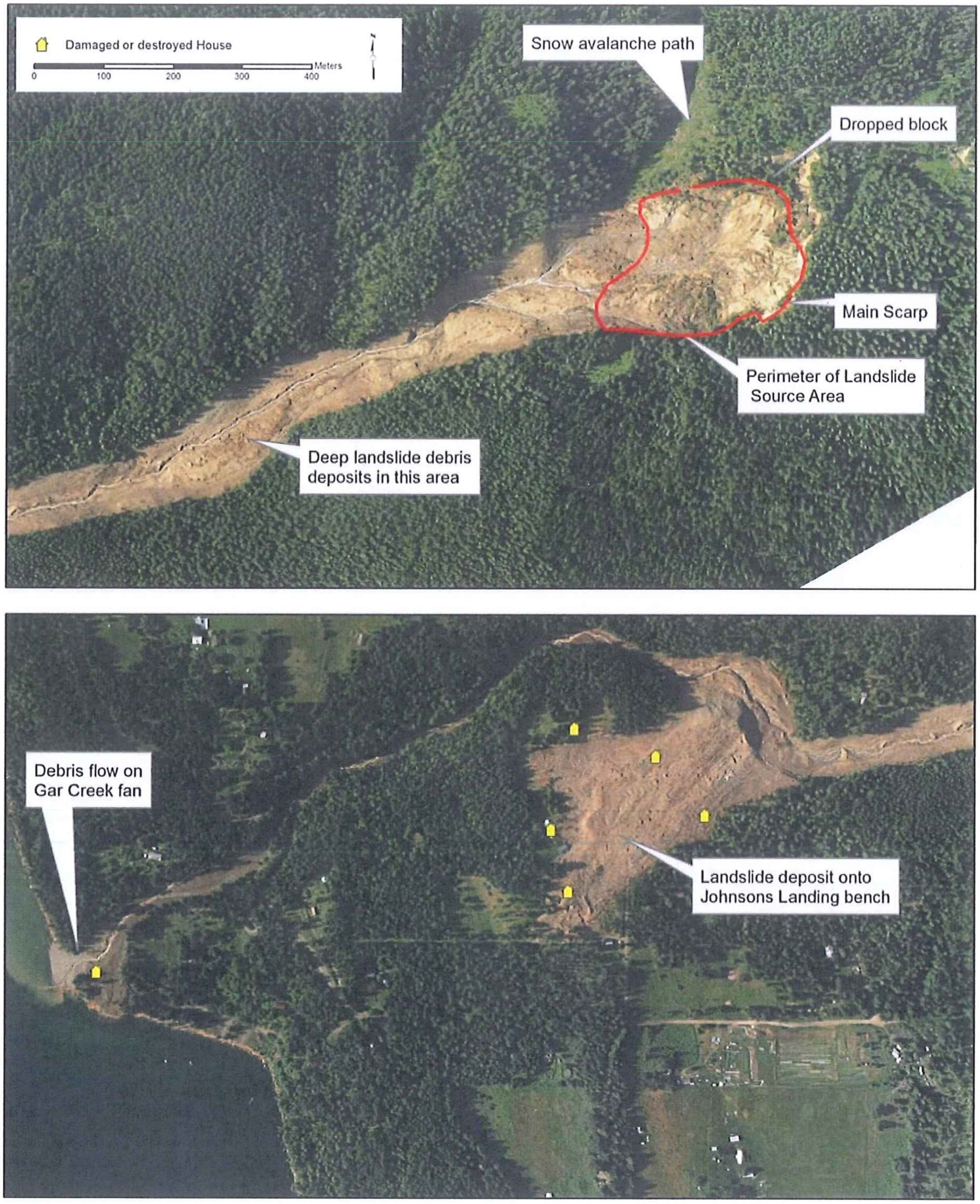

Figure 3: Features of the 2012 landslide source area (upper) and deposits (lower)

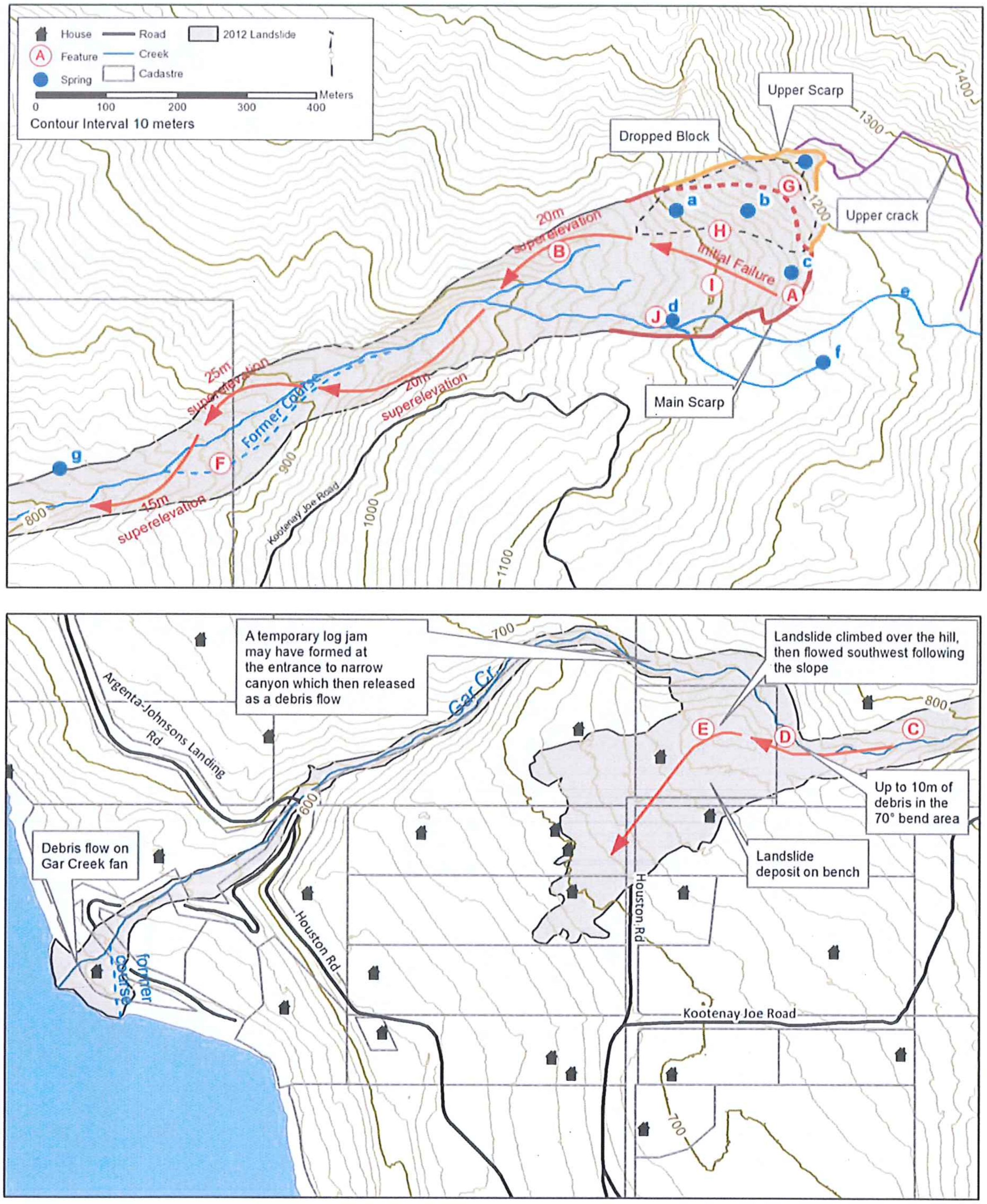

Figure 4: Landslide source area (upper) and deposits (lower) of the 2012 landslide.

Note: The main scarp of the initial landslide source area is shown in red (solid where intact; dashed where disrupted by the dropped block). The dropped block is outlined with a black dashed line, and its upper scarp is shown in orange.

Approximately 24 hours after the first landslide and debris flow, a second larger debris flow occurred, which originated from an area near the landslide source area and entrained loose landslide debris in the channel. This second debris flow remained in the Gar Creek channel, travelling through the 70° bend. It destroyed the already damaged house on the fan. There were several near misses but no additional fatalities (see Photos 9 through 16 Appendix A).

The total estimated deposited volume of debris is 382,000 m^3, of which approximately 44% was emplaced onto the Johnsons Landing bench, 37% in the upper channel, and 19% in the middle and lower channel, fan and lake (see section 6, Figure 18). The deposited volume is greater than the landslide source volume of 320,000m^2 due to the expansion of the landslide debris.

The landslide occurred during a dry period of sunny weather (daytime temperatures over 30° Celsius), approximately a week after an unusual rainy period of early summer. Record rainfall was recorded during the month of June in the West Kootenays (350% of normal at the Castlegar Airport and the greatest amount recorded for any month). When record rainfall was combined with a heavier than normal snowpack (June 1st snow bulletin reported the Kootenay Region at 124% of normal), the groundwater levels in early July were unusually high. Gar Creek is largely spring-fed, and responds more slowly to snowmelt and rainfall than most mountain streams. Post landslide reports by local residents indicated that creek levels were unusually high days before the landslide. Post landslide reports also noted some unusual creek activity in the form of increasingly muddy water and small debris flows in the days preceding the landslide (see section 3.6).

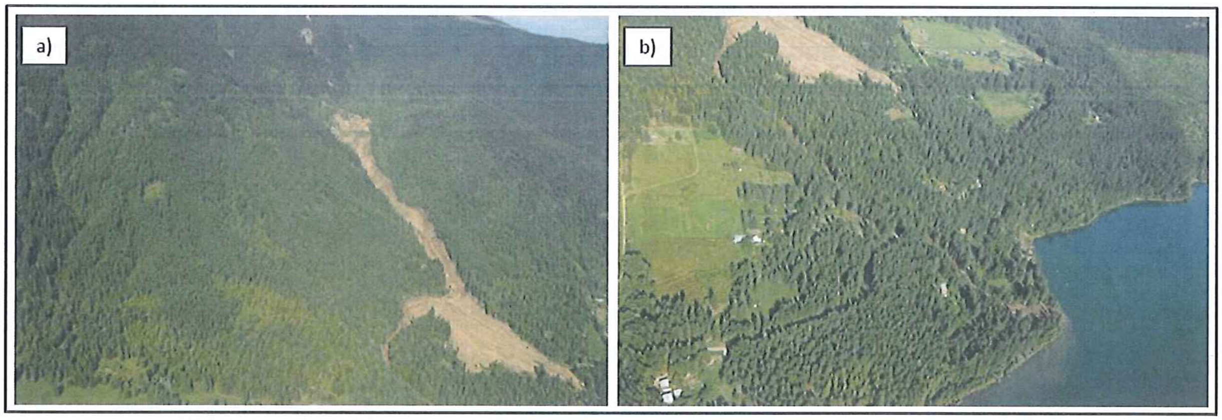

Figure 5: Photos of the landslide on the afternoon of July 12th. a) Initiation zone to Johnsons Landing bench, b) Johnsons Landing bench to Kootenay Lake.

3.2 Landslide Composition and Behaviour

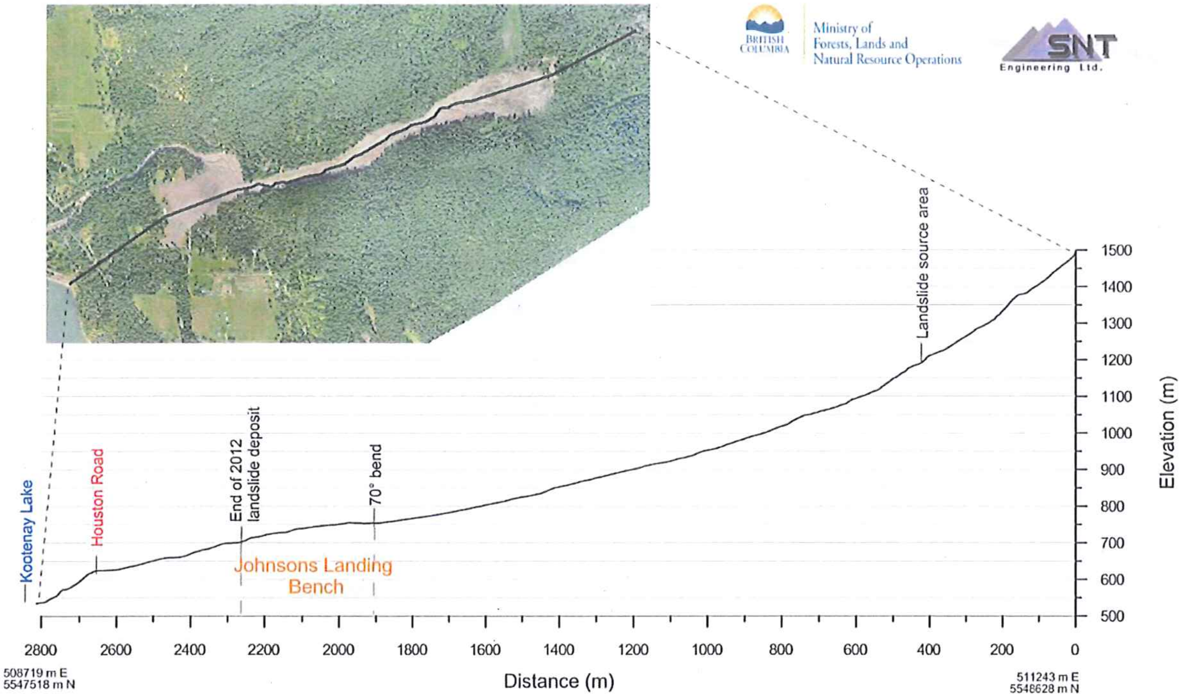

Figure 6: Longitudinal profile along the landslide path and the Johnsons Landing bench down to the lake

In the two months following the landslide, LIDAR imagery, orthophotos, and detailed topographic maps were acquired, which enabled the study team to make some interpretations of the landslide origin and behaviour before field work was undertaken in early September. During this field work, ground observations were made of the landslide deposits and source area, although observations at the scarp were somewhat limited by safety concerns, and by fallen trees and soil which obscured some features. The volume estimates given above are based on contour maps derived from the LIDAR imagery, pre-landslide air photos, and on field observations. These volume estimates are very approximate in the source area and upper channel areas (see section 6 for details), with uncertainties of about +/- 50%. Volume estimates are more precise on the bench and fan areas (about +/- 20%).

Figures 3 and 4 show the main features of the landslide, and Photos 1 to 6 (Appendix A) show aerial views of the source area and main scarp immediately after the event and during the following week. Figure 5 shows oblique photographs of the landslide source area and path while Figure 6 represents a longitudinal profile of the landslide path. The landslide consisted entirely of unconsolidated sediment (soil) of morainal, glacio-fluvial, and colluvial origin. These deep glacial deposits form an irregular, gently-sloping (20-40%) terrace between 1100 and 1300 m elevation, above the forks of the Gar Creek valley and below the steep bedrock bluffs of Kootenay Joe Ridge.

The landslide appears to have originated in the southern part of the source area (location A on Figure 4), where the main scarp is about 10 to 15 m high. The main scarp defines the upper surface remaining after the landslide occurred. The landslide gained speed rapidly, and climbed about 30 m up the opposite valley wall (location B, probably about 20 m above the average depth of flow). It then continued at high speed down the valley, climbing up the alternate valley walls three more times, with superelevations of 15 to 25 m. In the lower part of the valley, it straightened out (C), although still travelling at high speed with a depth of about 13 m.

At location D, there is a sharp right bend (about 70°) and widening in the valley, below which the creek enters a narrow canyon incised into the deep glacio-fluvial and morainal deposits of the Johnsons Landing bench. At this location, most of the landslide debris climbed onto a ridge (E), with enough speed to overtop it, and then spread out onto the bench to the southwest, where the homes were located. Debris filled the bend area to a probable thickness of 5 to 10 m. From photos taken soon after the event, and from later ground observations, a possible temporary blockage of trees formed at the head of the canyon, and this diverted most of the subsequent debris over the ridge and onto the bench. The blockage then may have broken, sending a debris flow which consisted mainly of trees down the canyon to the Gar Creek fan.

Most of the landslide volume originated from the source area. Erosion and entrainment of debris along the Gar Creek valley appears to be limited to the loose soil at the rooting depth of the forest, which is typically under 1 m. Assuming an average erosion depth of 0.5 m, about 70,000 m^3 of debris could have come from erosion along the channel. It is estimated that about 10,000 m^3 of trees were included in the landslide. Many of these trees were deposited in the lower channel and on the fan by the first debris flow, and were carried into Kootenay Lake by the second debris flow.

Although the landslide was described by eyewitnesses as a single event which lasted less than a minute, there is some evidence from the deposits that it may have been a more complex event with several surges of debris, maybe only seconds apart. Eyewitness accounts (next section) suggest that a smaller debris flow may have preceded the main landslide. In the widest part of the upper channel (F), there are deep deposits (probably 5 to 10 m thick) of debris which have a slightly different colour and surface texture, and appear to have been deposited in a drier state. This suggests that part of the landslide may have failed later (probably only seconds later), and travelled only about half as far as the main landslide. Above the main scarp, a prominent feature is a large irregularly shaped block (approximately 120 m by 60 m) of more-or-less intact glacial deposits (G) which dropped down about 20 m and then stopped. It may have been arrested by a bedrock outcrop (H) visible below the main scarp. During the search operations, there was concern that this block could fail; however, no further movement occurred. Within the source area, below the main scarp (I) a large area is covered with mostly intact trees with their root wads attached. This appears to be a result of a large block of debris which fell off the main scarp, and disintegrated on the slope below. This debris covers most of the area where the failure plane of the landslide might otherwise be observed.

Significant water was observed at the landslide scarps a week after the event; in particular, seeping from the upper scarp located above the dropped block (see Photos 24 and 25, Appendix A). Several springs were observed in the main scarp area immediately after the event (Photos 1 to 6). One large spring is located above the dropped block, and it took a day for water to find a passage through the block and form another spring below on the main scarp. The water from this new spring may have contributed to the initiation of the debris flow which occurred on July 13th (described below). An unusual mineral spring is located near the south margin of the scarp area (J). The spring emerges from glacial or colluvial deposits, which have been cemented and perhaps chemically altered by the minerals, to form zones of brightly coloured red, white, and grey soil. Several other smaller springs were observed along the Gar Creek channel, with similar altered soil material (Photo 41). Large quantities of the altered soil are found in the landslide debris on the Johnsons Landing bench.

The glacial deposits at the main scarp (Photo 37) largely consist of till and glacio-fluvial sediments of predominantly sandy loam texture, with roughly 50% gravel. This texture corresponds to silty sands (SM) and silty sandy gravels (GM) in the Unified Soil Classification System. The loose to compact deposits show some weak stratification and do not appear to be over-consolidated, and they are non-cohesive and non-plastic. One small lens of clayey silt, probably of glacio-lacustrine origin, was observed (Photo 39), and some coarse colluvial material, originating as talus or debris flows from the cliffs above, overlies the glacial deposits (Photo 38). No varved clays, compact basal till, or other layers which might have impeded groundwater flow or formed a sliding plane were observed. The sediments in the main scarp area are typical of kame deposits, which are mixed glacial till, glacio-fluvial sand and gravel, and some colluvial material, which typically form along valley sides and in tributary valleys alongside retreating glacial ice. The sandy loam texture of the glacial sediments reflects the sedimentary rocks of the area (phyllite, schist, quartzite, and limestone), and is typical of soils of glacial origin in this region. The glacial materials at this site are consistent with the terrain and soil map of the area (Kootenai Nature Investigations Ltd. 1983).

3.3 Gar Creek Fan

There was no evidence of recent (over the last 100 years) debris flow events onto the Gar Creek fan. However, from the topography and soil materials on the fan, it is evident that the fan was constructed, over the last 12,000 years, by earlier debris flow and flood events. The fan is delineated in Figure 7.

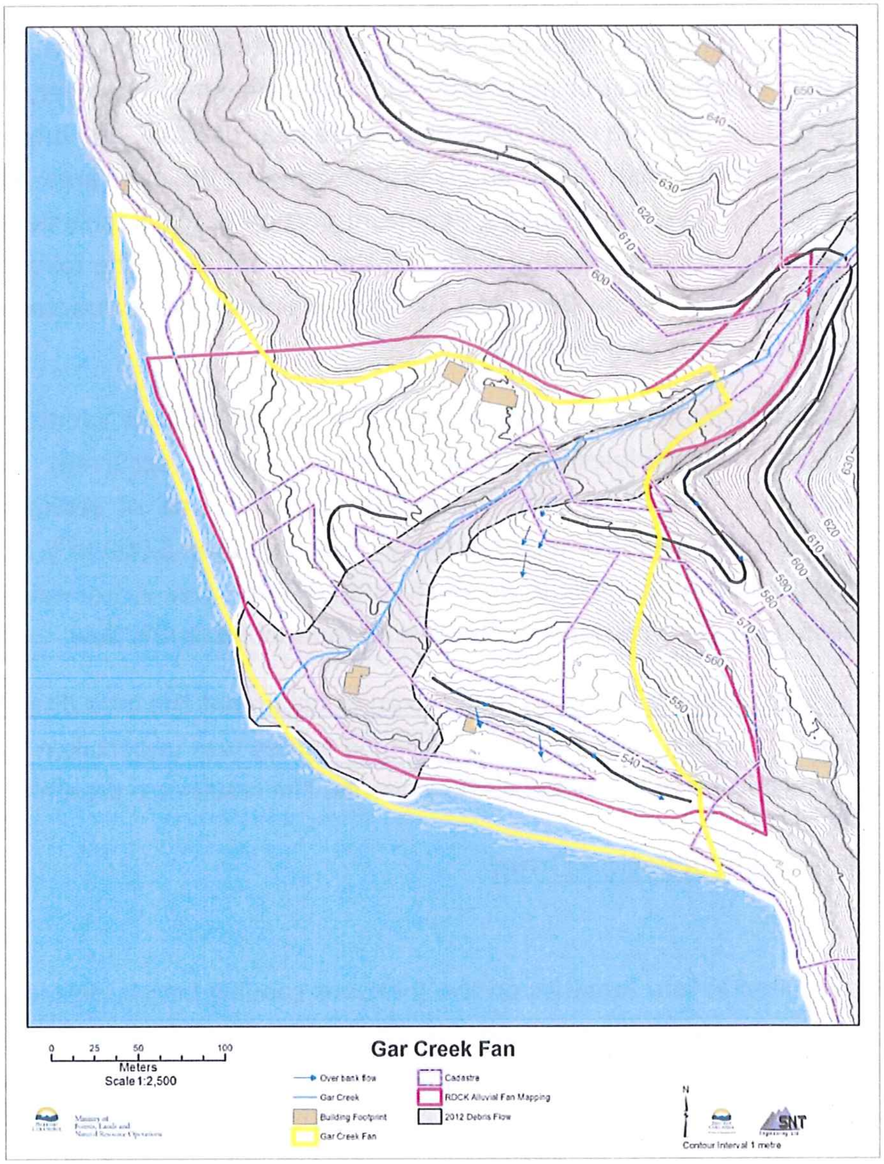

Figure 7: Gar Creek Fan. The 1 m contour map is derived from the post-landslide LIDAR imagery. The outline of the July 12th-13th debris flows is shown.

The fan has two levels. There is a more active smaller fan at the lake associated with the current lake level, which was completely inundated on July 12th/13th, 2012, and a higher larger fan (approximately 9.6 hectares) with the apex as shown on the map that is most likely associated with past debris flow events that occurred at higher lake levels. The area inundated during the July 12th/13th events is shown on Figure 7.

Several thousand cubic metres of material spilled over both banks from the apex down to the lake in the form of side channel levees. Some debris spilled over the left or south bank and flowed down the fan surface as shown on Figure 7 (and Photos 17 through 19 Appendix A). Debris did not spill over the right or north bank at or near the apex. However, there was some minor overbank spillage over the north bank downslope near the lake. The July 12th event filled much of the channel with timber debris and landslide debris at the apex area (Photos 7 and 8). The subsequent July 13th event entrained a significant portion of this freshly deposited material and transported it into the lake (Photos 9, and 17 through 19). Over the following week MoTI and Yellowhead Road and Bridge (the local highway maintenance contractor) re-established vehicle access across Gar Creek (Photos 20 to 23).

The estimated debris volume on the fan following the two debris flow events was 17,000 m^3, with average deposition thickness of 1 m (where deposition occurred) and a range of deposition thicknesses from 0 to 5 m. An undetermined volume of sediment flowed into Kootenay Lake, but this is believed to be relatively small (less than 5,000 m^3). However, a large volume of trees, possibly amounting to as much as 10,000 m^3, was entrained in the landslide, and most of these trees were carried into the lake by the second debris flow.

A field survey (using handheld GPS) was undertaken to document the area directly impacted by the July 12th and 13th debris flows. In addition a field survey was undertaken to delineate the area of the fan likely prone to future debris flow events. The results are presented in Figure 7.

3.4 Damage and Evacuation Order

The landslides resulted in four fatalities on the Johnsons Landing bench, destroyed four houses (three on the Johnsons Landing bench and one on the Gar Creek fan), severely damaged two other houses and destroyed out buildings, power poles, roads, water systems, vehicles and personal possessions. Gar Creek has been severely modified with the removal of riparian trees and vegetation, infilling of the channel along some segments, down-cutting in others, and undercutting of channel banks. Holmgren Road was entirely buried by debris while part of Houston Road was buried. The Argenta-Johnsons Landing Road was damaged at three locations where it crossed Gar Creek.

An evacuation order was immediately implemented by the RDCK. A total of 16 residents (from seven dwellings) were evacuated while six residents (from three dwellings) chose to stay. Within two weeks of the slide event four residents (of the 16) returned to their homes. As of May 2013 there are sixteen residents whose houses were either damaged beyond use, have no access to their house, or are still under evacuation order.

3.5 Early Response by the Geotechnical Community

The debris avalanche and initial debris flow occurred at 10:37 a.m. Response to the slide by the community was immediate, as emergency 911 calls were made within minutes of the event occurring. The first geotechnical personnel arrived by helicopter at 12:20 p.m. and began providing assessments of landslide hazard for the emergency search and rescue efforts. It was evident by the condition of the landslide main scarp that additional landslides were possible.

Initial and rapid geotechnical hazard site assessments are required as there are often secondary slides and flows following a first landslide event. At Johnsons Landing, a secondary debris flow occurred on the morning of July 13th. The debris flow stayed within the Gar Creek channel down to the fan area and overflowed the lower fan for a second time. Several people (responders, reporters, and local residents) were near the channel at the time, but fortunately, no one was injured.

Shortly after the landslide event a decision was made to increase the height of the left bank of Gar Creek at the 70° bend (750 m elevation). The temporary work was undertaken to reduce the likelihood of a debris flow or stream flow travelling onto the Johnsons Landing bench and threatening crews working on the landslide deposit (Photos 26 and 27 Appendix A). Channel reinforcement raised a portion of the low part of the ridge (Photo 28) separating the channel from the Johnsons Landing bench area (Photo 29).

3.6 Local Observations

3.6.1 Observation of Events leading up to the Landslide:

There were several eyewitness accounts of changes in turbidity and flows of Gar Creek leading up to the landslide event. Some of the eyewitness accounts collected after the landslide event are included in Appendix H. Of particular note:

- A week before the landslide the creek was very full – more water than ever observed in the memory of some long-time residents.

- Two 600 mm culverts at the main highway crossing were almost at capacity. Two 600 mm culverts at a lower road crossing (closer to the beach) were near capacity; however, one appeared to be partially blocked.
- The water in Gar Creek turned an unusual dark muddy colour about four or five days prior to the slide.
- The muddy water also acquired a distinct and unpleasant dank or musty "earthy" odor.
- Early afternoon on July 10th (2 days before the slide), although there were continued high flows, there was no turbidity. At 2 p.m. the creek abruptly turned to the colour of a well-brewed tea and there was a strong pine odor.
- Evening of July 10th the creek turned to a chocolate colour (see Photo 30 Appendix A). A 0.3 m deep channel had cut across the driveway (upper most crossing of Gar Creek). The creek channel upstream of the road crossing had flattened vegetation for up to 1 m above the creek elevation, suggesting a quick release of water had occurred. This surge destroyed the temporary community water intake system (established after the 2012 snow avalanche damaged the original intake system).
- July 11th at 6 a.m. a small debris flow or water release occurred resulting in a brief 0.3 to 0.6 m high surge of water and debris. A small debris flow or flood outburst at 9 a.m. deposited 1 m of debris over the upstream end of the culvert at the upper crossing. Four to six such surges occurred through the day. Two metre high log jams and debris deposits were observed. The second surge deposited about 1 m of gravel over the top of the upper road culvert resulting in the entire creek flowing down the driveway. The water was a darker colour than the night before but the same flow rate as the previous week. The surges on July 11th severed the emergency backup waterline that led from a spring to the community intake box. During mid-morning, local residents were in the creek channel re-establishing the water line.

3.6.2 Observations on the Day of the Landslide

There were several eyewitness accounts of the landslide event. Some of the eyewitness accounts are included in Appendix H. Of particular note:

- Early morning - the bank above the lowest house on the Gar Creek fan began to erode from thick slurry-like flows in the creek.
- Time from first hearing the landslide to the end of the movement on the Johnsons Landing bench estimated at 27 seconds.
- Time of debris flow from a location near (above) the Argenta-Johnsons Landing Road crossing of Gar Creek to the lake estimated at 5 to 10 seconds.

- Travel speed of the landslide in the portion that flowed onto the Johnsons Landing bench ranged from 40 km/hr to the speed of a fast car.
- Travel speed of slide in Gar Creek channel above the Johnsons Landing bench estimated at 160 km/hr.
- Height of moving landslide debris in the creek at the 800 m elevation estimated at 46 m. (This is inconsistent with the trim lines left by the landslide, and suggests that there may have been a cloud of dust, tree branches, or other fine debris above the main debris avalanche. Also, the eyewitness may have been looking at the superelevation of the landslide as it approached from upstream.)
- Height of moving landslide debris as it travelled onto the Johnsons Landing bench estimated at 30 m. (Again, this may have been a dust cloud. Or, the landslide may have become partially airborne as it rose over the ridge.)
- Debris was observed flowing down the lower portion of Gar Creek before the main slide travelled onto the Johnsons Landing bench.
- Landslide travelling down the channel sounded like a jet engine taking off and resulted in an air blast as it travelled past, bending trees nearly horizontal.

Given the above information and correcting for a delay in the time when the first sounds of the landslide could be heard (travel velocity of sound) the landslide velocity down the channel is estimated at 90 to 120km/hour or 25 to 33m/s) with a reduced speed as it flowed onto the Johnsons Landing bench. (This is reasonably consistent with superelevation in the upper channel, and run-up on the ridge approaching the Johnsons Landing bench, which indicated velocities of about 20 m/s.)

4. Physical Characteristics of the Study Area from Previous Studies

4.1 Physiography

The headwater elevations of the study area are characterized by steep-sided cirque basins separated by sharp peaks and ridges. Topography of the mid-elevation slopes is strongly controlled by bedrock structure. Slopes are steep and parallel to the predominant bedrock dip. The terrain is often strongly ridged where less resistant mica schists and phyllite have eroded adjacent to more resistant quartzites and marble. These slopes are dissected by deeply incised steep gradient stream channels. Topography of lower elevations in the study area is generally characterized by terraced valley deposits, late Pleistocene kame terraces, rock bluffs adjacent to Kootenay Lake, and small alluvial fans at stream mouths (EBA, 2003).

The biogeoclimatic zone below approximately 1000 m is classified as part of the Interior Cedar-Hemlock dry warm zone, and above 1000 m (encompassing the landslide source area) Interior Cedar-Hemlock moist warm zone.

4.2 Surficial Geology

Surficial materials and topography reflect the last major Pleistocene glaciation, during which coalescing ice sheets flowed south through the Kootenay Lake valley (Kutenai Nature Investigations Ltd., 1983). Upland areas became ice-free and deglaciation proceeded by down wasting and retreat of, first, local tributary and cirque glaciers, and finally the large valley glacier in the Kootenay Lake valley. Glacio-fluvial and glacio-lacustrine deposits on the lower slopes and benches of the study area were deposited and dissected during deglaciation. Colluvial and localized fluvial materials have been deposited since deglaciation (Kutenai Nature Investigations Ltd., 1983).

4.3 Bedrock Geology

The geology of the Argenta-Johnsons Landing area is complex. The bedrock is dominated by complex folded and faulted, low to medium grade, metasedimentary rocks of upper Proterozoic to lower Paleozoic age, that are steeply dipping, strike in a NNW-SSE trend and generally dip to the NNW. Bedrock is comprised of mica schists, quartzites, marble (metamorphosed limestone) and dolostone of the Hamill Group, Badshot-Mohican Formations, and the Lardeau group. These metasedimentary rock formations belong to the Kootenay Arc regional structural belt. The area south of Kootenay Joe Creek is underlain by the Fry Creek Batholith, which was intruded during the Cretaceous (Fyles 1964; Reesor 1973; Kutenai Nature Investigations Ltd., 1983). Formations are commonly repeated several times by folds and faults.

The Hamill group is overlain by massive grey to white marble of the Badshot formation which is in the order of 100 m thick, and is associated with quartz-mica schist of the Mohican formation The Badshot-Mohican formation is succeeded by the Index formation, the oldest of the Lardeau Group, characterised by a thick sequence of phyllites containing a few beds of limestone (Fyles and Eastwood 1962).

Figure 8 and Figure 9 illustrate the bedrock geology and representative cross section through the Gar Creek drainage. The location of known karst features are shown on Figure 8 and are discussed in Section 5.

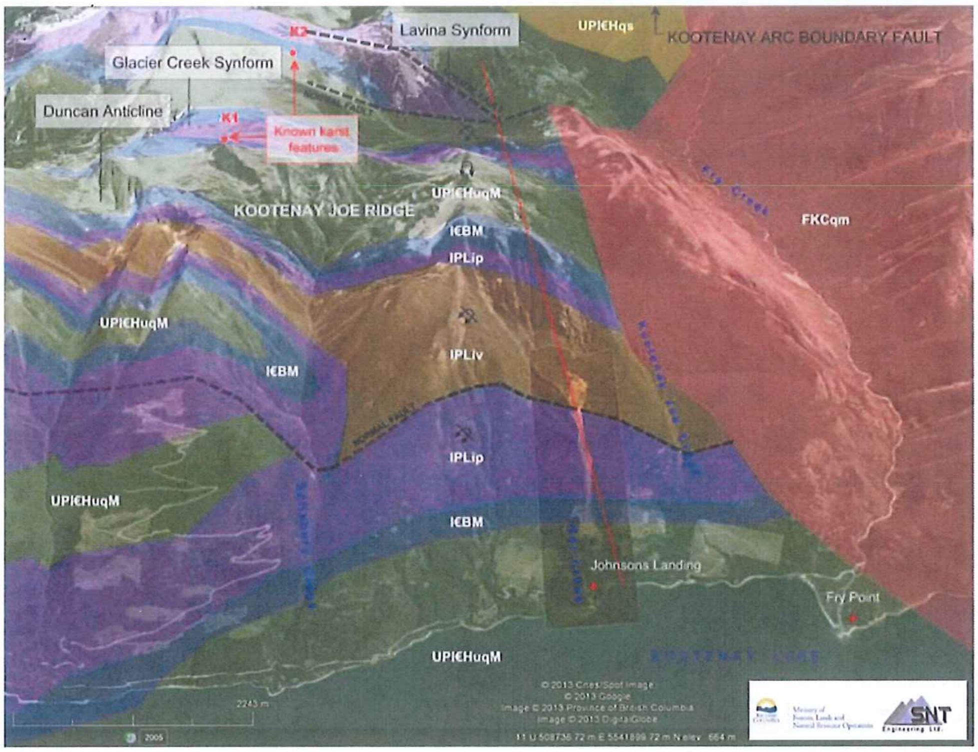

Figure 8: Bedrock geology overlay and known karst features (same legend as next Figure)

IPLiv – Lower Cambrian Lardeau Group, INDEX FORMATION Green phyllite: limy green phyllite, clorite-actinolite schist, garnet mica schist, greenstone

IPLip – Lower Cambrian Lardeau Group, INDEX FORMATION Grey schist: fine grained grey-mica schist and garnet mica schist

I€BM – Lower Cambrian BADSHOT-MOHICAN FORMATION: marble, phyllite, muscovite-quartz schist

UPI€Huq –Upper Neoproterozoic to Lower Cambrian, HAMILL GROUP Upper quartzite: Thin to medium bedded and cross-bedded white quartzite; minor dark quartzite and pelite (lower part); interbedded pink and green quartzite and dark pelite (upper part).

UPI€Hqs – Late Neoproterozoic to Lower Cambrian, HAMILL GROUP lower clastic volcanic unit: Dark gray and white quartzite, dark grey schist, feldspatic grit, and minor pebble conglomerate.

KFCqm – Cretaceous FRY CREEK BATHOLITH: Quartz, monzonite, granodiorite, biotite

⫽ Normal fault

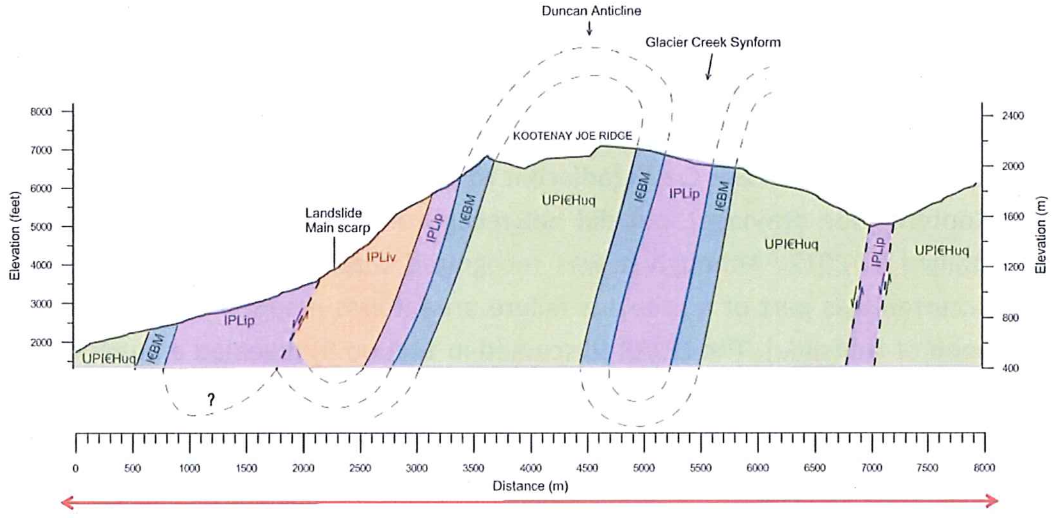

Figure 9: Compiled geological cross section through the Gar Creek drainage

4.4 Previous Terrain Stability Mapping and Assessments

4.4.1 Kutenai Nature Investigations Ltd.

The Resource Inventory of Argenta and Johnsons Landing Watersheds (Kutenai Nature Investigations Ltd. 1983; conducted by Greg Utzig, P.Ag. and Bill Wells P.Ag.) prepared for the Ministry of Forests includes mapping (1:15,840 scale) and descriptions of terrain, soil, and vegetation resources in the study area. Data maps include: bedrock geology, biogeoclimatic subzones, terrain, and soils and vegetation. Interpretive maps include: interpretations for predicting hydrological impacts, engineering features, and forest capability.

The terrain of the study area was classified and mapped using the Terrain Classification System developed in the 1970s by the B.C. Ministry of Environment (the current version of which is Howes and Kenk, 1997). Terrain mapping was based on interpretation of air photos (taken in 1968 at a nominal scale of 1:15,840). The information was then plotted on base maps provided by the Ministry of Forests and Kootenay Forest Products Ltd. A more recent revised version of the terrain mapping is shown in Figure 10.

Terrain interpretations for mass wasting, surface erosion, and sediment delivery used a Low-Moderate-High classification system, as the class I to V system for terrain stability was not yet in use in the BC Interior. In 1998, Kutenai Nature Investigations Ltd. re-interpreted the mapping to conform to the classification in the Forest Practices Code "Mapping and Interpreting Terrain Stability" guidebook (BC Ministry of Forests, 1999). Class III, IV, and V terrain is typically defined as having a low, moderate, and high likelihood of post harvesting landslide initiation. As noted in Figure 10 the landslide source area was almost entirely within a polygon mapped as Class III or low likelihood of landslide.

As part of the study several field checks were located in the immediate vicinity of the area that failed in the 2012 landslide. The mapping noted the presence of a previous large bedrock failure in the southeast tributary of Gar Creek (adjacent to the ridge separating the Gar Creek drainage from the Kootenay Joe drainage), but did not recognize its full extent as identified by LIDAR images obtained in 2012. Although it was recognized that the polygon in which the 2012 landslide occurred was part of a previous failure area it was mapped as inactive and Class III (low likelihood of landslide). The LIDAR (discussed in Section 9) revealed a much larger area of previously failed bedrock and surficial features.

Unfortunately the original 1983 maps, typed air photos, and field notes filed with the Ministry of Forests cannot be located.

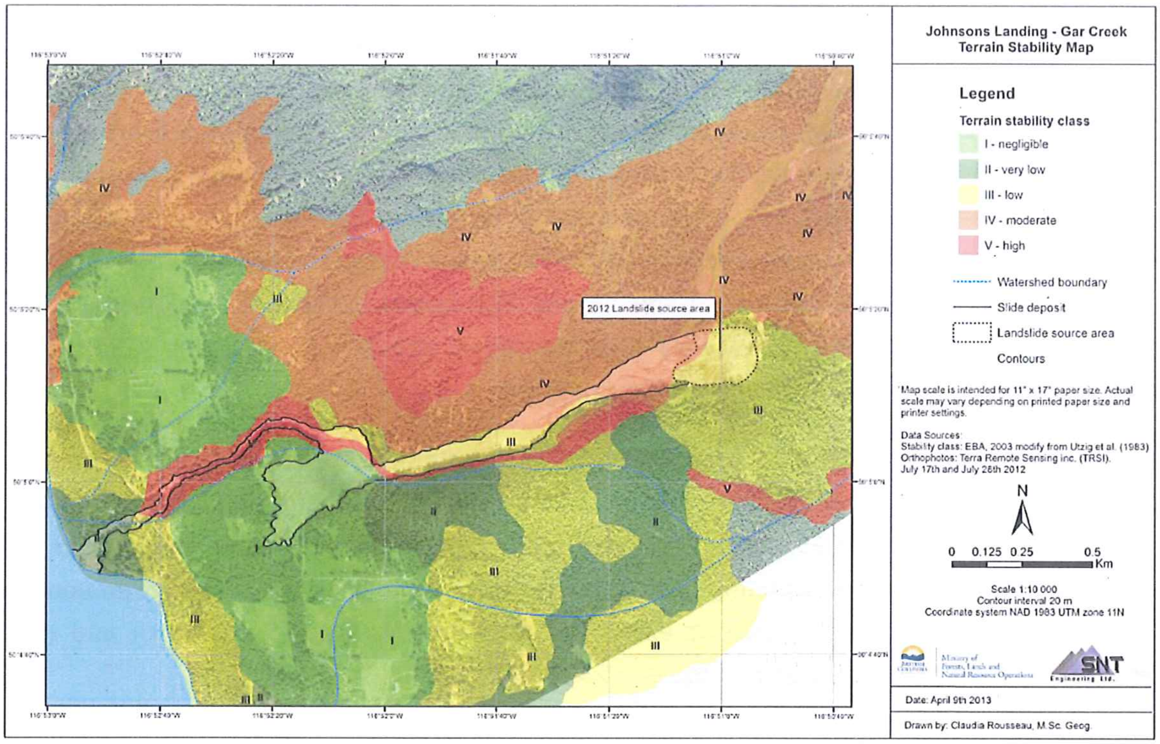

Figure 10: Landslide location relative to terrain stability polygons (polygons from Nature Investigations Ltd. 1983) digitalize by EBA (2003)

4.4.2 Jordan 1994 and 2001

In 1994-95 P. Jordan, P.Geo. (Ministry of Forest, Nelson) conducted a form of reconnaissance landslide hazard and risk mapping (commonly known as "corridor hazard mapping") for the Nelson Forest Region. The area mapped included all forest land in and above corridors, which included populated areas and highways. The mapping used an L-M-H-VH classification scheme, corresponding roughly to terrain stability Classes 1/2, 3, 4, and 5 respectively and also included a simple consequence rating and identification of upland areas draining into hazard polygons. The mapping was quite generalized compared with detailed terrain stability mapping, and corresponded to a Terrain Survey Intensity Level (TSIL) of D (the least detailed level of mapping done for forestry purposes in BC). A portion of the map including Johnsons Landing is shown in Appendix B Map 9 and 10. The mapping in this area included field checks on the Kootenay Joe road above Johnsons Landing.

The debris flow potential of Gar Creek, and the most prominent of the inactive bedrock failures in the Gar Creek watershed, was identified on this mapping. It is less detailed than the terrain/soil mapping which was done 12 years earlier; however, it is noted that the hazard ratings of the two sets of mapping are quite different. For example Polygon 491 was mapped as Class III (Kutenai Nature Investigations Ltd. 1983), while on the Jordan map this includes a polygon mapped as High due to a large bedrock slump feature. This polygon is the area shown on Figure 21 at, and to the south of, the 2012 landslide source area. These differences are mainly due to differing definitions and assumptions underlying the maps. The Kutenai Nature Investigations Ltd. map, like most mapping for forestry purposes done in the Interior in the early 1980's, mapped "mass wasting hazard" and other hazards related to soil degradation from ground skidding, which was the usual harvesting system at the time. Mass wasting hazard includes localized shallow processes such as dry ravel, soil creep, and retrogression of skid trail cuts, which do not constitute a landslide hazard. The Jordan 1994 landslide hazard mapping concentrated on the hazard of relatively large landslides, including deep-seated slump features, which were given less attention in the older mapping.

In June 2001 Jordan performed a field review for the Kootenay Lake Forest District. The purpose of the field review was to investigate terrain stability and erosion issues involved in the possible use of the Kootenay Joe FSR, and proposed helicopter logging of small patches for beetle control purposes (the small openings visible on the orthophotos). The feature noted above was recognized as part of an inactive or extremely slow-moving slump in bedrock and till. The location of the interpreted slump is shown in Appendix B Map 3 and 4.

4.4.3 EBA 2003

In 2003, EBA Engineering Ltd. completed an evaluation for BC Timber Sales (BCTS) of watershed impacts in terms of peak flow hazard, landslide hazard, and water quality impact hazard in the Argenta-Johnsons Landing area. The background information used soil surface erosion potential (high and extreme), sediment delivery hazard, and terrain stability class (Class IV and V) obtained from the digitized Resource Inventory mapping (Kutenai Nature Investigations Ltd. 1983).

Gar Creek was sub-divided into Reaches 1 to 4. Reaches were distinguished by changes in gradient, channel morphology, stream discharge, confinement, and riparian structure. Reach break analysis was based on a review of air photographs, topographic maps, and field verification.

The purpose of the stream channel mapping was to assess the sensitivity of the channel to impacts from proposed forest development, with respect to water quality and aquatic habitat, and not to assess the likelihood of debris flows or other natural hazards originating upstream.

4.5 Previous and Adjacent Landslide Activity

4.5.1 Comparable Landslides

The Johnsons Landing landslide was unprecedented in recent history in this region with respect to its large size. However, there are several other landslides that have occurred in British Columbia, which are comparable in some ways, and can provide some insight into the causes of the Johnsons Landing landslide.

At an unnamed creek west of Legate Creek near Terrace, BC, a large landslide occurred on May 27th, 2007 that caused two fatalities on Highway 16 and closed the highway for several days. An investigation and risk analysis was commissioned by the Ministry of Transportation (BGC Engineering Ltd., 2008), which included run-out modeling using the DAN-3D model. This event has a lot in common with the Johnsons Landing landslide. It was described as a debris avalanche – debris flow or a flow slide – debris flow, with a total volume of about 225,000 m^3. It originated in colluvium (talus) overlying glacial till, and consisted of cohesionless material. It was preceded by exceptionally high rainfall and high snow water equivalent that spring, which resulted in high groundwater levels. Unlike Johnsons Landing, the Legate Creek slide occurred in a watershed which had frequent (15-20 year return period) debris flows which reached the highway in the past, although the large 2007 event is estimated to have a return period of several thousand years.

Camp Creek near Three Valley Gap (west of Revelstoke) experienced a debris flow in 1968 which originated in a large first-time debris slide in deep glacial soil deposits. The resulting debris flow is reported to have killed five people on the Trans-Canada Highway (VanDine, 1985). From its appearance on air photos, the original slide had a probable volume in the order of 10,000 to 50,000 m^3, although the total debris flow volume including downstream entrainment would have been larger.

A very similar, although smaller, debris flow occurred in 1987 in the Barrett Creek watershed 15 km south of Nelson as it originated as a debris slide in deep glacial till. Recent air photos indicate the presence of tension cracks or scarps and continued movement. This event has some similarity to the Johnsons Landing landslide in that it was a first-time event in deep glacial till, and appears to have a retrogressively failing area upslope.

A large debris slide (order of 20,000 to 100,000 m^3) in deep glacial till occurred in 1996 in the Valhalla Provincial Park above Slocan Lake. It resembles the Johnsons Landing landslide in that it originated immediately below a zone of displaced bedrock which may be slowly moving, possibly loading or deforming the glacial deposits below. It occurred on a relatively gentle slope (15-30°) and did not progress very far down the mountainside.

4.5.2 Other Landslides in the Region

A number of other large landslides in glacial deposits have occurred in British Columbia in recent history, but none of them have very much in common with the Johnsons Landing landslide. Most of them are in deep, stratified, glacio-fluvial or glacio-lacustrine deposits, usually at the outside of river bends, or involve undercutting by a road or some other development, or are slow-moving slump-earthflows in cohesive (clay-rich) sediments. Some local examples follow.

In the spring of 2006, a debris slide with an estimated volume of 100,000 m^3 occurred in deep, stratified, glacio-fluvial deposits adjacent to a tributary of Dog Creek, 38 km west of Castlegar, in an area where large landslides are rare. It generated a debris flow and debris flood which travelled 15 km to Lower Arrow Lake. The slide occurred in a valley-edge escarpment which had experienced past landslides, probably in early post-glacial time, and clay beds were present in the glacial deposits. It occurred during the spring following logging of much of the contributing drainage area.

In April 2000, a 75,000 m^3, rapid debris slide-flow at Passmore in the Slocan Valley blocked Highway 6 and partially blocked the Slocan River. This landslide occurred in deep, stratified, glacio-fluvial deposits with varved clay or silt beds. It was located at the outside of a river bed, where there had probably been past failures, and undercutting by the highway may also have been a factor. There have been a number of other large slump-type landslides in clay-bearing glacial deposits along the Slocan and Little Slocan Rivers, most of them slow-moving, chronic failures. Such failures are common in similar river valleys throughout British Columbia and elsewhere in glaciated parts of the world.

In the north Kootenay Lake area, landslides in glacial deposits are fairly common. Most of them are chronic, slow-moving failures, and most are much smaller than the Johnsons landing landslide. Examples are found in the Glacier Creek, Howser Creek, Healy Creek, La France Creek, and Gray Creek valleys, and along Duncan Lake. Other such features nearer populated areas are found at Destiny Bay on the south arm of Kootenay Lake, the Whitewater Mine at Retallack and (outside this area) the Rialto Forest Service Road near Robson. An unusual, rapidly moving landslide in deep glacial deposits occurred in the spring of 2012 at Shutty Bench. It had glacio-lacustrine clay beds in its failure plane, and drainage diversions caused by upslope development may have been a contributing factor.

Many large, ancient, bedrock landslides are found in the north Kootenay Lake area, mostly associated with weak metasedimentary rocks such as the Lardeau Group. These are shown in Appendix J. The most notable example is the Lost Ledge landslide across the lake from Johnsons Landing, which probably failed rapidly in late glacial time, possibly onto glacial ice. Most other bedrock landslides are very slow-moving features, which have moved little or not at all since early postglacial time. Several of these landslides, however, show signs of slow continued movement, including the indistinct zone of creeping bedrock above the Johnsons Landing landslide main scarp.

Debris flows are the most common type of landslide in the region. Most of them are relatively small (less than 10,000 m^3), and they occur frequently in steep gullies or creek channels which are continually supplied with debris by rockfall, small debris slides, or snow avalanches. Many such channels have repeated debris flows with return periods of a few years to a few decades, which add to the accumulated volume of their alluvial fans. In a few especially unstable areas, there are very large debris flows which repeat annually, for example in the Lake Creek valley. It is not uncommon for debris flows (and rarely, other types of landslides) to impact houses and infrastructure in the Kootenays. A table has been included in Appendix J listing fifty three landslides that have impacted houses and properties in the Kootenays since 1979.

4.6 Magnitude-Frequency Relations and Estimated Likelihood of a Large Landslide

An inventory of landslides in the Kootenay Lake and Arrow Forest Districts was prepared by the B.C. Forest Service in 1997-2002. It provides a basis for estimating the annual probability of landslides of various size categories in similar terrain, assuming the distribution of landslides over the area is random. The assumption of a random distribution is reasonable, since the terrain at Johnsons Landing is typical of the region. Since the inventory did not contain any landslide occurrences larger than 100,000 m^3, an extrapolation procedure was used to estimate the likely frequency of large landslides. Details of this analysis are given in Appendix J.

The landslide data have a magnitude-frequency relation which shows that the return period increases (or the probability decreases) greatly with increasing landslide size – that is, small landslides are common while large landslides are rare. Similar relations have been found in landslide inventories elsewhere, including several in British Columbia. A rapid landslide of similar type and size to the Johnsons Landing landslide has not been recorded in the North Kootenay Lake area in historic time. The extrapolation of the inventory data indicates that the approximate estimated probability of occurrence of a landslide of 100,000 m^3 or larger is about

2×10^{-5} (1:50,000) per year in the entire area (about 1500 km^2 of mountainous terrain), or about 1.3×10^{-8} (1:75 million) per year per km^2.

Another approach is to look at the history of large landslides in a much larger area. In the southern interior of British Columbia in historic time, there have been three known landslides of similar order of magnitude to the Johnsons Landing landslide – the Dog Creek landslide mentioned above, a rock avalanche near Lumby in 2002, and a rock avalanche in Eagle Pass near Revelstoke in 1999. (Another landslide which blocked the Chilcotin River in 2004 is not included, for reasons discussed above – it was a river bend slump). The total area of the southern interior is about 200,000 km^2. It is assumed that half this area is potentially subject to landslides, and the historic period for which we have a reliable record is about 50 years. Therefore, the estimated frequency of a large landslide in the southern interior is about 3/50/100,000 or 0.6×10^{-6} (1:1.7 million) per year per km^2, about 50 times the frequency estimated above from the local landslide inventory. Of note is that all the known historic large ($>10^5$ m^3) landslides in the southern interior region have occurred since 1999. In comparison, very large rock avalanches, comparable to the 1903 Frank Slide in Crowsnest Pass, have a mean frequency of one or two orders of magnitude less (2×10^{-7} to 2×10^{-8} (1:5 million to 1:50 million) per year per km^2, Hungr et al 1999).

Thus, two different methods, using very different data sets produce estimates of the frequency of landslides larger than 100,000 m^3 in the order of 10^{-8} to 10^{-6} (1:100 million to 1:1 million) per year, per square km of mountainous terrain. Since the area above Johnsons Landing is about 10 km^2, it is estimated that the *a priori* probability of occurrence of a landslide similar to the 2012 event in this vicinity was approximately 10^{-5} to 10^{-7} (1:100,000 to 1:10 million) per year. Considering that previous field reviews by experienced professionals did not identify large scale active landslide features in the area, and given the low frequency of large magnitude landslides in the region, it is concluded that the hazard of a large rapid landslide at Johnsons Landing could not reasonably be determined.

5. Climatology, Stream Flow and Watershed Characteristics

5.1 Regional Climate

Johnsons Landing and surrounding area are located in the southern portion of the "interior wet belt". The climate is influenced by the physiographic region and travel pattern of pacific coastal systems. Air masses travelling from the coast release moisture as they ascend successive mountain ranges including the Columbia and Rocky Mountains (Moore et al 2010). Easterly moving air masses can lose a major portion of their moisture prior to crossing the Purcell

Mountains. During the winter, the mountains restrict the westward flow of cold, continental arctic air masses from east of the Rocky Mountains thus moderating the winter climate (Moore et al 2010). During the summer, hot dry air occasionally moves into the area from the Columbia plateau in the United States. The general patterns of temperature and precipitation are typical for mountainous terrain, with increases in mean annual precipitation and decreases in mean annual temperature coincident with increasing elevation (Kutenai Nature Investigations Ltd., 1983).

Precipitation patterns reflect the physiographic region and travel pattern of pacific coastal systems and summer convective cells. Annual precipitation is generally the highest in May, June, October, and November (Duncan Lake weather station) and the lowest in December through February. The combination of wet spring months with continued freezing temperatures at higher elevations results in the snowpack at high elevation generally peaking in the month of May.

The local climate is also influenced by atmosphere-ocean variability including El Nino/La Nina Southern Oscillation, Pacific Decadal Oscillation, Pacific North American Pattern, and the Arctic Oscillation (Moore et al 2010). These oscillations can have effects on local weather patterns over periods ranging from years to decades. In 2012 a lingering La Nina had the effect of cooler spring temperatures resulting in a lagging snowmelt.

5.2 2012 Weather

5.2.1 2012 Precipitation and Temperature

The June 2012 rainfall set many records in the West Kootenays. It set not only a new record for the month of June, but a new record for precipitation for any month for four of the five local weather stations. The exception was at the Duncan Lake Dam weather station which recorded 180 mm in June 2012 versus 186 mm in November 1990. Figure 11 illustrates regional monthly rainfall data since 1904 showing the June 2012 precipitation surpassing the previous maximum of October 1950.

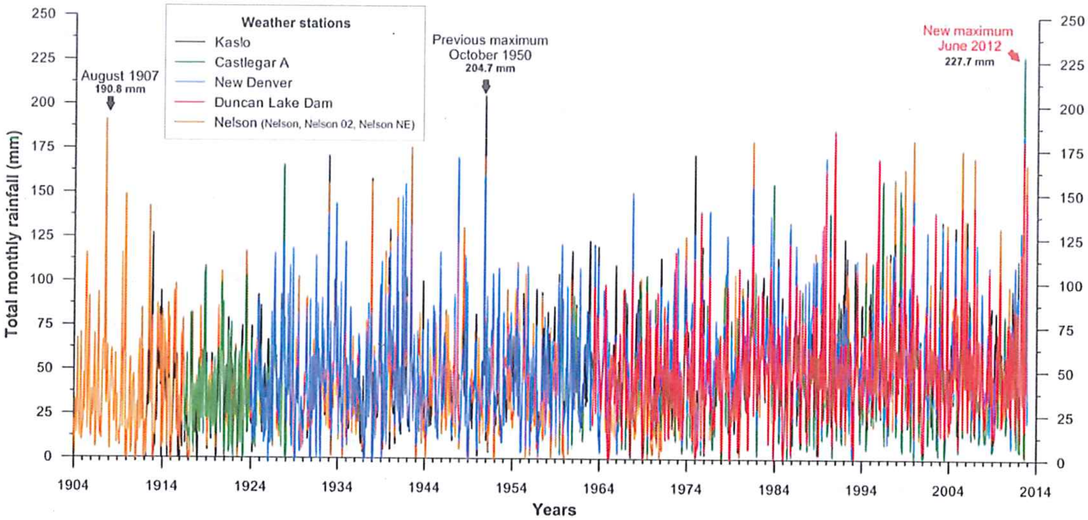

Figure 11: Total monthly rainfall recorded at weather stations near Johnsons Landing

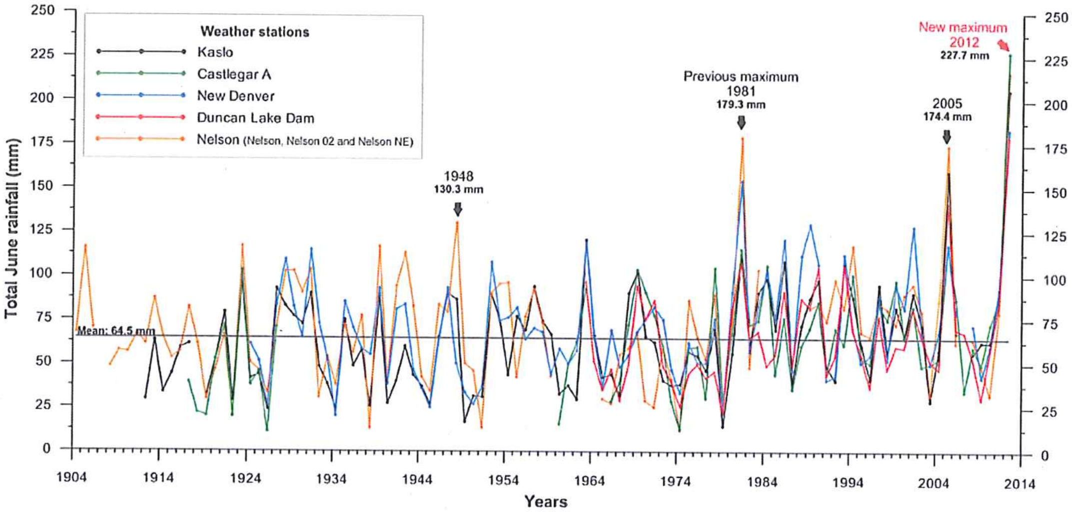

Figure 12: Total June rainfall recorded at weather stations near Johnsons Landing

Figure 12 shows the local rainfall during June 2012 compared with historical June rainfall data. Recorded 2012 June rainfall was 3.5 times the average (average of Castlegar, Kaslo, Nelson, New Denver and Duncan Lake stations). All five local stations recorded June rainfall over 180 mm with Castlegar at 227 mm (Environment Canada Climate Data).

The Duncan Lake Dam site 2012 cumulative yearly rainfall to the end of June was 435 mm compared with the average of 264 mm (an increase of 64% over the average). See data in Appendix C.

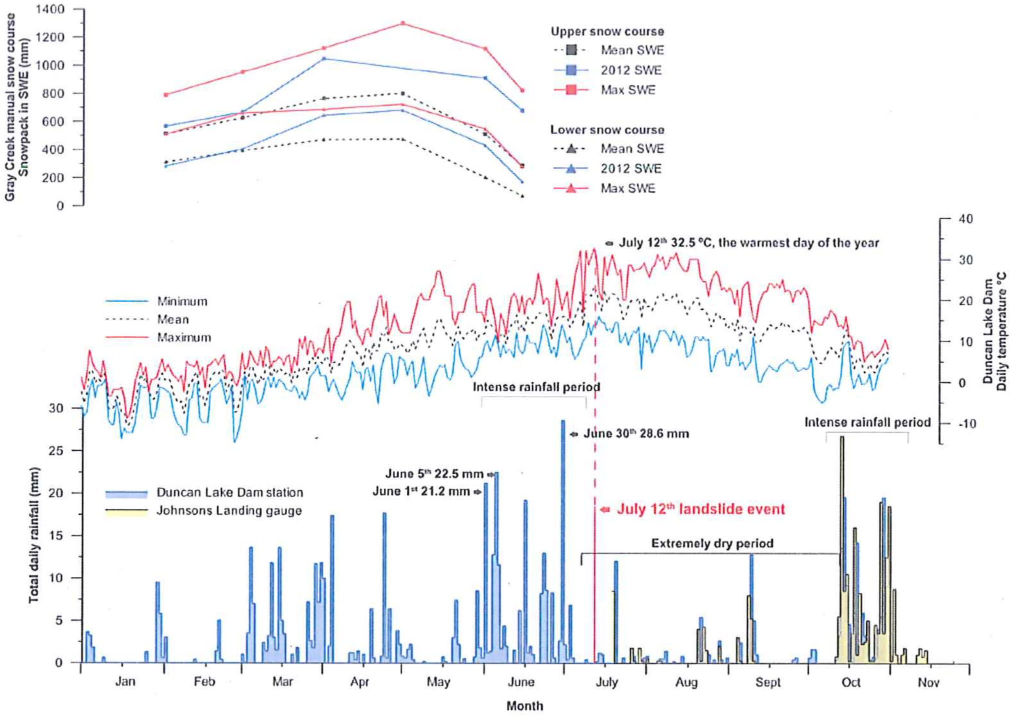

Figure 13: Summary of 2012 daily rainfall and temperatures from Duncan Lake Dam weather station and monthly snow pillow in snow water equivalent (SWE) from Gray Creek manual snow courses (Lower and Upper)

An early summer intense rainfall period occurred between May 28th and July 3rd. Four days in June (June 1st, 5th, 16th and 30th) recorded rainfall between 19 mm to 29 mm (Figure 13). This unusual wet period was followed by an extremely warm and dry period during which the landslide occurred. The nine days preceding the landslide event were dry with cumulative rainfall of only 1 mm. Moreover, according to the temperature records from Duncan Lake Dam weather station (20 km north of Johnsons Landing), the three days preceding and including July 12th were the warmest days of the year with a maximum of 32.5°C on the day of the landslide (see Figure 13).

A review was conducted by Environment Canada (Philip Jarrett, Engineering Climate Services Unit) of the estimated return period for the 30 day rain event. The review included a rainfall intensity-duration-frequency (IDF) analysis for 1-day to 30-day rainfall at Kaslo. This analysis includes 94 years of record dating back to 1894. The analysis indicated that the 100 year return period for a 30 day event is 228 mm. However, this data set includes a number of events in winter, suggesting that it might include some snowfall or mixed rain-and-snow events. An analysis filtered to include only April-October events suggests a 100 year return period 30-day rainfall is 200 mm which is similar to the 2012 30 day recorded rainfall of 214 mm at Kaslo. The review (details in Appendix C) indicates the 30 day rainfall (that occurred in June and early July) was approximately equivalent to the 100 year return period rainfall.

Rainfall records from a gauge installed at Johnsons Landing a few days after the landslide are illustrated on Appendix C. Daily rainfall on October 13th shows some of the variability between recorded rainfall at Johnsons Landing compared with the Duncan Lake station (26.75 mm versus 13.6 mm respectively).

5.2.2 2011/2012 Snowpack

There are no snow accumulation or snowmelt measurements for the immediate area of the Gar Creek drainage or Johnsons Landing area; however, a few nearby stations provide useful information. The Gray Creek manual snow courses (55 km south of Johnsons Landing) are located at 1558 m (lower Gray creek) and 1926 m (upper Gray Creek) elevation. Figure 13 (top left graph) provides plots of snow water equivalent (SWE) for both stations for the 2011-2012 season. The SWE for spring 2012 was not at record levels but was well above normal. The April 2012 SWE reached a maximum of 1048 mm (record of 1143 mm) for the upper snow course and 645 mm (record of 668 mm) for the lower snow course. On June 15th, approximately one month before Johnsons Landing landslide event, the SWE was 237% of the average at the lower Gray Creek snow course.

The late snowmelt and June rainfall caused landslides elsewhere in the Kootenays. The authors are aware of several landslides and slumps that occurred during the 2012 freshet many of which impacted houses, property and roads. Appendix J provides a summary of 16 landslides that MFLNRO staff responded to during the 2012 freshet for the provincial emergency management system.

The nearest automated snow pillow stations from Johnsons Landing are Redfish Creek located 47 km south-west of Johnsons Landing at 2086 m elevation and East Creek located 60 km north at the 2004 m elevation. The Redfish June 1st 2012 SWE combined with the June rainfall (recorded at Nelson) was 2021 mm (152% of the average). At East Creek the June 1st SWE combined with the June rainfall was 132% of normal. There have been higher rainfall/SWE combinations for nine of the last thirty years.

Given the 30 day rainfall was a record but the rainfall snowmelt combination was relatively common suggests the peak flows in Gar Creek may be more sensitive to rainfall than to snowmelt conditions. The combination of snow water equivalent (SWE) of the Upper Gray Creek station on May 1st plus the May and June rainfall in Kaslo was also not a record (however it was the maximum since 1972 – see Appendix C).

Some studies refer to the H_{60} elevation (elevation above which is 60% of the drainage area) as an influential snowmelt area affecting peak stream flows. Smith et al (2008) suggest a more influential indicator may be the H_{38} elevation. The Gar Creek drainage H_{60} and H_{38} are 1235 m and 1559 m respectively. For snowmelt comparisons the lower Gray Creek snow course (1550 m) had 176 mm of SWE on June 15th (the last reading date of the year) and the upper Gray Creek snow course (1910 m) had 682 mm. On July 12th the Gray Creek drainage was essentially snow free below the 2000 m elevation indicating that the area between 1500 m and 2000 m (essentially the H_{38} of the Gar Creek drainage) lost on average approximately 425 mm of SWE in less than 27 days corresponding to snow melt rate of greater than 16 mm/day. Typical warm weather snow melt rates can range from 20 mm to 50 mm/day of SWE. The Redfish Creek snow pillow, located at an elevation of 2086 m, lost 680 mm of SWE in the first 12 days of July while the East Creek (north facing station) snow pillow located at an elevation of 2004 metres lost about 200 mm of SWE over the same period. This compares with the rainfall rate of 206 mm (at Kaslo) in 30 days or 7 mm per day. The last remnants of the Gar Creek snow pack likely added to stream flow after the rain had stopped on July 3rd. There was little snow left in the Gar Creek drainage on July 12th.

5.2.3 2012 and Historical Stream Flow

Kaslo River discharge (below Kemp Creek – Water Survey of Canada Station ID 08NH005, drainage area 442 km^2) for 2012 (Figure 14) was later than average due to cool spring temperatures (lingering La Nina ocean-atmosphere weather patterns) and subsequently late snow pack melt. The 2012 discharge peaked above 140 m^3/sec twice (June 24th and July 1st) and was the second highest discharge recorded (highest occurring in 1916 at 160 m^3/sec).

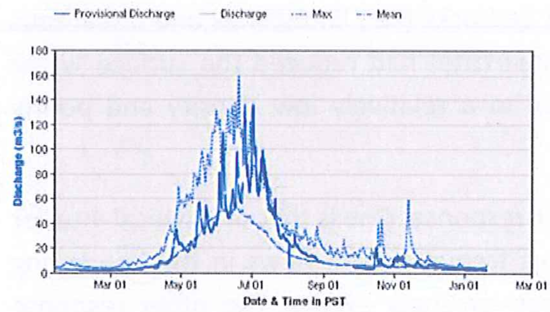

Figure 14: Kaslo River daily discharge for 2012

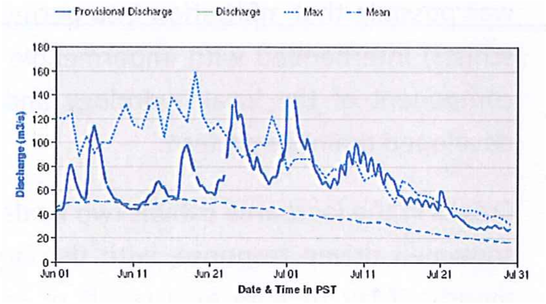

Figure 15: Kaslo River daily discharge from June 1st to July 31st 2012

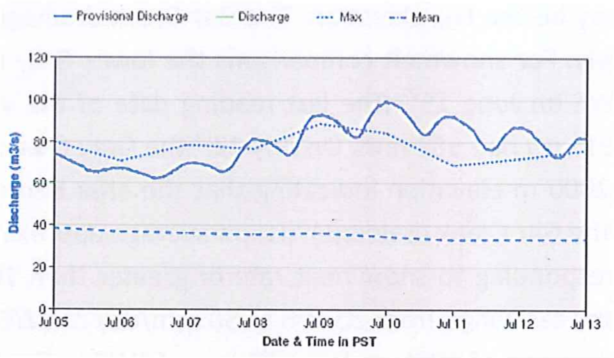

Figure 16: Kaslo River discharge from July 5th to July 13th 2012

The Kaslo River discharge shows a series of peaks during the month of June (Figure 15 and Figure 16), three of which are over 100 m^3/sec that correspond to rainfall events. Peaks on June 24th and July 2nd formed new discharge records for flows after June 20th. A fourth more gradual ascending peak occurred on July 10th as a result of warming temperatures and snow melt. The diurnal pattern of daytime heating and snowmelt is evident between July 8th and July 12th. The snowmelt related peaks produced record river discharges for the days of July 8th to July 13th.

5.3 Local Hydrology and Water Chemistry

5.3.1 Argenta-Johnsons Landing slope

The local hydrology is comprised of a complex system of surface water (including streams, lakes, and perennial snow), subsurface aquifers and springs, resulting from the combination of a dissected ridged mountain slope and bedrock aquifers. It was noted by Salway in 1983 that it was possible that infiltration into permeable soluble bedrocks (i.e., limestones and calcareous schists) interbedded with impermeable types (i.e., quartzite) had reduced the surface water component of the local hydrology and had resulted in a relatively low density and poorly developed drainage pattern.

Creeks in the local area exhibit two kinds of hydrologic response. One is that of a typical interior snowmelt driven response, with the largest and most frequent peak flows in the late spring months (May to July) as a result of snowmelt or rain-on-snow events. The other response exhibited by several creeks in the area is that of a dampened hydrologic response to precipitation and snowmelt attributed to the influence of groundwater recharge (Salway, 1983; EBA, 2003).

5.3.2 Gar Creek

The stream flow of Gar Creek was measured between May 19th and October 1st, 1981. A total of 28 flow measurements of Gar Creek were taken in 1981 (five measurements were taken in May, four were taken in June, seven in July, six in August, five in September, and one in October). Of note is the fact that 1981 was a year of high June rainfall (previous June record for many stations before 2012) and so it is unclear how the stream flow monitoring compares with "average years". The East Creek snow pillow peaked at a SWE of 959 mm on May 11th, 1981. By June 1st it was 725 mm and by June 30th it was 270 mm. Although the peak SWE for East Creek in 1981 was near normal there was a rapid melt between the middle of May and the end of June. According to the 1981 data, Gar Creek exhibits a smoothed, delayed response to snowmelt and calculations showed that total discharge for the period May to September was about double the amount (per drainage surface area) compared with other local drainages. An externally-supplied aquifer and/or deep groundwater storage was postulated by Salway (1983). It is likely that groundwater storage within fractured bedrock, and/or karst aquifers in this watershed are responsible for the hydrologic response exhibited.

Relationships of regional hydrology developed by Eaton et al (2002) and Eaton and Moore (2010) suggest the local peak runoff should be higher for the Gar Creek drainage than what is typically observed (by an order of magnitude) further supporting the idea of a dampened drainage response. This comparison does not however indicate that water is travelling subsurface from another drainage area, only that the runoff is not flashy and has significant groundwater storage.

During the field reviews (2012) no surface water was observed in the Gar Creek north tributary while two springs were observed (see Figure 17), originating from the southeast portion of the drainage, supplying a significant volume of water to Gar Creek. These two springs are likely responsible for much of the dampened flow volumes observed in Gar Creek. Significant subsurface and surface flows immediately post landslide were observed primarily on the north and east portions of the landslide main scarp. The subsurface flows near the landslide in all cases appeared to emerge from till and colluvium units at/ above the bedrock contact.

The two upper most springs contributing to Gar Creek emerge at discrete locations at the 1150 m and 1500 m elevation (as shown on Figure 17).

5.3.3 Gar Creek Hydrogeology

The Badshot Formation (outcrops located at the very top of the Gar Creek drainage and in the upper portion of the Salisbury and Kootenay Joe drainage) consists of marble (metamorphosed limestone). The schists and phyllites of the Badshot-Mohican and Index Formations have calcareous constituents which can dissolve in groundwater. In some areas the karst features (caves and subsurface streams) of the Badshot Formation may act as an aquifer, and could account for the springs in the Gardner Creek and Gar Creek drainages. The water from some of these springs was noted to be very limey (Kutenai Nature Investigations Ltd. 1983).

Photo 51 and 52 in Appendix A (courtesy of Greg Utzig) show karst features within the Badshot Formation at outcrop locations representative of different folds (arms) of the formation (see Figure 8).

At various locations in the Gar Creek drainage and within the 2012 landslide deposit sequences of white, red and grey altered soil were observed (see Photo 41 Appendix A). Sample analysis showed the white material was depleted in metals, while the red and grey material was enriched with iron and other minerals. At one location (near the southeast scarp) there is a mineral spring with a sulphur-like odour. Analysis of a water sample showed the mineral spring had a very high manganese content.

Water samples were collected from the water emerging at the landslide scarp and other springs, and test results are shown in Appendix L. None of the sampled springs appeared limey, although a tufa-bearing seep was observed on the north side of Gar Creek.

5.3.4 Watershed Characteristics

A preliminary identification of watersheds subject to debris flow and debris flood hazards can be made on the basis of morphometric characteristics (Jackson et al., 1987; Wilford et al., 2004 and Wilford et al 2009) such as the Melton ratio (watershed relief divided by the square root of watershed area) and the relief ratio (watershed relief divided by watershed length). These indices are essentially surrogates for average channel slope.

The Gar Creek watershed area is 4.2 km^2 and has a Melton ratio of 0.85 (see Table 1). Klohn Crippen (1998) estimated a Melton ration of 0.81 and concluded that the Gar Creek drainage contained an adequate supply of material for debris flow initiation. Its two main tributaries have drainage areas of 1.7 km^2 and 0.83 km^2 respectively with Melton ratios of 1.07 and 1.14. According to Wilford et al. (2004), these watersheds are all within the range which is likely to be susceptible to debris flows.

The fan surface slope ranges from 15% to 25%. The fan slope and Melton ratio are strong indicators that the Gar Creek fan is a debris flow fan. Post landslide site investigations identifying coarse, angular, unsorted cobbles and boulders within a fine textured matrix also confirmed the fan as having debris flow origin material present.

Table 1: Watershed characteristics

Watershed characteristics	1st tributary	2nd tributary	Gar Creek
Drainage area (km^2)	1.7	0.83	4.2
Watershed length (km^2)	2.22	1.63	4.25
Elevation range (m)	1040-2280	1040-2080	540-2280
Melton ratio[4]	1.07	1.14	0.85
Relief ratio	0.56	0.64	0.41

Some historical selective logging has occurred in the drainage; however, hydrologic recovery is such that there would not have been any appreciative effects of the logging on groundwater infiltration or surface runoff.

Limited roads and trails have been constructed in the drainage. One active road is the Kootenay Joe Forest Service Road on the south side of the drainage that extends into the Kootenay Joe drainage at the 1700 m elevation.

5.3.5 Water Chemistry

The location and status of points of diversion (PODs) in the area was confirmed in 2003 during the EBA field assessment. On, or adjacent to Gar Creek, there were seven PODs and 33 corresponding water licenses. Of the seven PODs, only four were found to be functioning. The total quantity licensed is 12,500 gallons per day.

Suspended sediment concentrations, sampled in the study area creeks between 1980 and 1982 were provided by Salway (1983). Gar Creek maximum Total Suspended Sediment (TSS) concentrations were quite low (between 6 and 15 mg/L). These observations were obtained during late spring snow-melt conditions.

Conductivity (or specific conductance) of Gar Creek water was measured (EBA 2003). Conductivity refers to the ability of a substance to conduct an electric current and is a function of water temperature and the concentration of dissolved ions. It is often a surrogate variable

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[4] Melton Ratio = relief / √ area. It is an index of average watershed slope. A study by Wilford et al (2004) in northwestern B.C. concluded that watersheds subject to debris flows and debris floods typically had Melton ratios of >0.6 and 0.3-0.6 respectively.

for Total Dissolved Solids (TDS), which is associated with residence time in bedrock, so measurements should provide some indication of water origin (i.e. whether it is groundwater or rain and surface runoff). Streams with a dominant surface water contribution generally have specific conductivities less than 300 µS/cm. This is the case for Gar Creek where measured conductivities remained relatively low with 219 µS/cm for lower Gar Creek and 199 µS/cm for upper Gar Creek (EBA, 2003).

During the landside field investigation several water samples were taken from seepage locations along the scarp and from springs. The chemistry of water sampled at these springs indicates the presence of moderate metal and alkalinity concentrations (results are included in Appendix L) with higher alkalinity on the north side seeps and high metal concentrations towards the southeast (consistent with groundwater flow through the Fry Creek Batholith).

6. LIDAR and Photogrammetry

Accurate mapping of pre and post landslide topography was required to estimate the volume of the landslide deposits (to calibrate the runoff model) and for use in run-out modeling and limit equilibrium analysis (slope stability analysis).

On July 27th and 28th, 2012, Terra Remote Sensing Inc. (TRSI) conducted Light Detection and Ranging (LIDAR) mapping of the Gar Creek and Gardner Creek drainages. LIDAR remote sensing uses laser light to reflect off the ground surface in order to develop an accurate representation of the post landslide topography. LIDAR can “see” under the tree canopy as some light directed at the ground surface travels through the canopy. TRSI acquired the LIDAR and orthophotography in the project area using the Terra Mk.IV Lidar and Image system – a combined GPS/INS System (Inertial Navigation System) for aircraft attitude and position as well as laser range data to obtain spatial surface data. Calibration data were acquired over the runway at the airport in Kaslo, BC, Canada. For more details, see Appendix G.

A hill shade image based on a digital elevation model of the LIDAR bare earth model is shown in Figure 17 (see also Appendix B- Map 2).

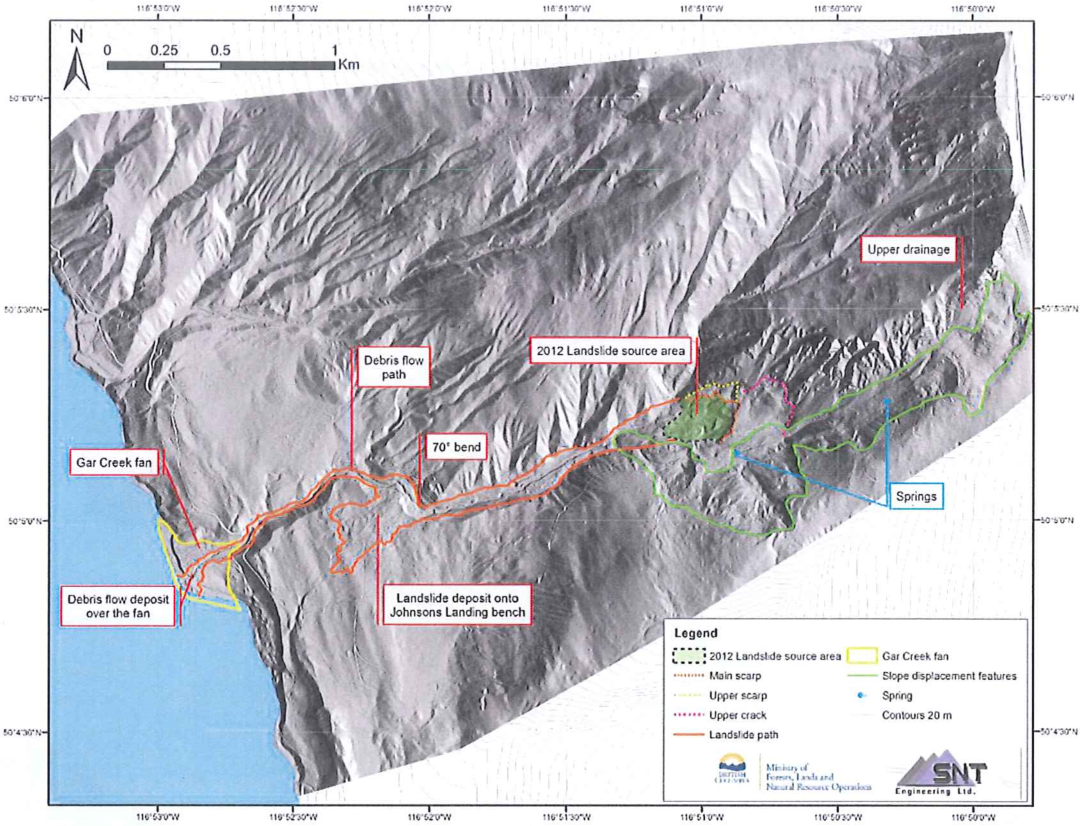


Figure 17: Gar Creek drainage (LIDAR image)

4DGIS Ltd. (4D) was retained to reconstruct the pre-landslide surface from historical air photographs. Photogrammetry was conducted using 1997 (Roll 30BCB97109), 2004 (Roll 15BCC0437) and 2012 (post-landslide) photos. The photogrammetry appeared to be accurate for the determination of landslide deposit volumes where there was minimum pre-landslide tree cover. However at the main scarp even a small error in the estimation of tree height results in significant variation of estimated volumes. The 20 ha area of the landslide source area and upper-middle channel was entirely covered by dense mature forest, except for a narrow strip down the Gar Creek channel. A 1 m error in estimating tree height in this 20 ha area would result in a +/- 200,000 m^3 error in the estimated initial landslide volume, and it is likely that the accuracy of tree heights estimated from photogrammetry, combined with tree height data from LIDAR imagery of adjacent areas, is no better than +/- 5 m.

An approximate contour map of the estimated pre-landslide surface in the landslide source area and upper channel area was drawn manually, based on field observations and on measured scarp heights around the landslide scarp perimeter. The estimated contours were adjusted by trial-and-error to make the source volume match the observed deposit volumes (see Figure 18).

The deposit volume on the Johnsons Landing bench as estimated from photogrammetry and field mapping is consistent with the deposit depths measured in our test pits, and the relatively small fan deposit volume is also consistent with field observations.

Figure 18 presents a map of estimated landslide erosion and deposition. Table 2 is a summary of the areas and volumes. The deposit volume is 19% greater than the estimated source volume, which is expected due to "bulking" or expansion of the original material upon failure.

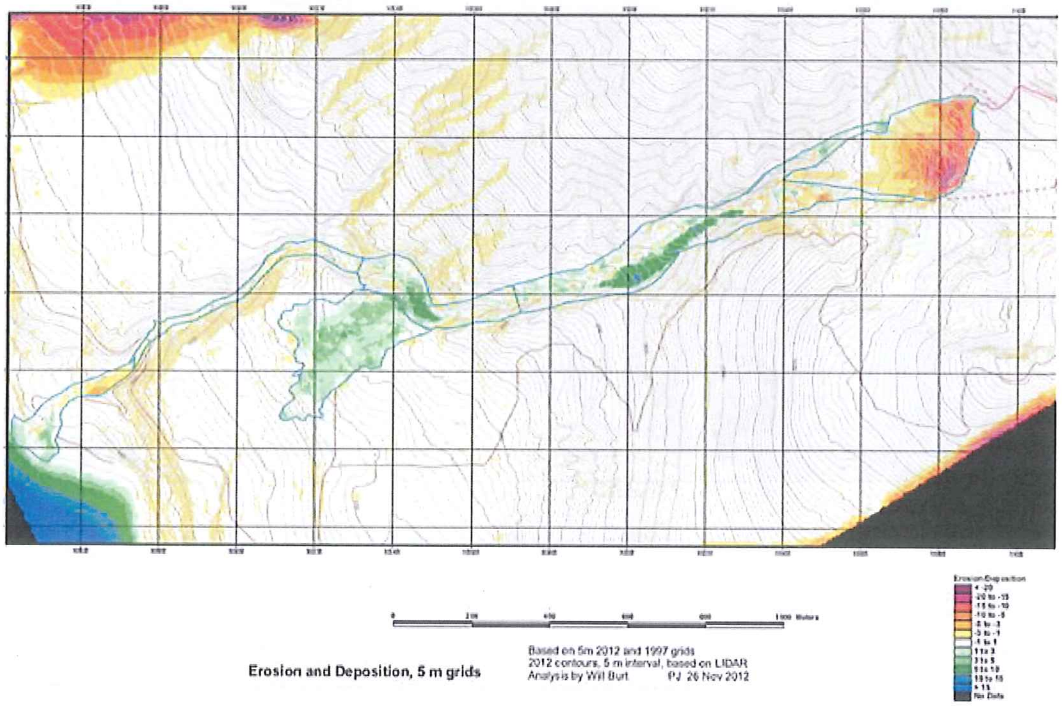


Figure 18: Estimated landslide erosion and deposition volumes

Table 2: Landslide erosion and deposition volume estimates

Location	Area (m^2)	Volume (m^3)	% of Total Deposit Volume
Landslide Source Area	75300	321000	
Upper Channel	93400	140400	37
Mid Channel	35000	55100	14
Lower Channel	17900	100	<1
Fan	21100	17200	4.5
Johnsons Landing Bench	65000	169000	44
Total Depletion		321000	
Total Deposit		381800	
Bulking Ratio		1.19	

7. Field Investigation

During the field reviews, various surficial deposits were observed including glacio-fluvial deposits found primarily on the Johnsons Landing bench. Other surficial deposits included till and colluvium (often colluviated till) with various grain size distributions (typically silty sand and gravel, and sand and gravel with some silt). Coarse fragment content ranged from 0 to 54%.

Soil samples were collected from the 2012 main scarp, upper scarp, upper cracks, and landslide deposit and from in-situ soil located under and adjacent to the landslide deposit (see Photos 31 through 43 Appendix A). Four test pits were excavated through the existing landslide deposit using a Hyundai 130LC3 excavator. One of these test pits was located in the Gar Creek channel, while the other three were excavated on the Johnsons Landing bench. Eight test pits were excavated with a smaller machine to the east of the landslide deposit in an area that was identified by the LIDAR as potentially having old landslide deposits. Twelve test pits in total (depths ranging from 2.5 m to 12 m) were excavated with over 40 soil samples for further classification and grain size analysis (see Figure 19). The purpose of the test pits was to examine the underlying soil for evidence of any previous landslide deposits, to measure the depth of the 2012 landslide, and to collect samples of the 2012 landslide deposit at depth.

The locations of test pits are shown in Figure 19 and grain size testing of selected samples is shown in Figure 20. The test pits were named corresponding to their location waypoint. Other locations are shown at which surface samples were collected. Samples were collected from selected layers in each test pit; however, not every layer was sampled, if the type of material in that layer was visually obvious. The classification of soil layers observed, cumulative grain-size distribution curves, and full test results are included in Appendix D.

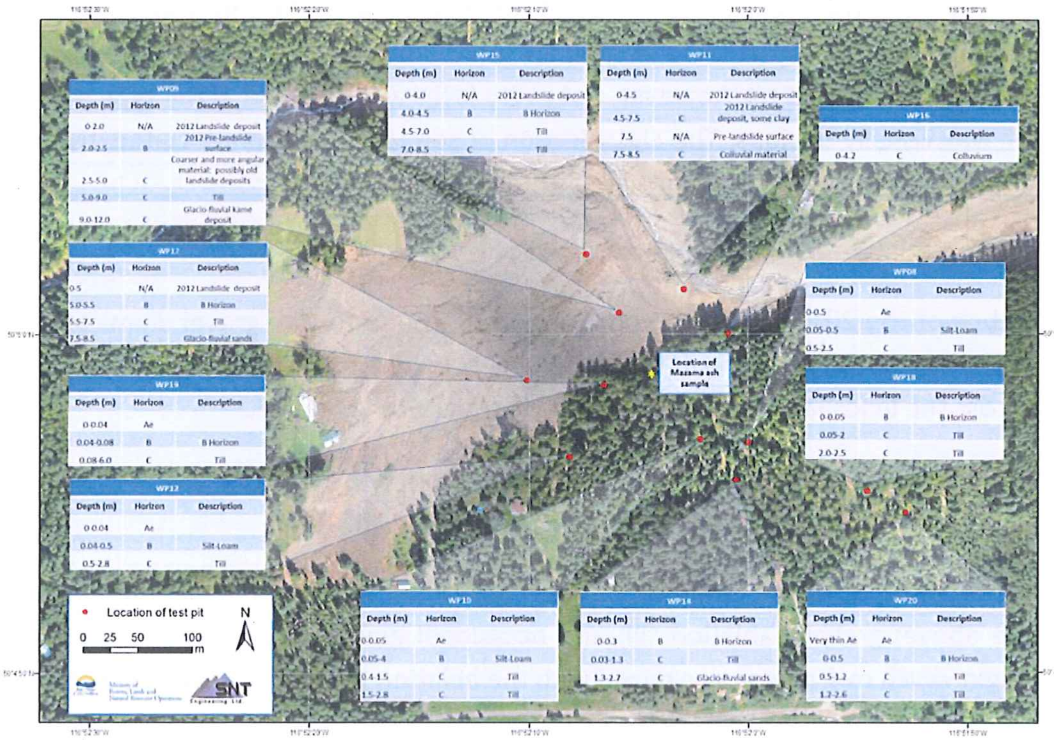
The typical materials found in the pits consisted of:

- Debris of the 2012 landslide, consisting of silty sand to silty gravel diamicton, with the same composition as the till and colluvium in the main scarp; quite variable locally across the landslide deposit. No plastic material was observed.
- Glacial till and glacio-fluvial material ranging from poorly sorted silty or sandy gravel to well-sorted fine sand, underlying the landslide deposit.
- South and east of the landslide deposit, glacial till and glacio-fluvial material similar to the above; gravelly ablation till; and occasional gravelly material of possible colluvial origin which overlain or was mixed with the ablation till. This material could be from late Pleistocene debris flows from the Gar Creek valley, which were deposited on or adjacent

to wasting glacier ice (the terrain mapping shows this area as "gF^{G}bf" [gravelly glacio-fluvial blanket fan] which is consistent with such an origin).

- One pit (WP16) contained a 4.2 m deep (or deeper) deposit of coarse gravelly diamicton of debris flow origin. This pit was in a narrow terrace which sits 15 m above Gar Creek, and has a mature soil profile. It was probably emplaced when Gar Creek was at a higher level, or possibly against glacier ice. No similar material was found further west on the Johnsons Landing bench.

In addition to the test pits, numerous shallow holes were dug by hand, and surface observations were made at natural exposures on the Johnsons Landing bench near the landslide deposit. These encountered morainal and glacio-fluvial materials similar to those found in the pits. In general, the glacial deposits encountered in the pits and surface samples were massive or weakly stratified, except for isolated lenses of well-sorted glacio-fluvial sand. No identifiable glacio-lacustrine or aeolian material was found (although the terrain map notes isolated occurrences of such materials elsewhere in the Johnsons Landing area). No materials or landforms indicative of previous landslides since deglaciation were found. The morainal, glacio-fluvial, and colluvial materials were often difficult to distinguish, as they usually had a similar silty sand matrix, similar colour, and similar lithologic composition of stones reflecting the metasedimentary rocks which form the source material for all the deposits



WP09

Depth (m)	Horizon	Description
0-2.0	N/A	2012 Landslide deposit
2.0-2.5	B	2012 Pre-landslide surface
2.5-5.0	C	Coarser and more angular material: possibly old landslide deposits
5.0-9.0	C	Till
9.0-12.0	C	Glacio-fluvial kame deposit

WP15

Depth (m)	Horizon	Description
0-4.0	N/A	2012 Landslide deposit
4.0-4.5	B	B Horizon
4.5-7.0	C	Till
7.0-8.5	C	Till

WP11

Depth (m)	Horizon	Description
0-4.5	N/A	2012 Landslide deposit
4.5-7.5	C	2012 Landslide deposit, some clay
7.5	N/A	Pre-landslide surface
7.5-8.5	C	Colluvial material

WP16

Depth (m)	Horizon	Description
0-4.2	C	Colluvium

WP17

Depth (m)	Horizon	Description
0-5	N/A	2012 Landslide deposit
5.0-5.5	B	B Horizon
5.5-7.5	C	Till
7.5-8.5	C	Glacio-fluvial sands

WP08

Depth (m)	Horizon	Description
0-0.5	Ae	
0.05-0.5	B	Silt-Loam
0.5-2.5	C	Till

WP18

Depth (m)	Horizon	Description
0-0.05	B	B Horizon
0.05-2	C	Till
2.0-2.5	C	Till

WP19

Depth (m)	Horizon	Description
0-0.04	Ae	
0.04-0.08	B	B Horizon
0.08-6.0	C	Till

WP12

Depth (m)	Horizon	Description
0-0.04	Ae	
0.04-0.5	B	Silt-Loam
0.5-2.8	C	Till

WP10

Depth (m)	Horizon	Description
0-0.05	Ae	
0.05-4	B	Silt-Loam
0.4-1.5	C	Till
1.5-2.8	C	Till

WP14

Depth (m)	Horizon	Description
0-0.3	B	B Horizon
0.03-1.3	C	Till
1.3-2.7	C	Glacio-fluvial sands

WP20

Depth (m)	Horizon	Description
Very thin Ae	Ae	
0-0.5	B	B Horizon
0.5-1.2	C	Till
1.2-2.6	C	Till

Figure 19: Classification of test pit stratigraphy

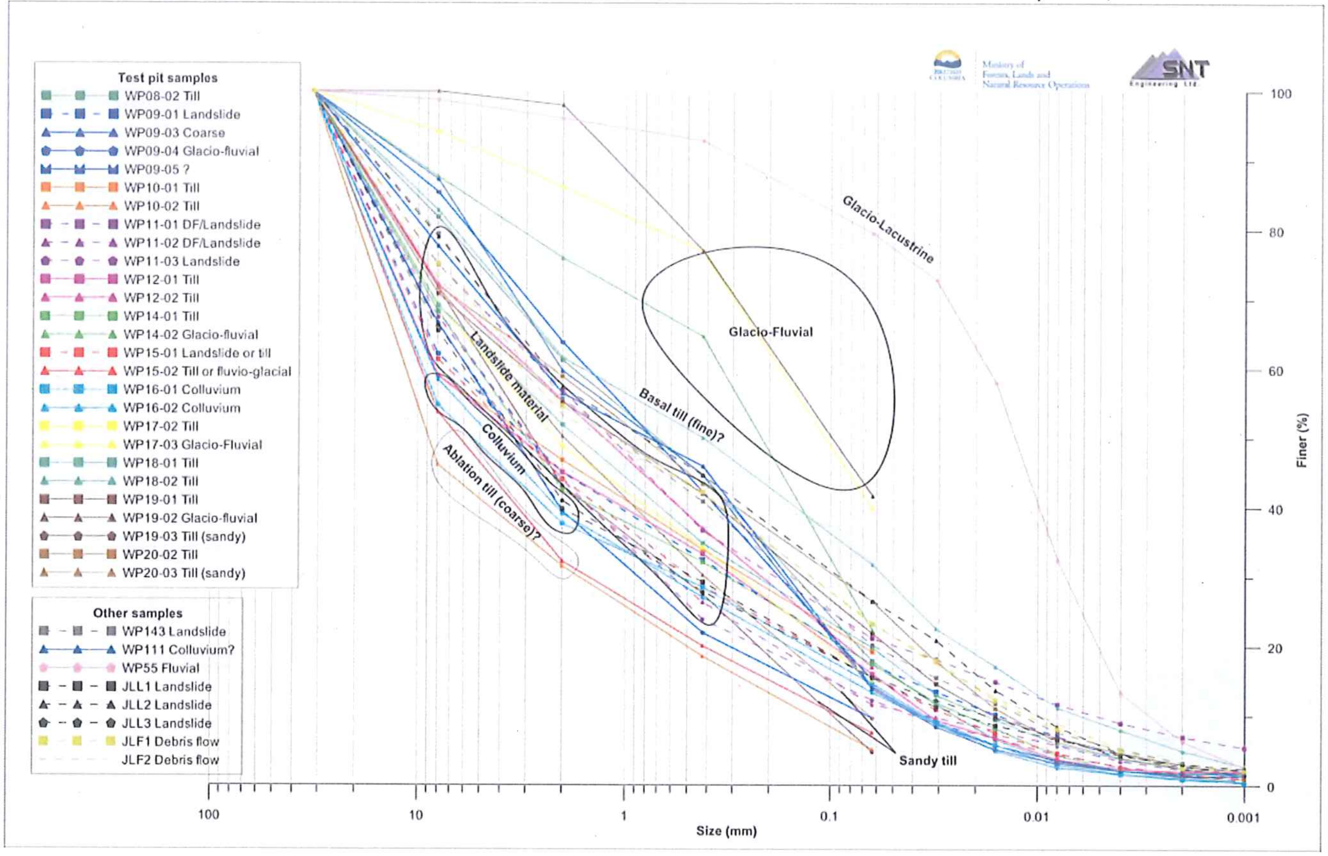


Figure 20: Grain-size cumulative curves

At one location immediately adjacent to the upper part of the landslide deposit, on the surface of the Johnsons Landing bench at a 20 cm depth, a layer of Mazama ash was uncovered (Figure 19, and Photos 34 and 35 Appendix A). Mount Mazama is a volcano in Oregon which spread a layer of ash across southern BC approximately 7700 years ago. A sample of the ash was sent to and tested by the Washington State University, who confirmed its origin. The observation of the ash layer at a shallow depth provides additional confirmation that a large landslide has not deposited debris onto the Johnsons Landing bench in at least the last 7700 years.

Terrain mapping by Kutenai Nature Investigations Ltd. (1983) has mapped the area of the Johnsons Landing bench (Figure 21) now covered by landslide debris as fgMbt (gravelly fines morainal terraced blanket) and gF^{G}bh (gravelly glacial fluvial hummocky blanket) consistent with our field observations and test pits, which showed a lack of previous landslide debris.

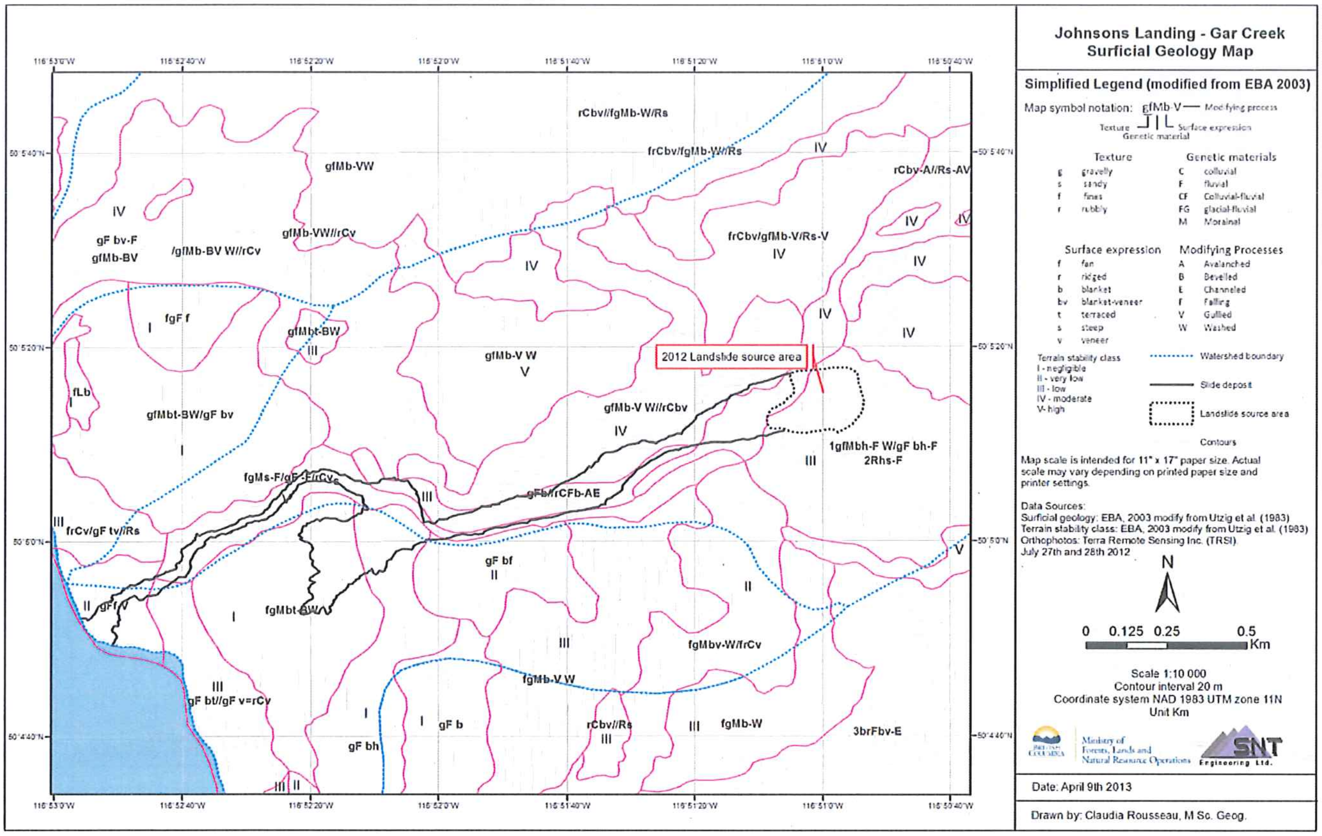


Figure 21: Gar Creek surficial geology map (modified from EBA 2003 and Kutenai Nature Investigations Ltd., 1983)

The test pitting and laboratory testing of acquired samples supports the interpretation made using the LIDAR data (see Section 6) that a landslide of the magnitude of the 2012 event had not occurred since deglaciation and that, furthermore, no landslide has overflown the channel at the 70° bend during this period.

Post landslide field reviews identified several outcrops of the Index, Badshot and Mohican Formations. Old bedrock failures were observed in the upper eastern portion of the Gar Creek drainage and were mostly located in the Index Formation, although several occurrences of possible Mohican Formation and Hamill Group rocks were also noted in the failures. Sackungen (slope deformation) features representing toppling bedrock structures were also observed.

Some slope movements have occurred in the upper drainage over the last 60 years (see Figure 25). Photograph 45, in Appendix A, taken in 2012 shows a 1.2 m drop in the Kootenay Joe FSR at the location shown on Figure 25. Photographs 46 to 48 show a split tree at a tension crack that first split 60 years ago and has since moved 100 cm. The average annual slope movement has been 2 cm (likely occurring at greater rates during wet freshets and less displacements during dryer years).

Recent (2012) cracks and shear zones were observed approximately 200m upslope of the upper scarp and are shown on figures 23 and 24 and are discussed further in section 9 and 11.

8. Landslide History and Deglaciation

Considering the volume of material missing from topographic depressions on the slope, which is interpreted as ancient landslide scars, there must have been prehistoric landslide volume releases in the order of millions of cubic metres of rock and soil. However, corresponding voluminous debris deposits have not been identified on the lower slopes. In particular, there is no evidence of any large (in the order of the 2012 landslide) landslide deposit on the Johnsons Landing bench area. Most landslide activity in the drainage probably occurred shortly after deglaciation, and significant volumes of slide material were likely deposited on retreating valley ice. One area of deposits that could be interpreted as landslide debris re-transported by ice is located 100 to 350 m to the south of the 70° bend in Gar Creek where hummocky terrain can be detected both on the ground and on the LIDAR image. Test pits and surficial review of existing deposits on this part of the Johnsons Landing bench indicate that typically there is a mix of shallow colluvium overlying tills and glacio-fluvial (kame) deposits, which probably date to the end of deglaciation in the region.

The slow moving bedrock landslides in the Gar Creek southeastern tributary have apparently not produced any significant rapid landslides and the displaced material has remained in the upper basin. There have probably been small debris flows and debris avalanches involving bedrock, but material from these has likely accumulated in the upper channel of Gar Creek.

The conclusion that there has been a lack of significant landslide activity since the early postglacial period is supported by the small size of the active Gar Creek fan, and the fact that the larger inactive fan appears to be graded to a higher lake level. There are many large fans and river deltas along Kootenay Lake graded to the current lake level, which implies that the lake level has been at or near its present level for a long time. Also, there are few or no examples known to the authors (or obvious on air photos) similar to the Gar Creek fan, where there is an older fan graded to a level several metres higher. However, slightly raised fans would not be detectable on available 20 m contour maps, or on air photos in heavily forested locations. There are numerous late glacial period terraces and fans graded to a much higher lake level, including the Johnsons Landing bench, probably corresponding to the Kootenay – Pend d'Oreille divide south of Bonners Ferry. It is likely that the raised fan on Gar Creek was built in a short time in the early postglacial period, when the lake may have been a few metres higher due to blockage by remnant ice or sediment in the West Arm, or to differential isostatic adjustments following deglaciation.

9. Slope Stability Analyses

Two dimensional Limit Equilibrium Analyses (LEA) were conducted to assess the stability of select slopes above the main scarp and to assist with the estimation of the size of a potential landslide above the 2012 main scarp and upper scarp. Back analyses were performed to estimate the pore pressure required in order to trigger the 2012 landslide event. The back analyzed pore pressure was then compared with the pore pressure required to achieve a Factor of Safety (FoS) of 1.0 for various forward analyses of different landslide locations and magnitudes.

Pre-2012 landslide profiles were reconstructed using information from the photogrammetry, LIDAR, and field reviews. The post 2012 landslide profiles were constructed using the LIDAR DEM. A typical profile is shown in Figure 22 . Profile locations are shown in Figure 23.

Based on local experience with sandy and gravelly subangular tills an effective friction angle of 39° was used for the modelling, with zero cohesion. It is noted that if the soil deposits were pre-sheared with previous movements of greater than 1 m the residual friction angle could be lower (35° range). Analyses were conducted, to determine the R_u (pore pressure/soil pressure ratio) for each reconstructed pre-2012 landslide profile in order for the FoS to drop to 1.0 (slope failure).

Forward analyses were conducted using the post 2012 profiles. Analyses considered potential failure of soil masses above the 2012 main scarp. The same effective friction angle (39°) was used for the forward analyses as was used for the back analyses. Various potential slip surfaces were analyzed to determine the required R_u to achieve a FoS of 1.0. The R_u's at failure are shown on the profiles in Appendix E and a summary is provided in Table 3:

Table 3: Slope stability analyses and R_u values

Profile	Back analysed R_u at failure for 2012 slide	Required R_u for intermediate slope failure above July 12th scarp (forward analyses)	Required R_u for failure to upper crack (forward analyses)
1	0.28	0.25	0.32
2	0.38	0.29	0.53 (essentially fully saturated)
3	0.4	0.39	>0.5 (essentially fully saturated)
5	0.23-0.26	0	n/a

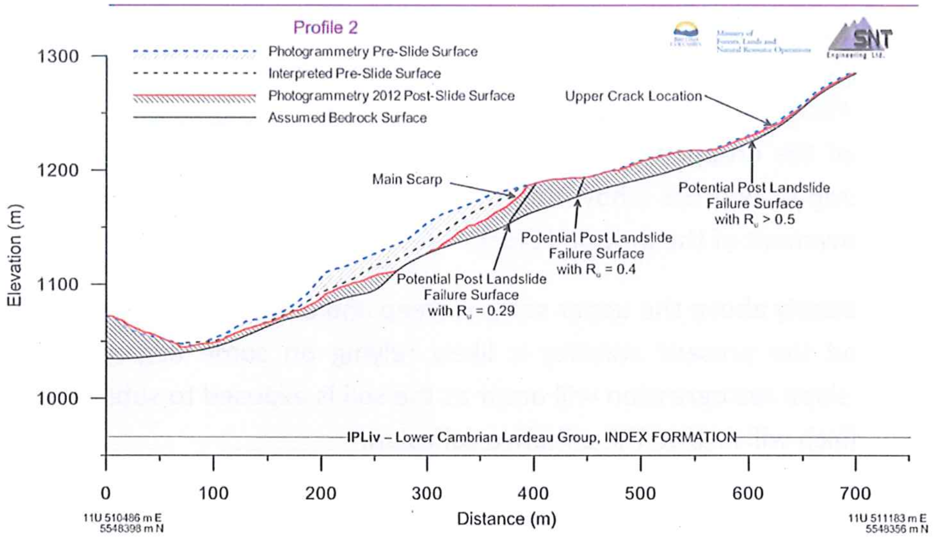


Figure 22: Profile 2 slope stability analyses

Profiles 1 through 3 are located through the north side and the south side of the main scarp respectively (Profile 2 trends almost due East/West). Profiles 1 and 2 extend upslope beyond the upper crack. The upper crack is actually a small scarp (4 m of displacement) at its northern extent (Profile 1) with progressively less shear towards the south. At a location between Profile 2 and Profile 3 the upper crack was not present (could not be traced). Profile 5 is located at the northern side of the main scarp (trends NE to SW). Profile 5 includes the dropped block and upper scarp.

An R_u of 0.32 and >0.5 for Profile 1 and Profile 2 respectively is required for the potential landslide block to extend all the way to the upper crack. The higher R_u required for failure on Profile 2 is primarily a result of the lower slope gradient. The results are consistent with the field observations of the magnitude of displacement of the shear zone at the upper crack location at the upper edge of Profile 1 compared with Profile 2 and the lack of a visible crack beyond Profile 2 (towards Profile 3).

For intermediate potential landslide blocks (that don't extend all the way to the upper crack) lower R_u's are required to reach a FoS of 1.0. (see slip planes in Appendix E and Table 3 summary).

Profile 3 is located to the south of the location where the upper crack could be traced. The analyses indicate that the potential landslide block can only extend upslope about half the distance (compared with Profile 1 and 2) even under fully saturated conditions.

Profile 5 is located at a location that includes the dropped block (irregular shaped block with length up to 120 m and width of 60 m that is bounded by the main scarp and the upper scarp).

In its pre-2012 position, the slope including the dropped block required an Ru of 0.26 to decrease its Factor of Safety to 1.0; however, the slope immediately in front of the dropped block reached a Factor of Safety of 1.0 with an Ru of 0.23. The removal of the source material caused the FoS of the dropped block to reduce to 1.0 (loss of toe support and retrogressive failure). An outcrop of bedrock (shown on the Profile) may have provided enough support to arrest further movement of the dropped block.

The slope immediately above the upper scarp is steep and even with low R_u values the factor of safety is low and the present stability is likely relying on some degree of cohesion. It is anticipated that slope retrogression will occur as the soil is exposed to subsequent wetting and drying periods which will reduce the effective cohesion.

Potential landslide blocks of various sizes are shown in Figure 23.

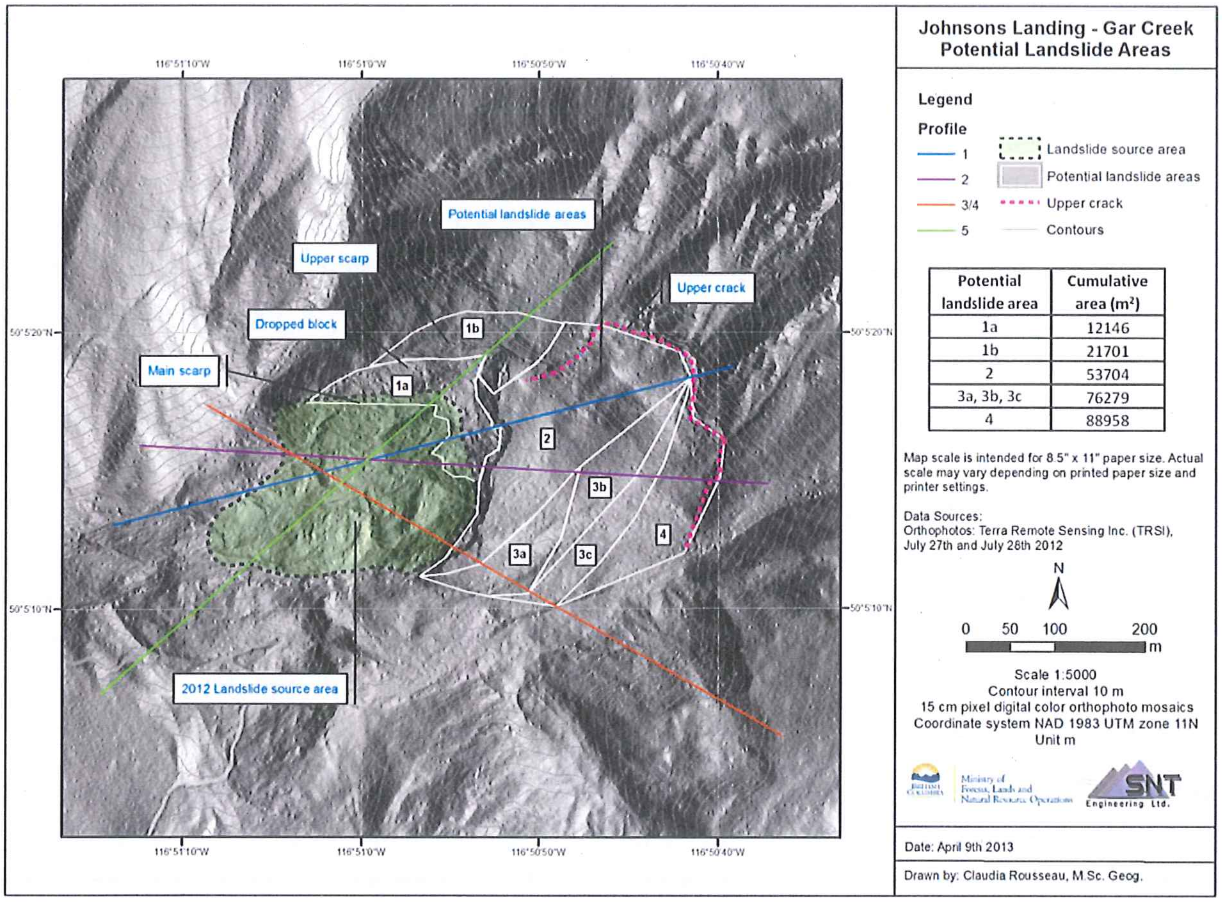
The blocks are described as follows:

- Case 1a – dropped block
- Case 1b – dropped block and retrogression of steep slopes above the upper scarp to outcropping bedrock
- Case 2– potential landslide block extends to the upper crack along Profile 1
- Case 3 – various potential landslide blocks that intersect Profiles 2 and 3. The upper extent of the blocks is defined by block FoS of 1.0 for various R_u values (between 0.3 and 0.5).
- Case 4 – extension of potential landslide block to the upper crack and/or to the location where the R_u is >0.5.

There are significant uncertainties in such analyses including applicable shear strength, actual pore pressure levels, bedrock location, variability of soil types both vertical and areal, and the influence of effective cohesion. Nonetheless the analyses provide some insight as follows:

- They provide an explanation for the "dropped block".
- Aid in the estimation of future landslide volumes as a function of saturation and thus return period.
- Support the limit of reasonable maximum landslide volume estimates (especially along Profiles 2 and 3).

Based on field observations and supported by the limit equilibrium analyses a total of four primary landslide scenarios as shown in Figure 23 were selected for further consideration for potential landslide magnitude and run-out analyses.



Potential landslide area	Cumulative area (m²)
1a	12146
1b	21701
2	53704
3a, 3b, 3c	76279
4	88958

Map scale is intended for 8.5" x 11" paper size. Actual scale may vary depending on printed paper size and printer settings.

Data Sources:
Orthophotos: Terra Remote Sensing Inc. (TRSI), July 27th and July 28th 2012

Scale 1:5000
Contour interval 10 m
15 cm pixel digital color orthophoto mosaics
Coordinate system NAD 1983 UTM zone 11N
Unit m

Date: April 9th 2013

Drawn by: Claudia Rousseau, M.Sc. Geog.

Figure 23: Slope stability cases map

10. Landslide Causes and Triggering Mechanism

10.1 Short-term hydrologic factors

The July 12th, 2012, landslide was triggered by a very high groundwater table that reduced the effective strength of the soil. The high groundwater levels were due to record high rainfall in June (to July 3rd) and to higher than normal snowpack (SWE) combined with delayed snowmelt.

Local observations, reported post landslide, indicated that Gar Creek may have been flowing at its highest level in over 40 years for the week preceding the landslide. Slope movements were occurring at least two days before the slide occurred. The slope movement could have taken place in the form of progressive failure – with a gradually developing sliding surface, decay of cohesion and friction on shear surfaces and the front face of the landslide falling into or being eroded by the creek. Alternatively, the movement could have had the form of slope retrogression, where the front face was failing in segments and removing support from the larger slide mass. Some initial slope movement may have blocked subsurface seepage paths, resulting in higher pore pressures which would have further reduced slope stability. Also, opening tension cracks may have gradually filled with surface water, applying hydraulic thrust, while the piezometric pressure on the sliding surface was being increased by seepage from higher levels of the slope, or from structures in the underlying bedrock.

Gar Creek has a delayed response to surface flows compared to most other creeks in the area. This is likely due to significant seepage into, and storage in fractured bedrock or karst aquifers. The last rain that occurred before the landslide occurrence was on July 3rd which corresponds approximately with the observation of the beginning of the high creek levels. What was unusual at Gar Creek were the sustained high flows for the following eight days consistent with a groundwater dominated flow regime. In addition, water could have been supplemented by flow from other drainages, via subsurface bedrock fractures or karst aquifers. Soon after the landslide occurred, the creek flows dropped significantly over the following several days.

Immediately after the landslide event, subsurface flows were observed exiting the landslide scarp at several locations. Some flows emerged from seeps in colluvium and till while other seeps were observed near the bedrock contact. Photographs 42 and 43 in Appendix A show seepage emerging from thick till deposits on July 17th directly above the bedrock contact. The two main tributaries of Gar Creek appear as springs on the east side of the drainage (see Figure 17). The groundwater source remains uncertain and it likely originates from a variety of locations as demonstrated by its varied chemistry. Whatever the source of the groundwater, the record June rainfall, combined with late snowmelt at high elevation resulted in high groundwater levels and contributed to the slope instability.

It was not considered practical to attempt to identify all subsurface water sources that contributed to the local high-water level for the following reasons:

- The seepage likely has several sources including shallow infiltration and deeper seated bedrock.
- There were many observed surface and subsurface seeps spread across hundreds of meters.

- The path of water from source to slide is likely complex with possible additions to flow from adjacent drainages.
- There was contributing snowmelt between July 4th and 12th with warmer days (up to 32°C at Duncan Lake). See Section 5.2 for SWE and melt rates

In conclusion, the groundwater level in the Gar Creek watershed was exceptionally high in early July, due to record high rainfall in June, rapid snowmelt in early July, and possible contributions from springs originating in bedrock. This reduced the stability of slopes in the area, and was the main triggering factor of the 2012 landslide.

10.2 Long-term Geological Factors

High groundwater levels, due to exceptionally high rainfall and above average snowmelt rates, were the triggering mechanism for the landslide. However, the geotechnical factors which contributed to instability in the landslide source area are less certain. The return period of the precipitation and late snowmelt event may have been in the order of 500 years. If this is the case, similar hydrologic circumstances must have occurred often (maybe 20 times) since deglaciation, but did not trigger a large landslide. Some other process must have occurred, which caused the stability to decrease over time. The geological investigations made after the landslide, combined with other observations such as the studies done in 1981-83, allow us to provide a possible reconstruction of events preceding the landslide, and to present some theories about its possible cause.

During and immediately following deglaciation, there were probably numerous landslides and debris flows from the Gar Creek watershed, and for similar drainages throughout the region. These events were responsible in part for building the large valley-bottom kame terrace complexes, which include the Johnsons Landing bench. Road cuts along the Argenta-Johnsons Landing road reveal many debris flow deposits, as well as glacio-fluvial sands and gravels. However, no deposits have been observed which appear to be of rock avalanche or rockfall origin. On top of the Johnsons Landing bench, at the mouth of the upper Gar Creek valley, two small deposits of colluvial origin were observed which probably occurred during late deglaciation; these are noted in Section 7. Both of these have their origin in glacial deposits, not bedrock, based on their texture and on the roundness and lithology of stones.

Based on the LIDAR imagery and the field reviews, a complex of inactive or slow-moving bedrock failures was found to occupy most of the area of the south fork of Gar Creek, east of the landslide (Section 7, Figure 24 and Figure 25 below). Relatively inactive toppling deformation features were noted along with recent transverse cracks. The age of these failures is unknown, except that they are older than the age required for growth of an old-growth forest and development of a mature soil profile (perhaps 1000 years). The most southwestern failure (Figure 24, units 1 and 2) appears to be the largest and second-youngest, and it has no evidence of recent movement. Failures in the central part of the valley appear to be much older, based on their more subdued topography on the LIDAR images. Only the uppermost part of the failure complex shows signs of recent movement, and this does not appear to be directly connected to the 2012 event. It is unlikely that any part of the bedrock complex ever failed rapidly, as no rock avalanche debris has been observed further down the Gar Creek valley. The rock displaced by the failures constitutes the irregular benched and ridged topography in the lower part of the south fork valley (between about 1000 and 1300 m elevation).

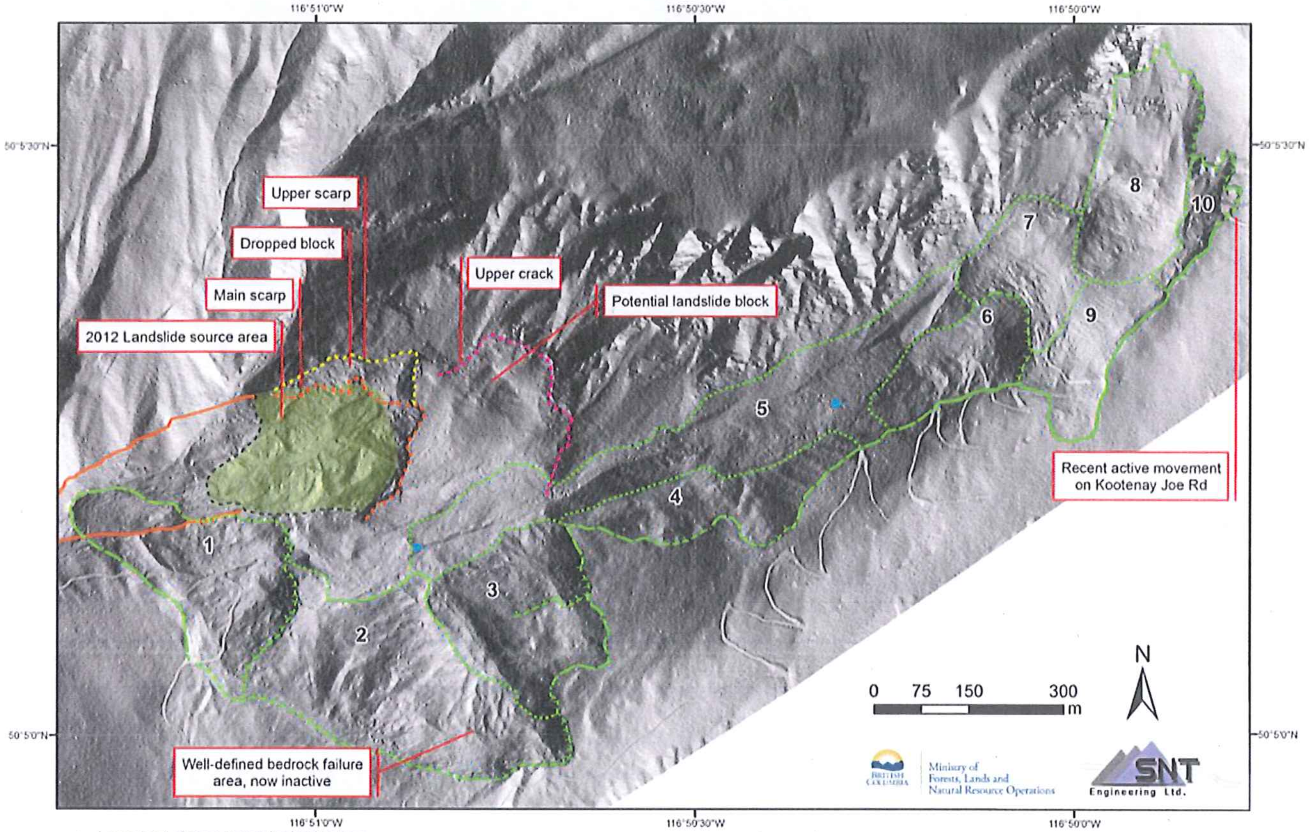
The continual movement of material may have resulted in the establishment of new subsurface drainage paths or blocked previous drainage paths. It is possible that movement at the toe of the bedrock failure complex placed stress on, and probably deformed the thick glacial deposits in which the failure occurred. This deformation could have reduced the strength of these deposits by creating small fractures, causing dilation of the sediment in some places. The deformation may also have contributed to the brittle failure of the thick glacial deposits (see section 8 above). We hypothesize that this is the most feasible mechanism that contributed to the landslide.

Two other mechanisms may have had some influence on the slope stability. The first is the role of the karst aquifers that may carry water from part of the higher elevation Salisbury Creek to the north, into the Gar Creek valley. Photos 51 and 52 Appendix A show the presence of some of the karst features 6 km to the north of the 2012 landslide source area. These aquifers have probably existed for a very long time. For them to have had any effect on slope stability would require some change. It is probable that random changes occur in karst aquifers, as continued solution and occasional cave collapses cause changes in the subsurface path of water. However, it is very difficult to map or study these likely very complex aquifers. If any such changes did occur, they could result in changes to the location or volume of springs, which could increase or decrease slope stability or have no effect on it.

Another possible mechanism might be related to the mineral spring (spring "d" on Figure 4) which is in the south part of the landslide source area. It might be possible that over geologic time, alteration of soil in the spring area could result in an accumulation of clay or of mineral salts which could conceivably weaken the soil in the vicinity. However, this is speculative, as only small amounts of clay were noted in the spring deposits.

Pre-landslide air photos show that the downstream face of the bench-like deposit of deep glacial sediments which failed was steep and gullied. The 1983 terrain mapping shows two field check locations in this vicinity, and it was mapped as part of a terrain class IV polygon, with the gentler bench above being mapped as class III. (Unfortunately the field notes from this mapping have been lost.) Three springs are mapped above the edge of the bench; these may be the same springs that currently exist on the landslide scarp. It is likely that this steep gullied area below the springs has had a history of small failures; however, an unstable area was not noted by the terrain mapping, and the area was covered by mature forest. The failures which formed the gullied area may have occurred in early post-glacial time, and could, in part, have formed the raised Gar Creek fan, or they may have been deposited in the upper Gar Creek valley.

All the available evidence indicates that there has not been a large landslide in the Gar Creek valley since early postglacial time.



1 Lower part of more recent bedrock failure.
2 Upper part of more recent bedrock failure.
3 Very old bedrock failure scarps (as indicated by more subdued topography)
4 Very old bedrock failure scarps (as indicated by more subdued topography)
5 Undifferentiated colluvium - probably includes deposits originating from bedrock failure sources to south and east, talus and debris flow deposits from steep slopes to north, and displaced glacial deposits.
6 Relatively recent, mostly inactive, bedrock failure zone; minor ongoing movement indicated by displacement on road.
7 Relatively inactive part of bedrock failure zone in upper Gar Creek valley.
8 More recently active part of bedrock failure zone in upper Gar Creek valley.
9 Lobes of displaced debris which have moved south across drainage divide into Kootenay Joe Creek watershed.
10 Most recently active headscarp area of bedrock failure zone in upper Gar Creek valley.

Legend

🟩 2012 Landslide source area
------- Dropped block
------- Main scarp
------- Upper crack
—— 2012 Landslide path
—— Definite boundaries
—·—·— Indefinite boundaries
········ Assumed boundaries
⊥⊥⊥⊥ Rock scarp
● Spring

Figure 24: Slope features adjacent and upslope of 2012 Landslide source area

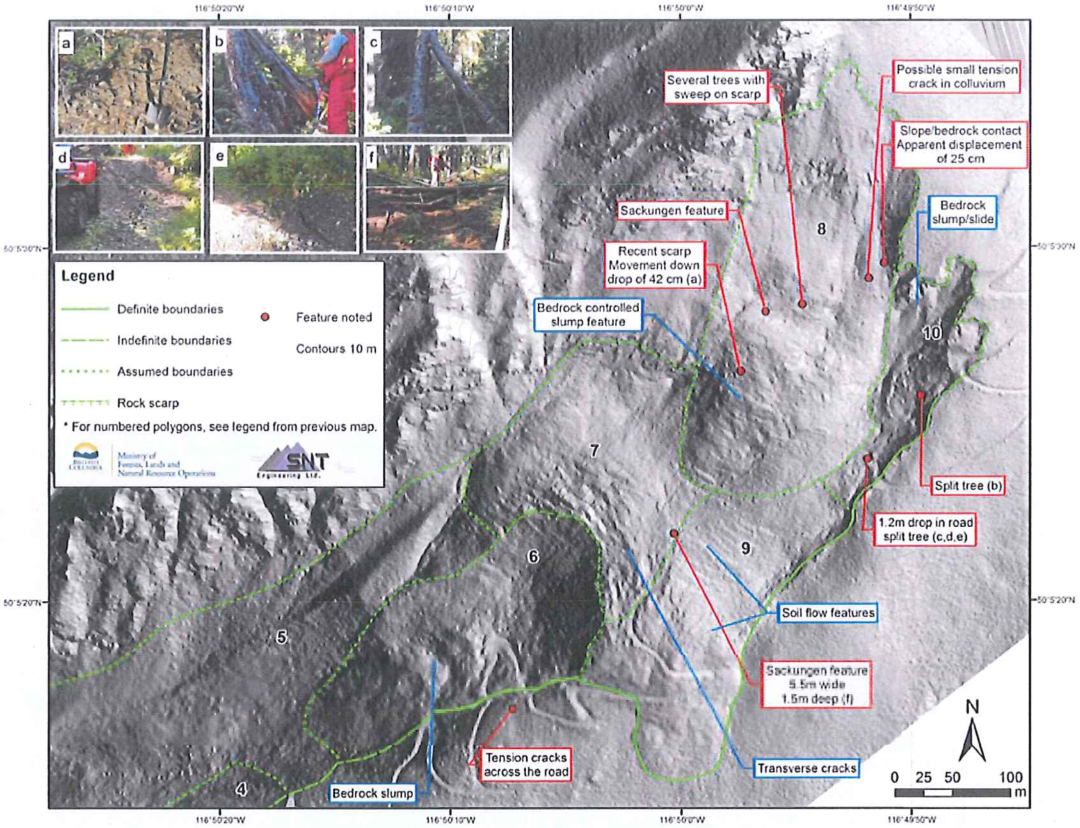


Figure 25: Slope features in upper Gar Creek drainage

11. Potential Future Landslide Magnitude

The absence of large rapid bedrock failures in the past, combined with the lack of bedrock in the 2012 landslide, suggests the likelihood of future large landslides involving bedrock is negligible. It is assumed that any future landslide will involve the potentially unstable volume of glacial and colluvial deposits described above.

The upper crack is located approximately 200 m above the main scarp. The crack is actually a continuous shear plane that extends for several hundred metres with visible displacements of up to 4 m (see Photo 49 and 50 Appendix A and Figure 24 and Figure 25). At one location a seep was observed immediately below the upper crack which contributed to a small debris slide. The water source for the seep is likely from bedrock storage supplied by snowmelt and rainfall within the Gar Creek drainage and perhaps from adjacent drainages as noted earlier.

The surface area bounded by the upper crack and the main scarp 200 m downslope is 6.4 hectares (64,000 m^2). The depth to bedrock is unknown and the average depth of a potential failure surface is uncertain. The shear plane appears to be relatively shallow at the northern portion of the tension crack (1 to 5 m deep) but has the potential to intersect the main scarp at depths of 8 to 12 m. Using the field observations and results of the limit equilibrium analyses with various pore water pressure levels, a range in landslide volumes was developed, and corresponding return periods were assigned by judgement and consensus amongst the four authors of this report (see Table 4 and Figure 26). These return periods (or annual likelihoods of occurrence) are very approximate, and may be revised in the future, if observations in the potential future landslide source area provide information on subsequent ground movement. The probable maximum estimated potential landslide volumes corresponding to the 1:10,000 per year and 1:100,000 per year events are defined by the area bounded by the upper crack and the main scarp.

The estimated landslide magnitude verses annual probability of occurrence is illustrated in Figure 27 utilizing the data from Table 4. Although it is recognized that the relationship is not a continuous function as plotted, Figure 27 nonetheless provides some insight when making regional and provincial comparisons of landslide magnitude/probability relationships.

Table 4: Landslide frequency magnitude estimates

Likelihood of Landslide Occurrence per year	Landslide Magnitude (m^3)	Description
0.02 (1:50)	50,000	Failure of dropped block that moved several meters during 2012 landslide event (see Figure 24). The area is represented in plan view as Case 1a of Figure 23.
0.01 (1:100)	96,000	Failure of dropped block that moved several meters during 2012 landslide event and failure/ retrogression of oversteepened upper scarp see Figure 24. The area is represented in plan view as Case 1a and 1b of Figure 23.
0.001 (1:1000)	288,000	This is the approximate volume represented by failure of the dropped block and retrogression of the upper scarp with an Ru of 0.3. Would require a similar rainfall event and late snowmelt as 2012 (1:100 per year rain event combined with the late snowmelt = 1:500 per year) plus an additional increase in ground water level. Representative of Case 1a, 1b and 2 of Figure 23.
0.0002 (1:5,000)	424,000	Landslide events of between 288,000 m3 and 500,000 m^3. Representative of Cases 1 through 3 of Figure 23. Represents factor of safety of 1.0 for Ru range of 0.3 to 0.5.
0.0001 (1:10,000)	500,000	Representative of Cases 1 through 4 of Figure 23. Represents factor of safety of 1.0 assuming Ru of 0.5 or failure to bedrock with an average landslide thickness of 5-6 m. Failure extends to the upper crack.
0.00001 (1:100,000)	889,000	Representative of Cases 1 through 4 of Figure 23. Represents factor of safety assuming Ru of 0.5 or failure to bedrock with an average landslide thickness of 9 m. Failure extends to the upper crack.

Landslide thicknesses were assumed to average 5 to 6 m (the 2012 landslide averaged 4.3 m thick). A slightly thicker landslide was assumed (compared with the 2012 event) due to the increased thickness of soil deposits at the 2012 landslide main scarp (forming the toe of a potential future slide), while also accounting for a thinning of the soil cover upslope. A thicker (9 m) landslide was assumed for the 1:100,000 per year event. While a landslide greater than 500,000 m^3 is considered unlikely (unlikely defined as 1:10,000 per year as per AGS 2000 and Wise et al 2004) a landslide or debris flow of magnitude less than 25,000 m^3 is considered likely. The distribution of frequent small events and infrequent large events is typical of landslide occurrence distribution as noted in Section 4.

Of consideration in determining the frequency and future landslide activity is the potential for increased ground water levels as a result of climate change and extreme hydrological conditions.

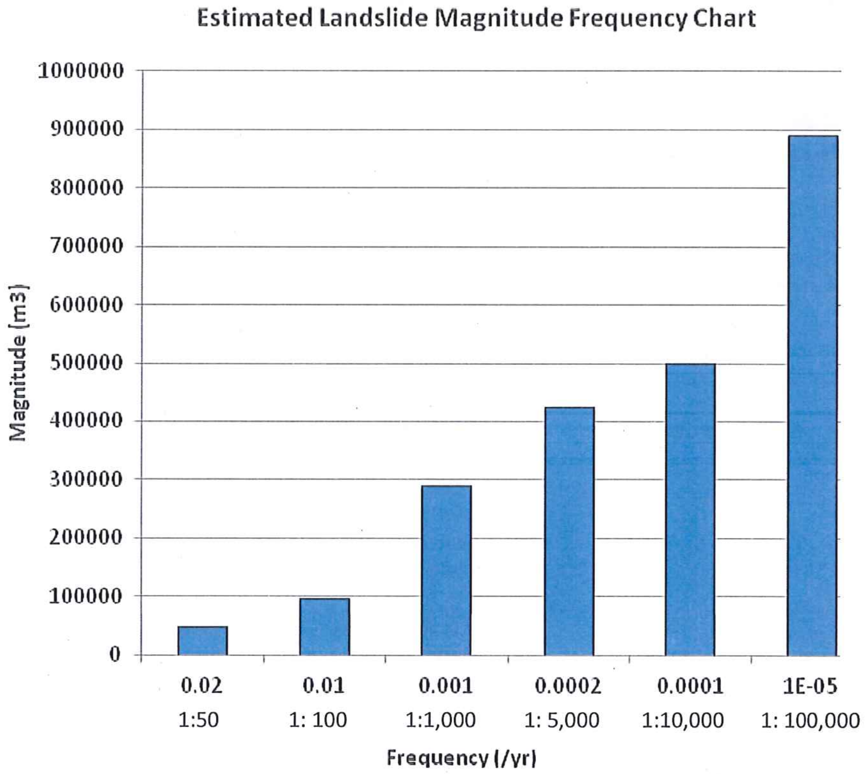


Figure 26: Estimated landslide magnitude frequency chart

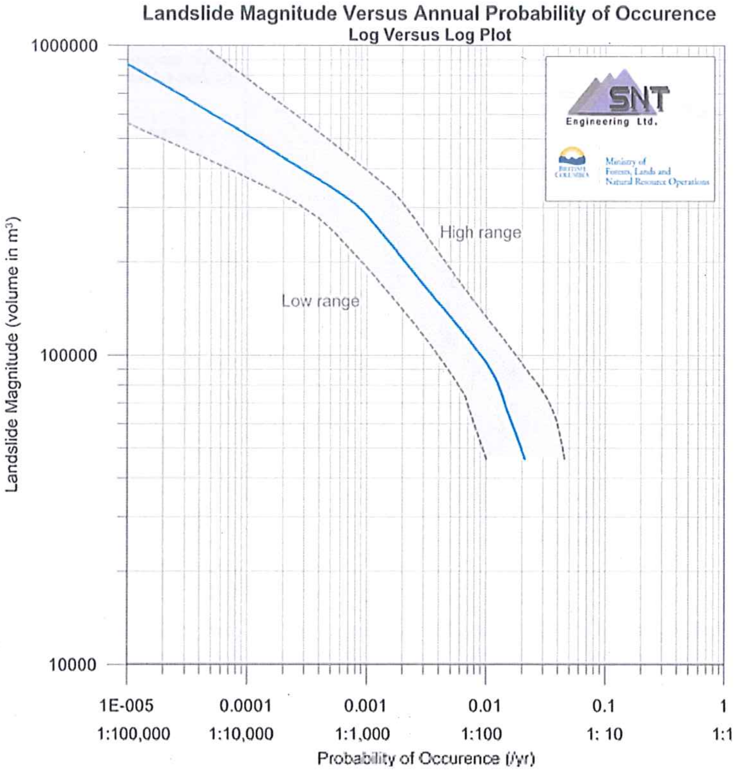


Figure 27: Landslide magnitude versus return period, log versus log plot

12. Landslide Run-out Assessment

12.1 Empirical Comparisons

The landslide run-out distance was compared with other recorded large landslides. The run-out distance, L, is defined as the horizontal distance between the crown of the landslide source and the toe of the deposit. It can also be calculated from the height of the slope, H, divided by the tangent of the angle between the deposit elevation and source elevation, called "reach angle". The reach angle can be estimated empirically as a function of the volume of the landslide, from a correlation developed by Corominas (1996) for debris flows and debris avalanche events (see Figure 28 and Appendix F).

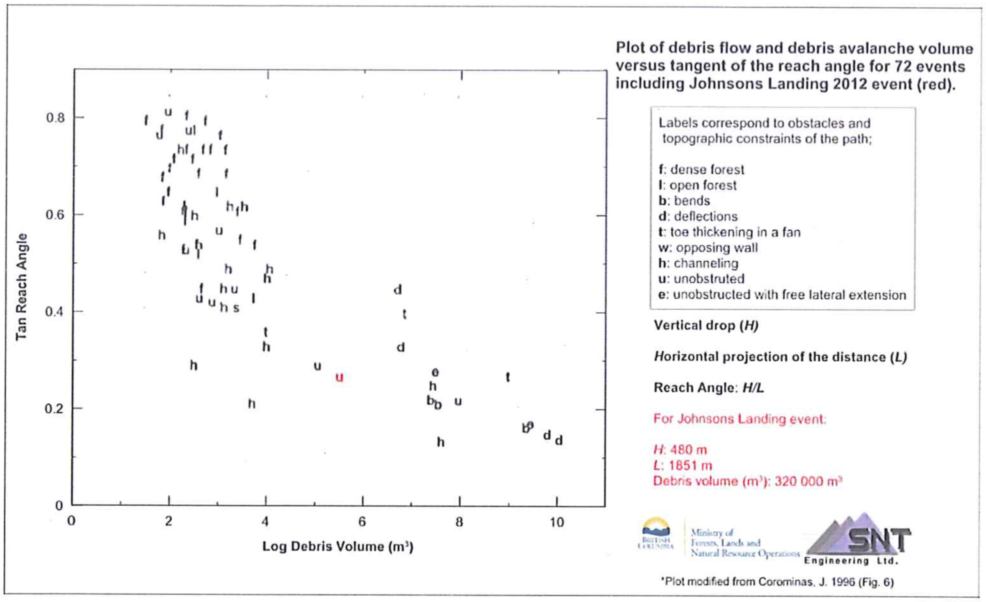


Figure 28: Plot of Debris flow and debris avalanche volume versus tangent of the reach angle for 72 events including Johnsons Landing 2012 event (modified from Corominas 1996)

The July 12th event falls in the middle of data collected for 72 debris flow and debris avalanche events and 101 "unobstructed" landslides. Additional correlations are shown in Appendix F.

In summary the mobility of the 2012 landslide is found to be similar to other large unobstructed debris avalanches.

12.2 Modelling

Two landslide run-out models were utilized, which were developed by Prof. Oldrich Hungr and graduate students at the University of British Columbia (Hungr 1995; McDougall and Hungr 2004): DAN-W and DAN-3D. Landslide modelling was conducted at UBC by Jordan Aaron and Giacomo Marinelli to estimate the potential run-out distances and deposit thickness for select magnitude events as discussed in Section 11. The inputs to the model include basal shear resistance parameters that can only be determined through empirical means. To determine these parameters a back analysis of the landslide event was undertaken. This back analysis provided the calibrated parameters used for the forward analysis. Both DAN-W and DAN-3D were used in order to exploit the strengths and weaknesses of both models. DAN-W was able to simulate the July 12th, 2012 debris avalanche with minimal assumptions. This, combined with the fact that DAN-W provides fast results that are comparable to DAN-3D (Hungr & McDougall, 2009), allowed for DAN-W to be effectively used for the forward analysis as well as for comparison to the DAN-3D analysis. The drawback in using DAN-W is that it is a two-dimensional model and cannot produce a three-dimensional deposit shape.

It was noted that DAN-3D had difficulties in reproducing the extreme overtopping of the channel at the 70° bend of Gar Creek. This is likely due to a combination of two factors. It is hypothesized that a channel obstruction composed of timber at the flow front developed during the debris avalanche. This obstruction would contribute to the volume that deposited in the debris field. Additionally, DAN-3D explicitly neglects lateral shear strength, and it is likely that significant lateral shear stresses developed when the flow reached the 70° bend. With the inclusion of a channel obstruction it was possible to achieve reasonable results using DAN-3D; however both the volume and geometry of this obstruction are assumed parameters. The DAN-W back analysis determined that there are two sets of parameters that are able to reproduce the bulk characteristics of the July 12th landslide. One set of parameters uses only one rheology to model the channel and debris field, an approach consistent with past analyses undertaken with DAN-W. The other set of parameters uses two flow rheologies, one to simulate the channel and another to simulate the debris field where basal resistance was expected to be higher due to the fact that it is heavily forested. Both sets of parameters were able to reproduce the run-out, duration, velocities and debris field volume observed during the event. The only significant characteristic that these analyses were unable to predict was the location of the upper channel deposit. This was not seen to invalidate the model as the location of the simulated upper channel deposit does not affect the volume that deposits in the debris field or the simulated run-out. The back analyzed simulated landslide deposit depths, velocities, and maximum flow depths from DAN-W are shown in Figures 29, 30, 31.

Based on this back analysis a forward analysis was conducted with DAN-W for both sets of parameters. The forward analysis evaluated the run-out and overtopping volume for potential landslide magnitudes. The forward analysis determined that the two rheology set of parameters provided more conservative results. It was found that landslides of 50,000 m^3 (1:50 per year event) and 100,000 m^3 (1:100 per year event) were confined to the Gar Creek channel (did not flow onto the Johnsons Landing bench) while landslides of volume 200,000m^3 to 400,000m^3 travelled to a location near the end of the Johnsons Landing bench. Landslides greater than 400,000m^3 (1:5,000 per year event) travelled all the way to the beach and Kootenay Lake. DAN-W run-out distances for various landslide magnitudes are shown on Figure 32.

The back analysis conducted using DAN-3D determined that only a two-rheology set of parameters could reasonably reproduce the bulk landslide characteristics of the July 12th, 2012, event. This back analysis did not predict that any material would deposit in the upper channel, however; the back analyzed volume deposited on the Johnsons Landing bench was relatively close to that determined in the site investigation. The duration, velocities and 3-D debris deposit shape of the event were well predicted. Figure 33 shows the DAN-3D back analyzed deposit shape and Figure 34 shows the back analysed landslide velocities.

The forward analysis conducted using DAN-3D produced similar conclusions to that of DAN-W. Results of the DAN-3D analyses assuming there is no channel blockage resulted in significantly more debris traveling to the Gar Creek fan.

12.2.1 Berm Influence

The construction of a berm placed on top of the channel bank at the 70° bend could result in less landslide material travelling onto the Johnsons Landing bench, with a shorter travel distance. Berm heights of 5 m and 10 m above the height present after the 2012 landslides were added to the models to determine their influence on landslide run-out distance. The DAN-W analyses determined that for the 200,000 m^3 (1:500 per year event), 300,000 m^3 (1:1,000 per year event), and 400,000 m^3 (1:5,000 per year event) events the height of the berm appreciably reduced the overtopping volume. In the case of the 200,000 m^3 (1:500 per year) event the berm height reduced the run-out distances on the Johnsons Landing bench. A 5 m berm limited the 200,000 m^3 (1:500 per year) event run-out to the area covered by the 2012 landslide deposit. A 10 m berm contains the 200,000 m^3 (1:500 per year) event to the Gar Creek channel. The run-out distance on the Johnsons Landing bench of the two larger events (800,000 m^3 and 1,500,000 m^3) were not significantly affected by the height of the berm. DAN-3D analyses indicated a greater sensitivity of berm height and run-out distance for the 400,000 m^3 (1:5,000 per year event). With a 10 m berm the 400,000 m^3 (1:5,000 per year) event did not reach the two lower houses on the Johnsons Landing bench.

See Figure 35 for DAN-3D predicted landslide run-out location for a 400,000 m^3 (1:5,000 year) event. Complete details of the run-out modelling are included in Appendix F.

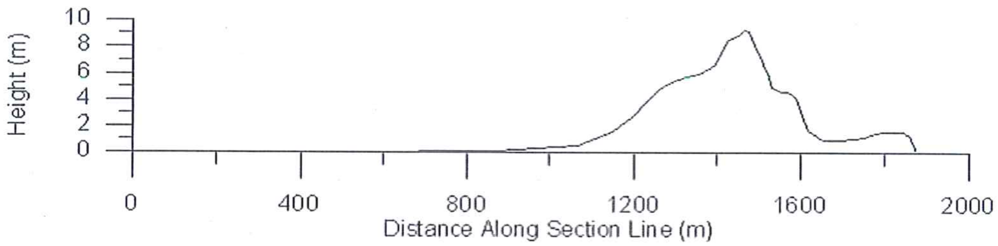


Figure 29: DAN-W (2D) back analyses of predicted run-out distances and deposit thickness

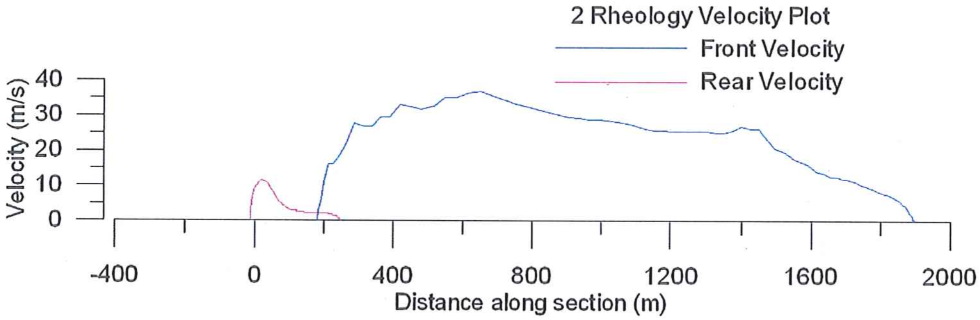


Figure 30: DAN-W (2D) back analyses of predicted landslide velocity

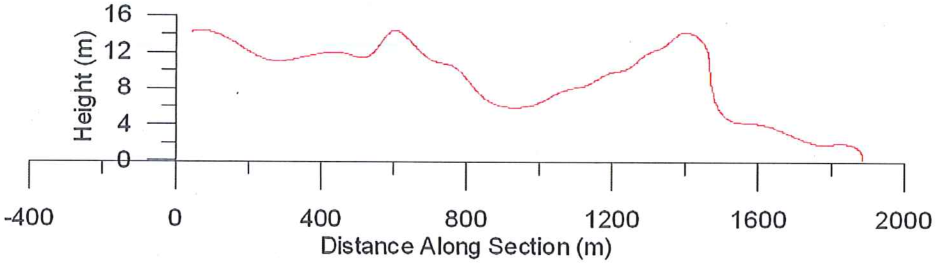


Figure 31: DAN-W (2D) back analyses of predicted maximum flow depth (2 rheology cases)

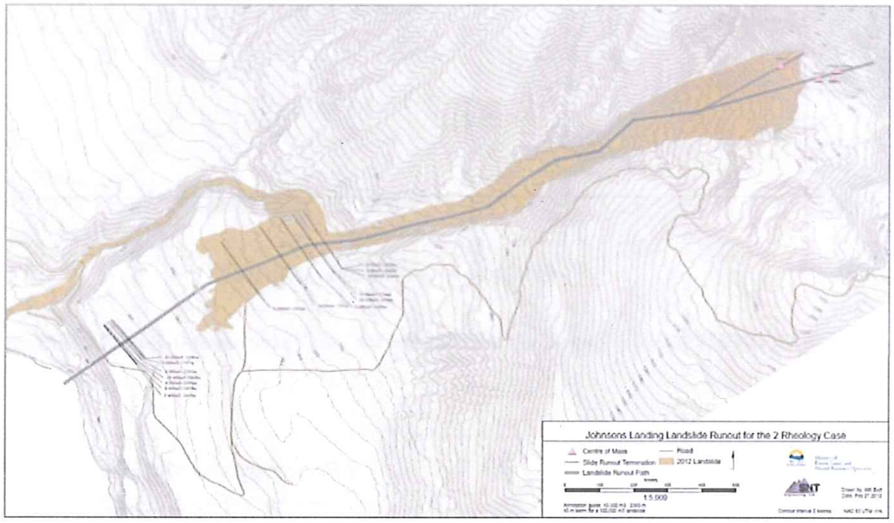


Figure 32: DAN-W run-out for the 2 Rheology Case

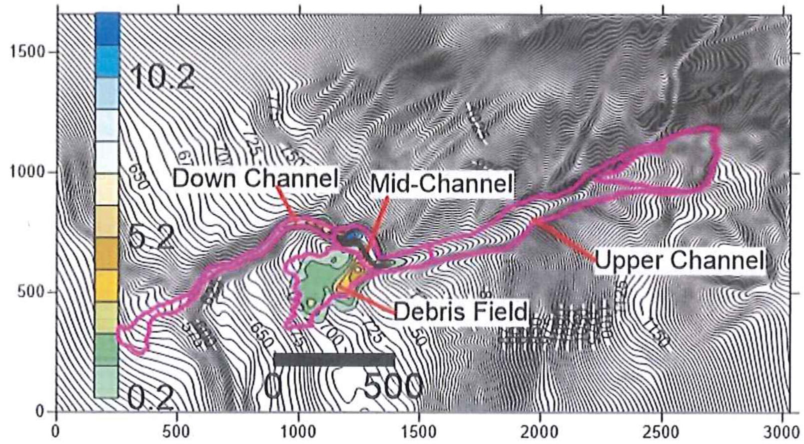


Figure 33: DAN 3D back analysis with estimated deposit thickness.

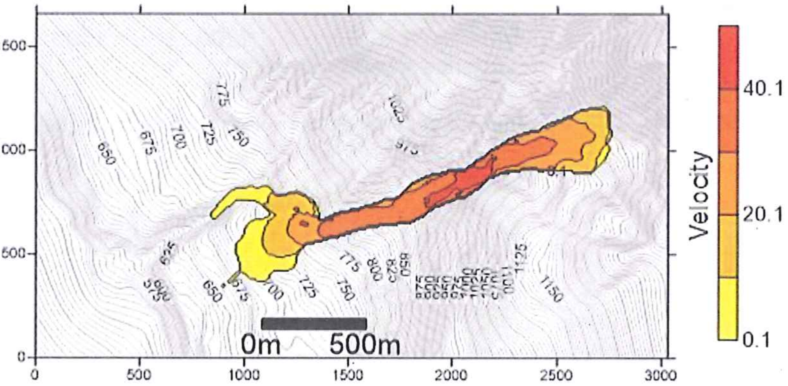


Figure 34: DAN 3D back analysis with estimated landslide velocities

12.3 Landslide Run-out Conclusions

The 2012 landslide event was back analysed using DAN-W (a two-dimensional model) and DAN-3D. Both models were able to reasonably reproduce the deposit shape. An assumption had to be made of a channel obstruction (which may have been caused by the trees incorporated into the landslide mass) in order for DAN-3D to reasonably match the deposit shape.

The modelling indicates that as the landslide volume approaches 200,000 m^3 (1:500 per year) the landslide run-out extends to a location near the downslope end of the Johnsons Landing bench. As the volume exceeds 400,000 m^3 (1:5,000 per year) more landslide volume travels over the edge of the Johnsons Landing bench to the lake. A future landslide of similar magnitude as the 2012 landslide will travel much further than the 2012 landslide due to the lack of trees in the channel and on the Johnsons Landing bench resulting in lower basal friction, and because the model assumed a 4 m channel to stream height differential that was present after the 2012 landslide compared with 9 m present before the landslide.

The volume of landslide material that flows onto the Johnsons Landing bench and the landslide travel distance down the Johnsons Landing bench are both affected by a potential channel obstruction. The likelihood of another channel obstruction is less than during the 2012 event due to fact that there will be fewer trees incorporated into a landslide (at least for the next several hundred years).

The volume of landslide material that flows onto the Johnsons Landing bench and landslide travel distance could be reduced by the construction of a berm at the location of the 70° bend in the Gar Creek.

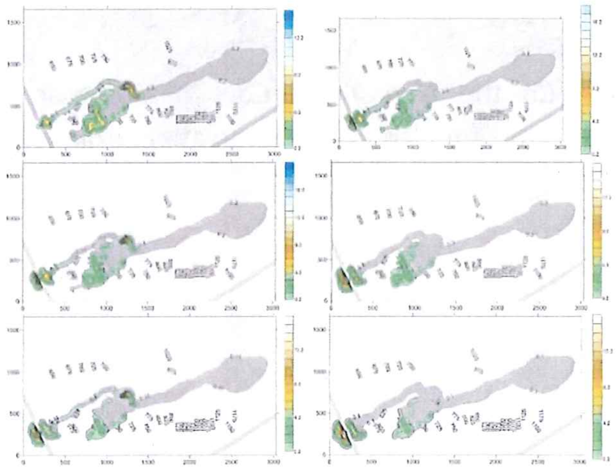


Figure 35: Modelled deposits in the left column with channel obstruction and in the right column with no channel obstruction. The top row has no berm, the middle row has a 5 m berm and the bottom row has a 10 m berm. The source volume for all events was 400,000m^3

Of note is the fact that although a berm reduces the volume and run-out onto and below the Johnsons Landing bench it also results in increased volume of debris transported to the Gar Creek fan.

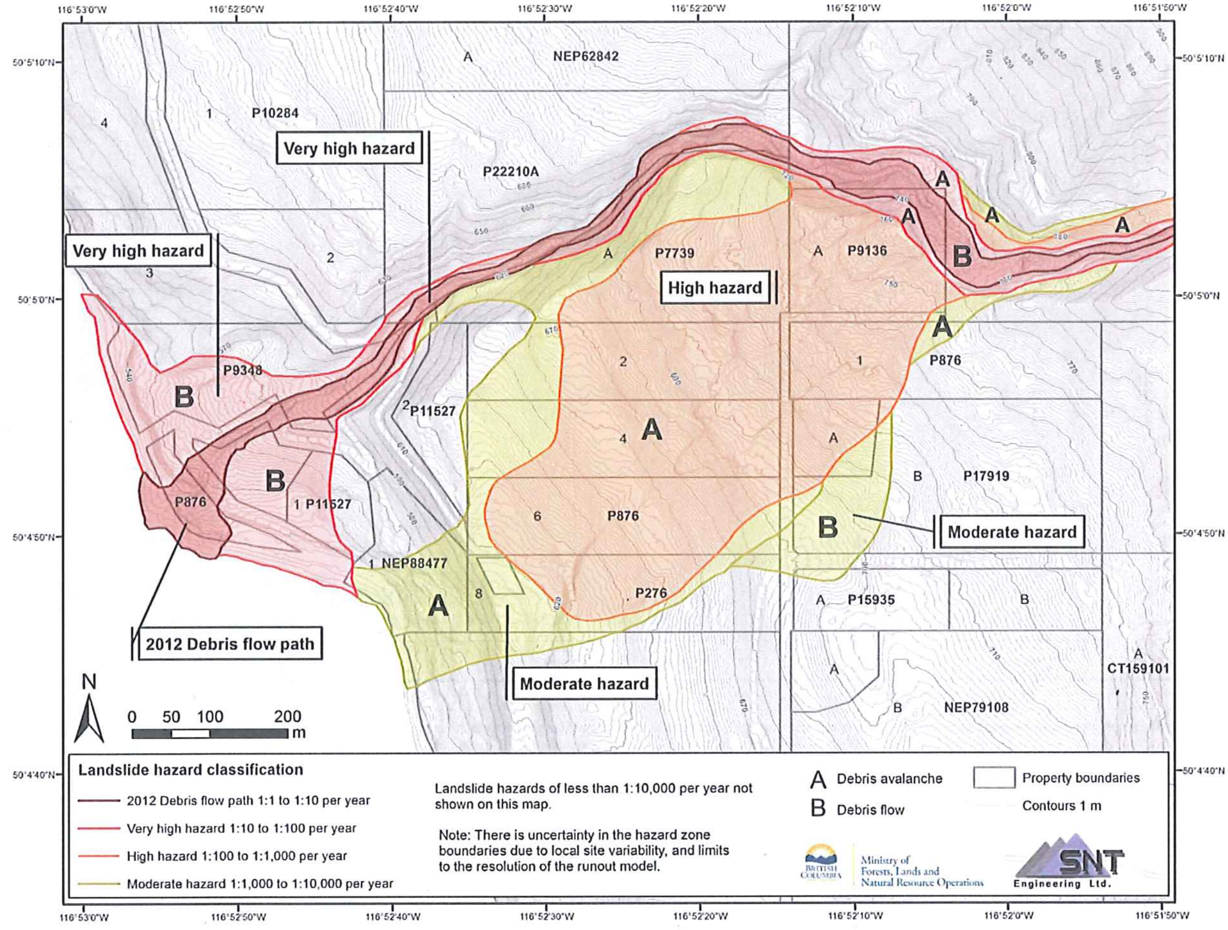
13. Landslide Hazard Areas

13.1 Johnsons Landing Bench Hazard

Appendix F contains landslide run-out maps for select magnitude landslides and berm heights arrived through the DAN-W and DAN-3D modelling. For landslides up to 200,000 m^3 (1:500 per year) the debris deposits upslope of the 2012 landslide toe. For landslide volumes in the order of 300,000 m^3 (1:1,000 per year) to 400,0000 m^3 (1:5,000 per year) the end of the deposition zone extends to the lower Johnsons Landing bench area with some spillage over the steep slope at the end of the bench. For larger slides more landslide debris travels to the beach and lake (see Figure 35). Appendix F contains detailed information of the run-out model, velocities, and deposition depths.

The run-out modelling and landslide magnitude frequency (from Section 11) were utilized to develop a landslide hazard run-out map as shown in Figure 36. The hazard map assumes no berm is constructed at the 70° bend in the Gar Creek channel; however, it does assume that there is a height difference from the channel bottom to the top of channel bank of at least 4 m (similar to the natural height difference present after the July landslide events). The map divides the Johnsons Landing bench and Gar Creek fan into zones of moderate, high and very high hazard pertaining to the likelihood of a landslide flowing onto the area described as shown in the Figure 36 legend.

There are significant uncertainties inherent with the landslide run-out hazard map. It represents the authors' consensus utilizing the results of the analyses, observation, experience and significant judgement.


116°53'0"W
116°52'50"W
116°52'40"W
116°52'30"W
116°52'20"W
116°52'10"W
116°52'0"W
116°51'50"W
50°5'10"N
50°5'0"N
50°4'50"N
50°4'40"N
NEP62842
P10284
P22210A
Very high hazard
Very high hazard
P7739
P9136
High hazard
P9348
P11527
1 P11527
P876
P876
P876
P17919
Moderate hazard
Moderate hazard
1 NEP88477
P276
P15935
CT159101
NEP79108
2012 Debris flow path
A
B
N
0 50 100 200 m
Landslide hazard classification
2012 Debris flow path 1:1 to 1:10 per year
Very high hazard 1:10 to 1:100 per year
High hazard 1:100 to 1:1,000 per year
Moderate hazard 1:1,000 to 1:10,000 per year
Landslide hazards of less than 1:10,000 per year not shown on this map.
Note: There is uncertainty in the hazard zone boundaries due to local site variability, and limits to the resolution of the runout model.
A Debris avalanche
B Debris flow
Property boundaries
Contours 1 m
British Columbia
Ministry of Forests, Lands and Natural Resource Operations
SNT Engineering Ltd.

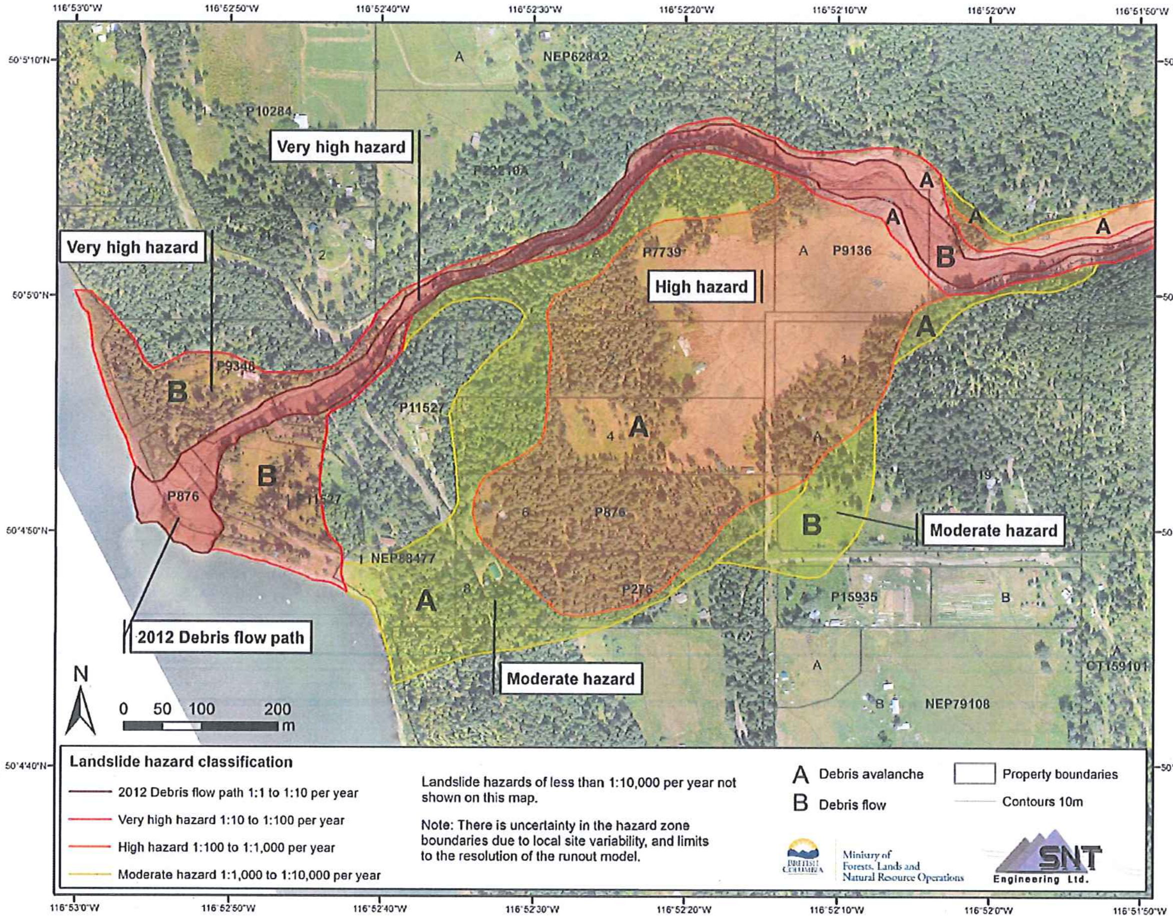


Figure 36: Johnsons Landing landslide hazard zoning maps

13.2 Fan Hazard

The landslide resulted in significant changes to the Gar Creek channel. It left several over steepened, unstable side slopes and loose deposits and disturbed areas in and near the channel leaving an abundance of soil available for entrainment in future debris flow events. Consequently, there is a high likelihood of more debris flows in subsequent years until disturbed areas and channels stabilize or another major event occurs (debris flow) that results in channel infilling. Of particular concern is the area near the 70° bend at elevation 750 m. It is highly probable these smaller debris flows will infill the channel at or above this area priming the channel for a large event to entrain this material and continue down to the fan with larger volumes and destructive power similar to or larger than the July 13th event. The likelihood of debris flow occurrence is estimated at 1:10 per year until the channel stabilizes.

The 2012 debris flow events resulted in the deposition of approximately 17,000 m^3 on the fan areas. This corresponds to a channel yield rate of approximately 9 m^3/m of linear channel, or areal yield of 4,000 m^3 per km^2 drainage area. These values compare well with other local debris flow events the authors are familiar with. There are several requirements for the initiation and transport of debris flows including sufficient sediment supply and water supply. At Gar Creek there is sufficient sediment supply; however, the maximum debris flow magnitude is likely limited by water supply (as discussed earlier due to dampened response). The combination of near saturated ground conditions, landslide debris in the channel at the 750 m elevation that was mobilized during the July 13th debris flow, and high creek flows indicates that the 17,000 m^3 is a near maximum future debris flow magnitude (without a corresponding large landslide which could further increase the volume of material directed to the fan).

The entire lower and upper fan area as outlined in Figure 36 (also see Appendix B, Map 8) is rated as a Very High Hazard.

14. Landslide Prediction

At this time it is not possible to predict if or when another landslide will occur. However there are times, during adverse climatic conditions and high ground water levels, when the likelihood of another landslide will increase and there may be indicators or signs leading up to another landslide event such as:

- Significant or record snowpack combined with rapid snowmelt;
- Delayed snowmelt season and or high SWE;

- Significant or record rainfall during the months of May or June;
- Very high stream flows (above average freshet levels);
- Small movements of any of the blocks at or above the 2012 landslide head scarp;
- Abnormal water and turbidity surges in Gar Creek; and
- Wildfire events.

Small movements of the landslide may be noticeable above the main scarp, upper scarp, and upper cracks or at the landslide toe (release of debris into Gar Creek). The release of debris can cause high turbidity and erosion within the channel that can be observed downstream (as occurred in the days leading up to the 2012 event).

A more in-depth discussion on possible monitoring strategies is presented in Section 16.

15. Landslide Risk Analysis and Evaluation

15.1 Risk Analysis

Risk is defined as the measure of the probability and severity (or consequence) of an adverse effect to health, property or the environment or other things of value (CSA 1997). Risk is often estimated by the product of probability of a phenomenon of a given magnitude times the consequences. Several risk analyses were conducted. Some considered varying occupancy rates of the community hall and public beach while others considered only house occupancy.

Generally the risk analyses conducted considered three simplified outcomes as follows:

1) The occurrence of a 1:10,000 per year landslide. Part of this landslide would travel onto the Johnsons Landing bench and down to the beach while part of landslide (debris flow component) would cross the Argenta-Johnsons Landing Road at the Gar Creek crossing and impact the beach area at the fan. The landslide would potentially impact 3 houses, the Community Hall, Houston Road, the public beach, and the Argenta-Johnsons Landing road at the Gar Creek crossing (debris flow component).

2) The occurrence of a 1:1,000 per year landslide. Part of this landslide would travel onto the Johnsons Landing bench while part of the landslide (debris flow component) would cross the Argenta-Johnsons Landing Road at the Gar Creek crossing and would impact the beach area near the fan. The landslide would potentially impact 2 houses on the

Johnsons Landing bench, the Community Hall, Houston Road, the public beach, and the Argenta-Johnsons Landing road at the Gar Creek crossing (debris flow component).

3) The occurrence of a 1:10 per year landslide/debris flow. This landslide would remain confined in the Gar Creek channel with no deposit onto the Johnsons Landing bench. A debris flow would travel to the Gar Creek fan and would potentially impact the public beach and the Argenta-Johnsons Landing road at the Gar Creek crossing.

The values at risk considered in the risk analyses are shown on Figure 37.

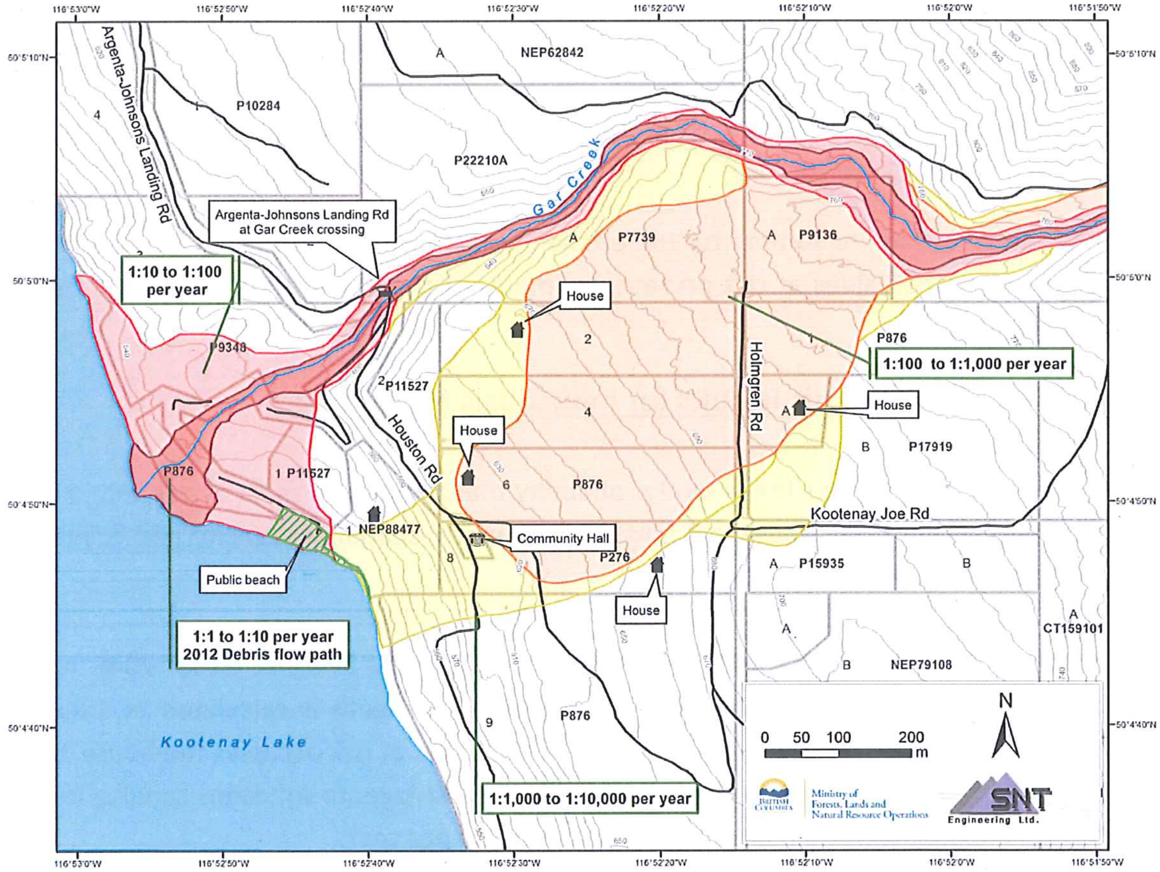


Figure 37: Values at risk

Risk analyses were conducted utilizing relative mobility indexes for various landslide events to account for some uncertainty in landslide run-out locations. Risk analyses also considered a simplified summary of the potential values present as follows:

1) Two residences on the Johnsons Landing bench that are exposed to the 1:1,000 per year event and the 1:10,000 year event (this does not include the houses damaged by the

July 12th 2012 landslide which are assumed to remain unoccupied and the house on the Gar Creek fan).

2) One additional residence exposed to the 1:10,000 per year event.
3) Community Hall exposed to the 1:10,000 per year event. Time of exposure considered for separate group sizes of 5, 10 and 20 people and for an average group size of ten people.
4) Houston Road use of 50 passes per day
5) Users of the public beach are exposed to the 1:10 per year event (debris flow) and the 1:10,000 per year event (landslide over Johnsons Landing bench). Time of exposure was considered for various group sizes.
6) Argenta-Johnsons Landing Road at the Gar Creek crossing. The travelling public is exposed to the 1:10 per year event (debris flow). It was assumed that there are 50 vehicle passes per day and it takes 18 seconds to travel through the Gar Creek crossing at velocity of 21 km/hr.

Fault trees were utilized to summarize the possible outcomes for the various landslide run-out scenarios and for the values at risk present. Examples of the risk analyses and fault trees are included in Appendix I.

15.1.1 Risk Analysis Results for Individuals Most at Risk

For life loss, risk is defined as the annual probability that the person most at risk will lose their life taking into account the landslide hazard, the temporal-spatial probability and vulnerability of the person (Fell 2008).

The results of the risk analyses indicate that for an individual living at either 2046 Argenta-Johnsons Landing Road or 2223 Houston Road the risk of death is calculated at 1.6×10^{-3} or 1:625 per year. This conservatively assumes the person most at risk occupies the house 100% of the time. For an individual living in the lower house at 2230 Argenta-Johnsons Landing Road the risk of death is calculated at 3.3×10^{-4} per year or 1:3,300 per year.

An individual travelling the Argenta-Johnsons Landing Road over Gar Creek on a daily basis (two passes per day) the risk of death is calculated at 1.8×10^{-5} per year or 1:54,000 per year. For an individual travelling Houston Road two passes per day, the risk of death is calculated at 5×10^{-7} per year or 1:2,000,000 per year. For an individual using the beach for an average of 104 hours per year the risk of death is calculated at 2.4×10^{-5} per year or 1:42,000 per year and for an individual using the community hall for 120 hours per year the risk of death is calculated at 4.2×10^{-6} per year or 1:240,000 per year.

15.1.2 Individual Risk Evaluation

Over the last several decades there has been a greater desire to define and quantify acceptable, tolerable, and unacceptable risk. In Berger (1973), Justice Thomas Berger upheld a decision of an Approving Officer which rejected a proposed subdivision for which there was a likelihood of a major landslide of likelihood 1:10,000 per year on the basis of the public interest provisions of the Land Registry Act. Justice Berger ruled that for a major landslide affecting a multi-family residential development, the likelihood of occurrence should be less than 1:10,000 per year. The MOT during the 1980s and 1990s asked professionals who performed geotechnical reviews of residential subdivisions to consider the likelihood of landslide events capable of producing damage as acceptable only if their probability of occurrence was less than 10% in 50 years (i.e. 1:475 per year). In 1992 the Fraser Valley Regional District published levels of landslide safety (Cave 1992) that recommended for major catastrophic landslides the hazard to a new proposed house should be lower than 1:1,000 per year (with conditions) and the hazard to a new subdivision should be less than a 1:10,000 per year.

In November of 2009 the District of North Vancouver adopted an ALARP (As Low As Reasonably Practicable) risk tolerance criteria for Probability of Death of an Individual (PDI) of 1:10,000 per year for redevelopments involving an increase to gross floor area on the property of less than or equal to 25% and 1:100,000 per year PDI for new developments and redevelopment involving an increase to gross floor area on the property of greater than 25%. This followed several risk analyses completed by BGC Engineering (2006 to 2009) as follow up to a fatality causing North Vancouver landslide in 2005. The Australian Geomechanics Society (2000) guidelines suggest a tolerable PDI of 1:10,000 per year for individuals most at risk in existing buildings and 1:100,000 per year for new developments. ALARP examples have been published whereby the typical ALARP range extends from 1:1,000 to 1:100,000 per year PDI (Fell et al 2005).

In 2009 MoTI developed a Subdivision Preliminary Layout Review and Natural Hazard Risk document that indicated for life-threatening or catastrophic events the Qualified Professional is to consider events having a probability of occurrence greater than 1:10,000 per year as unacceptable.

Apart from the above examples, risk acceptance criteria for landslides in British Columbia have not been formally defined for use by professionals, resource managers, or approving officers.

Some principles for risk acceptability evaluation criteria are (Leroi et al. 2005):

- the incremental risk from a hazard to an individual should not be significant compared to other risks to which a person is exposed in everyday life;

- the incremental risk from a hazard should be reduced wherever reasonably practicable, i.e. the As Low As Reasonably Practicable (ALARP) principle should apply;

- higher risks are likely to be tolerated for existing slopes and developments than for planned projects and modified slopes; and,

- tolerable risks may vary from country to country, and within countries, depending on historic exposure to landslide hazard, and the system of ownership and control of slopes and natural landslide hazards.

Risk analysis differentiates between the risk to an individual most at risk and societal risk or risk to any person or group of people.

For comparison of risks to which people are exposed, in 2008/2009 the estimated mortality rate in Canada (as a whole) was 1:137 per year (Statistics Canada 2010). A Canadian's annual risk of death from motor vehicle accidents is 1:11,000 or 1:122 million per vehicle kilometre (WHO 2009). In the United States the annual risk of death from traffic accidents has been dropping from 1:4,500 in 1980 to 1:7,500 in 2007 (US National Safety Council 2008).

Risk zoning descriptors for annual probability of death of the person most at risk as recommended by Fell et al (2008) are as shown in the Table 5. Using these risk zoning descriptors the houses at 2046 Argenta-Johnsons Landing Road and 2223 Houston Road are within a risk zone considered Very High. The lower house at 2230 Argenta-Johnsons Landing Road is within a risk zone defined as High. It is assumed that the houses damaged by the 2012 landslide and the house on the Gar Creek fan are not re-occupied (i.e. houses at 2254 Holmgren Road, 2051 Argenta-Johnsons Landing Road and upper buildings of 2230 Holmgren Road). It is also assumed that the houses destroyed by the 2012 landslide are not rebuilt at their previous locations.

Table 5: Risk zone descriptor (from Fell et al 2008)

Annual probability of death of the person most at risk in the zone	Risk Zone descriptor
$>10^{-3}$/annum	Very High
10^{-4} to 10^{-3}/annum	High
10^{-5} to 10^{-4}/annum	Moderate
10^{-6} to 10^{-5}/annum	Low
10^{-6}	Very Low

The landslide run-out hazard map (Figure 36) was adopted for presentation purposes rather than an individual risk zone map (as per Table 5) to convey the landslide impact areas without inherent assumptions about occupancy and vulnerability that a risk map considers. A landslide run-out hazard map is also more useful when considering new development applications.

15.1.3 Societal Risk

Societal Risk is the risk to society as a whole. The calculation of societal risk considers the potential for multiple fatalities as a result of a single or multiple landslide events. Societal risk can be represented by plotting the frequency (F) of the occurrence of a number (N) or more fatalities per year versus the number (N) of fatalities (referred to as an F/N plot or F/N curve). Three examples of F/N plots for the Johnsons Landing area are shown in Figure 38, Figure 39, and Figure 40. Figure 38 considers events that impact the houses, Community Hall, the travelling public and public beach users (with or without an impact to a house) while Figure 39 only considers events that impact houses. Figure 40 considers events impacting the house in the moderate hazard zone, community hall, road users and beach (i.e. the two houses exposed to the 1:1,000 per year event removed). Details of the fault trees and individual and cumulative frequencies are contained in Appendix I.

15.1.4 Societal Risk Evaluation

There is no clear consensus on criteria for societal risk evaluation. One criteria in use is plotted on Figures 38 to 40 which uses a framework recommended in Hong Kong (1998). Societal probable loss of life criterion is superimposed on an F-N plot where F is the frequency of N or more potential fatalities per year. The figure identifies three risk zones; broadly unacceptable risk, broadly acceptable risk and a middle ALARP zone defined as As Low As Reasonably Practicable. The ALARP zone is often interpreted as a zone where the risk may be tolerable (not acceptable) as long as all reasonable efforts have been made to reduce the risk. Because of the difficulties in applying and assessing societal risk it is recommended that a qualitative approach be used in combination with an F/N plot and typical criteria.

For the Johnsons Landing area an individual occasionally occupying the Johnsons Landing Community Hall is exposed to a relatively low risk (PDI less than 1:100,000 per year). However the societal risk of a larger group exposure plots above the broadly acceptable criteria as shown on Figures 38 to 40. The societal risk is also above the broadly acceptable criteria when considering the combined population of exposed residents, which is to be expected considering the results of the individual risk analysis.

While an individual user of the Argenta-Johnsons Landing Road, Houston Road and the Beach is exposed to relatively low risks (less than 1:10,000 per year) the societal risk plots in the broadly unacceptable range due to the number of different vehicles and individuals traveling the road and using the beach.

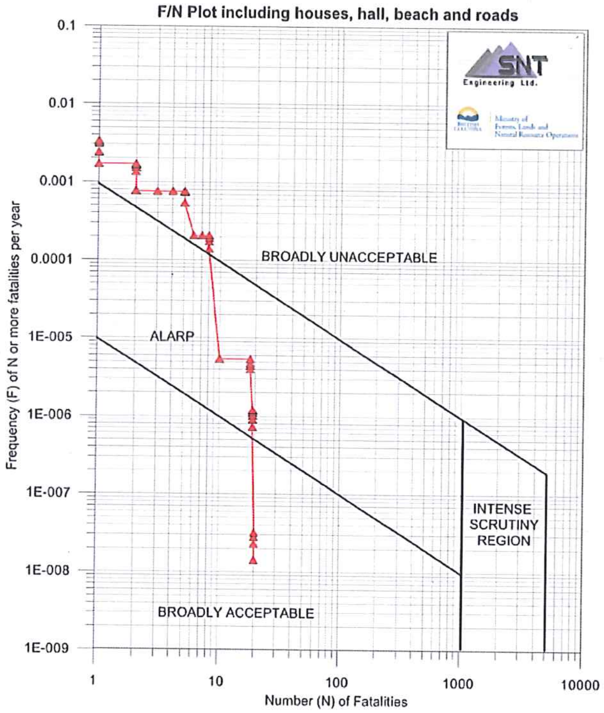


Figure 38: F/N plot considering houses, community hall, road users and beach users (criteria modified from Hong Kong Government Planning Department (1994), Morgan (1991) and Fell (1997))

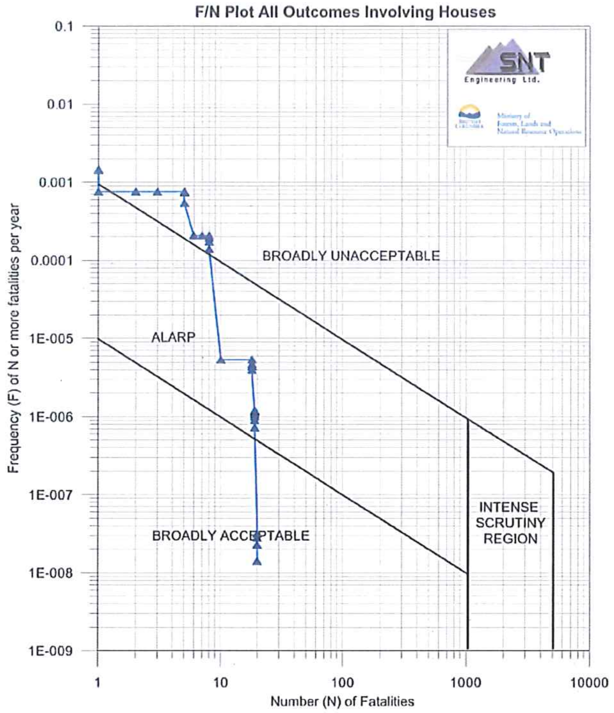


Figure 39: F/N plot considering only events affecting houses (criteria modified from Hong Kong Government Planning Department, 1994, Morgan, 1991 and Fell, 1997))

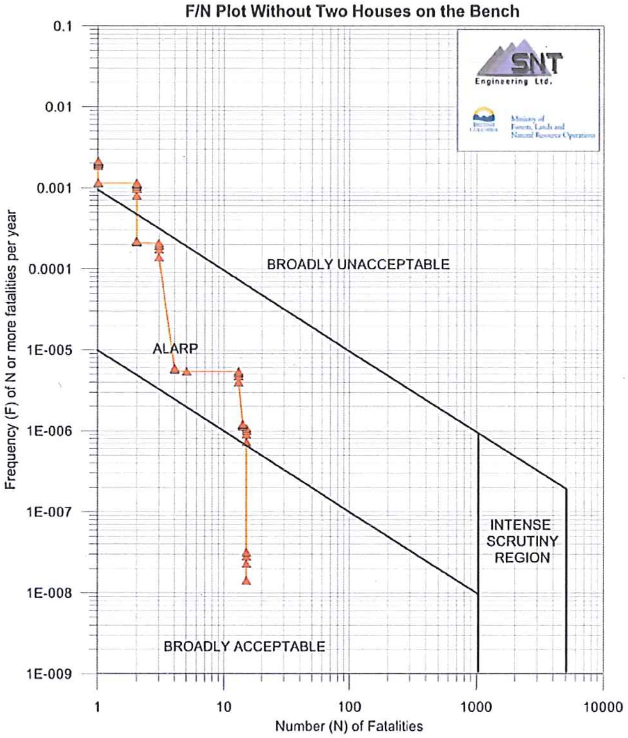


Figure 40: F/N Plot considering house in moderate hazard zone, community hall, road users and beach (criteria modified from Hong Kong Government Planning Department (1994), Morgan (1991) and Fell (1997))

15.2 Risk Results Discussion

The quantitative risk analysis indicates the risk to some individuals living on the Johnsons Landing bench is unacceptable (higher than typical published acceptability criteria). The individual risk by property is discussed above. As previously noted, it is assumed that the houses damaged by the 2012 landslide and the house on the Gar Creek fan are not re-occupied (i.e. houses at 2254 Holmgren Road, 2051 Argenta-Johnsons Landing Road and upper buildings of 2230 Holmgren Road). It is also assumed that the houses destroyed by the 2012 landslide are not rebuilt at their previous locations. Decisions to not re-occupy the above noted house are consistent with the determination of individual risk levels determined to be very high.

The risk to individuals using the Argenta-Johnsons Landing Road, Houston Road and the Public Beach is in the range considered acceptable/tolerable by some jurisdictions.

Some of the properties noted above have areas of low hazard whereby a house could be re-established. Each property will require a site specific summary and review in conjunction with the landowner to determine if an alternative site location is suitable.

A hazard map is shown in Appendix B, Map 8 and shows the cadastral information and hazard zoning classification.

16. Landslide Hazard Mitigation

16.1 Passive Options

Passive hazard mitigation can include modifications to land use and/or landslide movement monitoring that could provide early warning of landslide movement. There are several types of slope monitoring devices. Monitoring is broadly divided into surface monitoring and subsurface monitoring. Monitoring that has been used at other local landslides include the following:

a) Survey of reference targets placed at selected locations to measure horizontal and vertical movement of unstable terrain. At Johnsons Landing, prisms could be placed on the dropped block and upper scarp and measured from the 70° bend in Gar Creek (750 m elevation); however, this would require monitoring distances in the order of 1800 m which reduces accuracy. Alternatively the site could be monitored from the upper look-out location with monitoring distances ranging from 200 m to 500 m. The disadvantage of monitoring from the upper look-out is the time required to travel the Kootenay Joe FSR and hike the small ridge to the look-out location.

b) Slope Inclinometers typically installed within boreholes drilled into the unstable soil, through the failure plane and into stable ground provide information on depth of movement and movement rate. Standard inclinometers need to be read on site, so that each reading requires personnel access. Permanent inclinometers, or accelerometer arrays, can be read remotely, but are expensive and would require maintenance. All inclinometers are destroyed once movement on the shear surface displaces laterally several centimetres through the inclinometer casing.

c) Surface wire extensometers measure extension of wires stretched across the slope surface in the landslide source area. Surface extensometers can be fairly simple and the data can be relayed remotely. However, these instrumentations are prone to damage and false warnings.

Landslide warning systems have not been widely used in Canada, except in connection with mines and dams. The devices could provide advance warning in the range of days or hours. However, this would require remote (radio) transmission of the signals, full time surveillance of the system by qualified personnel and extremely efficient means of warning and evacuation of the residents. It is considered unlikely that such a system can be practically established at this site. Therefore, a complex warning system consisting of slope inclinometers or similar instrumentation is not recommended for Johnsons Landing.

A simple slope surface displacement monitoring system (comprised of surface monitoring pins and perhaps some extensometers) would allow for a better understanding of longer term movements and landslide behaviour but would not likely form an integral part of an early warning system.

Providing landslide hazard information to and training of residents will reduce risks, though the effects are difficult to quantify. The residents should be informed about the ongoing hazard and made aware of the influence of high rainfall and snowmelt rates, changes in the Gar Creek stream flows and turbidity levels. Field training of what to look for and observe in terms of slope movements should be considered. Additionally, clear contact lines should be provided for residents to report their observations or concerns. The hazard areas should be posted on the ground by signs. Land-use planning and regulation should be used to control the type of development within the area shown on Figure 36 (Appendix B Map 8). The RDCK and MoTI can restrict land development within the area identified as moderate and high hazard by requesting an assessment, compatible with the Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC (APEGBC, 2010), before any further development occurs.

During the week leading up to the 2012 landslide there were many indicators of extremely high creek flows and slope instability. A future landslide may have similar early warning indicators as the 2012 event. Such indicators could be used to guide personal choices such as beach and road use during high hazard periods. By adjusting to and responding to potential early warning indicators it is possible to reduce the level of risk for users of the roads, beach, and community hall.

16.2 Active Options, Johnsons Landing Bench Area

Active landslide mitigation can include the stabilization of a landslide or the construction of barriers, catch basins, or deflectors to physically protect an area or value.

The stabilization of the slopes above the 2012 main scarp is not considered practicable.

After the 2012 landslide the Gar Creek channel bank at the 70° bend was temporarily increased by 1 m to 4 m to help protect people working on the landslide deposit from a post- event debris flow. At the time the bank was increased in height it was acknowledged that the measure was temporary and subject to further review to determine its effectiveness and longevity.

The landslide run-out modelling indicates the raised channel bank is not required for events smaller than 100,000 m^3 (1:100 per year event); however, the modelling assumes a minimum long term channel bank height of 4 m. A 10 m high berm could reduce the run-out of a 200,000 m^3 (1:500 per year) event, but would not be sufficient to contain a 300,000 m^3 (1:1,000 per year) event. The 3D analyses indicated the run-out distance of a 400,000 m^3 (1:5,000 per year) could be reduced with a 5 m and 10 m high berm; however, more material is deflected towards the Gar Creek fan. Based on the investigation completed, it would appear prudent not to rely on a berm for risk reduction of permanent residences. This conclusion may be modified with more detailed engineering analysis, which could possibly lead to the design of a more robust (higher) defence structure, albeit likely at considerable cost. It is considered prudent to maintain a minimum height differential of 5 m between the creek bottom and top of channel in the 70° bend to reduce the potential for debris flows, creek flows, and landslide debris to travel onto the Johnsons Landing bench.

Ultimately, a determination of the value of a berm (in reducing the run-out distance and volume of material deposited on the Johnsons Landing bench) will depend on land use decisions both on the Johnsons Landing bench and on the fan, in addition to who would be responsible for berm design, maintenance, and construction.

16.3 Active Options, Gar Creek Fan

Physical works can be constructed to reduce debris flow hazards on alluvial/debris flow fans. Types of structures include:

- Impact barriers constructed in the channel or gully upstream of the apex of the fan area
- Debris catchment basins
- Debris flow deflection berms constructed on the fan

To reduce the frequency and/or magnitude of a debris flow that can impact residents on the fan, users of the beach, or users of the Argenta-Johnsons Landing Road at the Gar Creek crossing, a debris flow catch basin could be considered at approximately the 730 m or 740 m elevation within the channel. A 25 m high berm constructed at the 730 m elevation would create a basin having a storage capacity of 107,000 m^3 while 20 m and 15 m high berms would create basins having approximate storage capacities of 60,000 m^3 and 24,000 m^3 respectively (see Figure 41 and 42). Ten metre high and 15 m high berms constructed with a base at the 740 m elevation would create basins having approximate storage capacities of 13,000 m^3 and 33,000 m^3 respectively. This storage volume compares with 17,000 m^3 thought to have passed through this location during the July 12th and July 13th debris flow events. However, the volume of debris diverted towards the fan in 2012 was likely substantially reduced by the presence of a log dam near elevation 740 m. Future events may not contain comparable amounts of timber debris and may flow to the fan. An example of such a structure is shown in Photo 53. During and after a debris flow, the structure would block debris flow material from travelling further downstream while allowing creek flows to continue downstream (either upper straining device, upper culvert or spillway). When works are constructed to protect private properties any structure or combination of structures built require the establishment of an ongoing maintenance plan to inspect the works and excavate materials accumulated usually requiring the establishment of a Local Services Area by the local government. An approval under the Dike Maintenance Act is also required.

A detailed cost benefit analysis has not been undertaken but it is well known that these structures are costly to construct and have high annual maintenance costs. A debris flow barrier/basin capable of protecting the Gar Creek fan area would likely involve capital costs in excess of one million dollars, plus maintenance cost. A deflecting dike system would probably be comparably expensive. The additional risk reduction to road and beach users may support the construction of a small barrier or basin that could withstand a small debris flow in the 5,000 m^3 to 10,000 m^3 volume range; however, a more detailed cost estimate and cost/benefit review would be required. Small barriers could also be located adjacent to the Gar Creek channel on the fan.

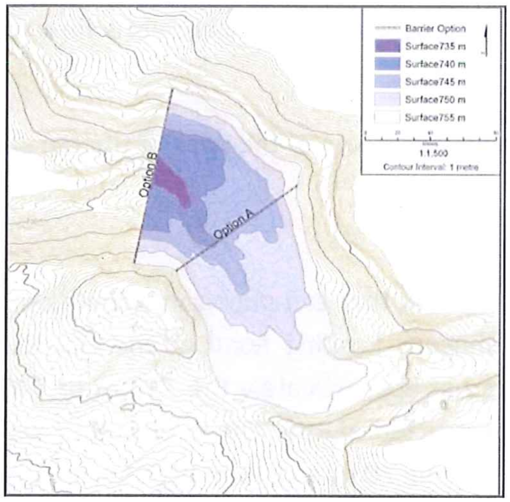


Figure 41: Channel berm construction option A and B

Figure 42: Storage capacity

17. Snow Avalanche Assessment and Risk Analysis

Several large snow avalanches have been documented in the Gar Creek drainage over the last half century. Of particular note is an avalanche that occurred in 2003 and one that occurred in 2012 that damaged the community water intake. All of these documented avalanche events deposited snow and debris near the 70° bend in Gar Creek. Some run up of snow occurred on the outside stream channel bank; however, there has been no evidence of snow avalanches flowing onto the Johnsons Landing bench. With the changes in the post landslide channel and removal of trees within the channel and on the Johnsons Landing bench a review of the snow avalanche hazard was undertaken to assess the likely limits of snow avalanche run-out in relation to house locations and properties.

The snow avalanche assessment was conducted by Dynamic Avalanche Consulting Ltd. and the full report is included in Appendix K.

Two avalanche hazard scenarios were considered:

- A temporary bank height increase constructed at the 70° bend in the Gar Creek gully at 750 m; and
- The post 2012 landslide geometry without the temporary increase in channel bank height at the 70° bend in the Gar Creek gully.

The high risk Red Zone in Scenario 1 is located within the Gar Creek channel. This area overlays portions of Lot L9663 and P9136. In Scenario 2, the Red Zone includes portions of Lot L9663, P9136, and Block 1 P876.

The moderate risk Blue Zone in Scenario 1 is located on the landslide debris fan at an elevation of 735 m to 760 m. The Blue Zone is the area where avalanche impact loads are greater than 1 kPa with a return period in the range of 30 to 300 years. This area overlays parts of Lots P9136 and P876. Avalanches may reach outside of the Blue Zone, but are expected to have impact pressures of less than 1 kPa or have impact pressures greater than 1 kPa with a return period of greater than 300 years. In Scenario 2 the Blue Zone is located further downslope and includes parts of Lots P9136 and Block 1 P876.

Figure 43 and Figure 44 show the results of the avalanche assessment in terms of the run-out of the Red Zone and Blue Zone. The Red Zone is a high risk area where construction of permanently occupied structures is not permitted according to the Guidelines for Snow Avalanche Risk Determination and Mapping (CAA 2002). The Blue Zone is a moderate risk area where construction of permanently occupied structures is normally not permitted according to the Guidelines for Snow Avalanche Risk Determination and Mapping (CAA 2002).

While the landslide hazard and risk extends beyond the snow avalanche run-out area and therefore controls potential areas for development the landslide hazard exposure window is typically in the spring during or after snow melt. During the winter months the snow avalanche hazard is greater in those areas shown on the map (Red and Blue zones).

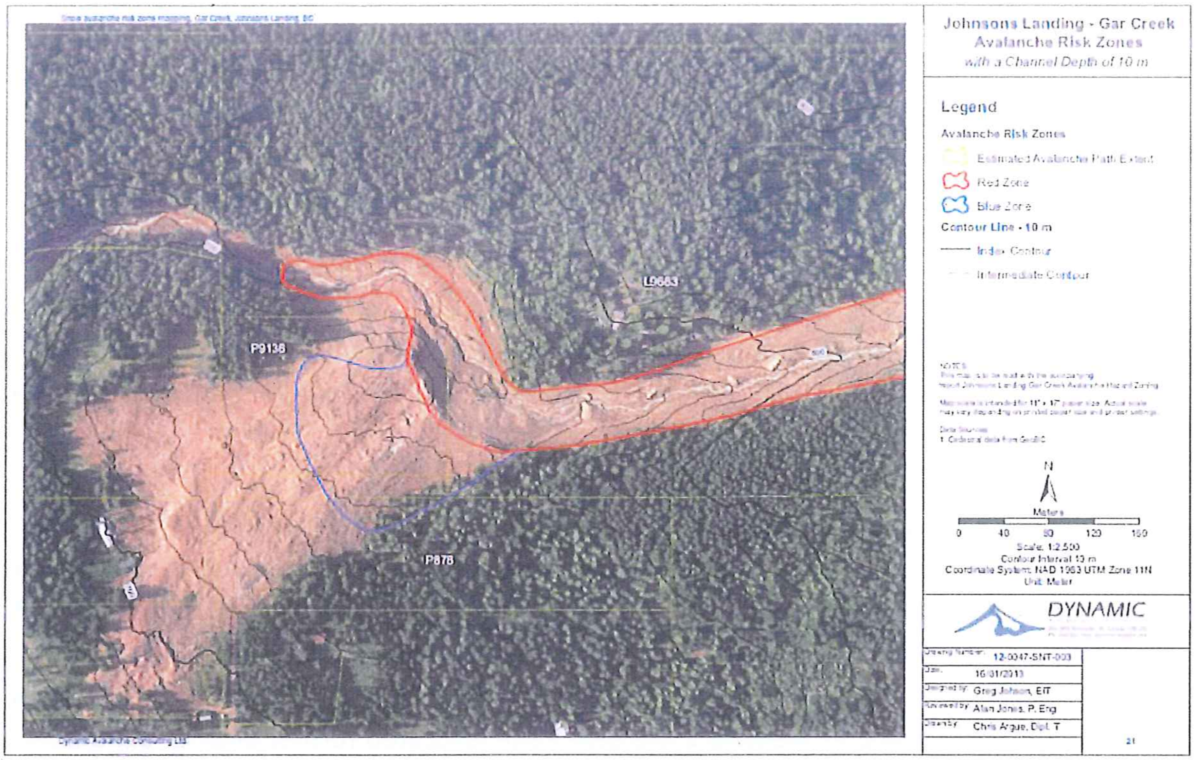


Figure 43: Avalanche risk zones with a channel depth of 10 m (from Dynamic Avalanche Consulting Ltd's report, Appendix K)

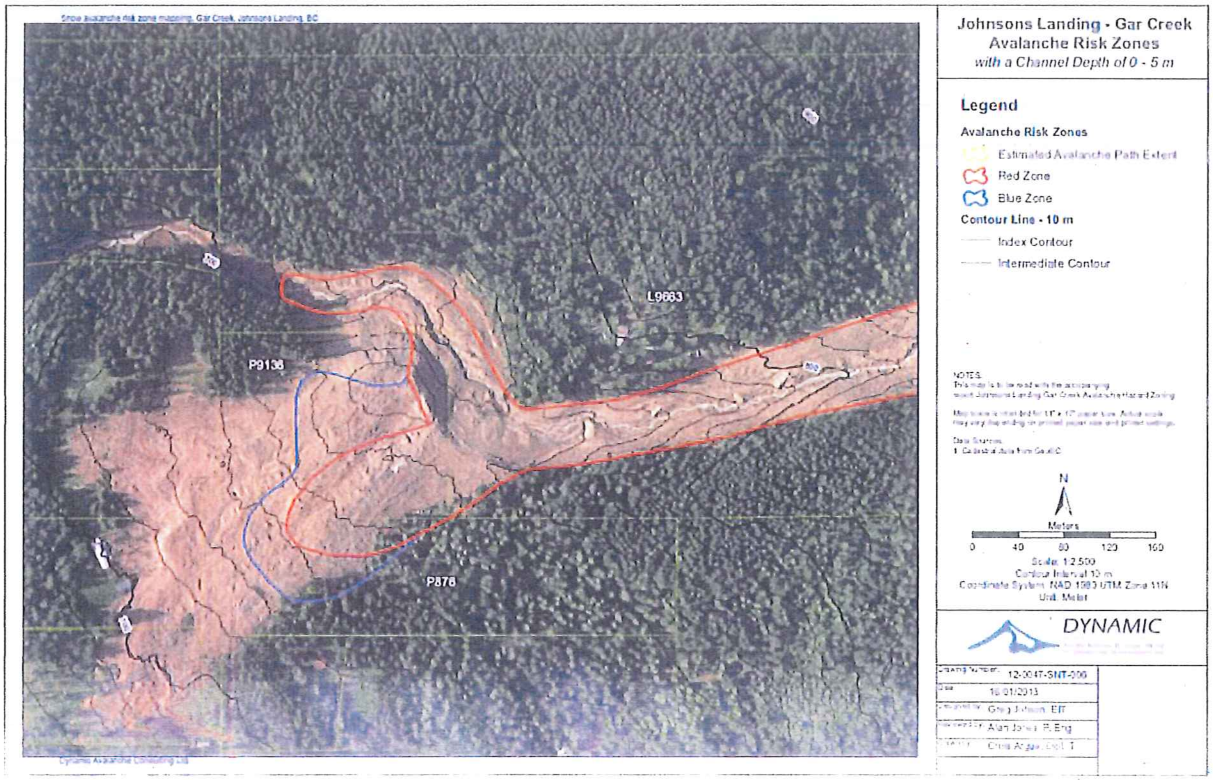


Figure 44: Avalanche risk zones with a channel depth of 0-5 m (from Dynamic Avalanche Consulting Ltd's report, Appendix K)

18. Forestry Development, Wildfires, and Climate Change

Forestry development can lead to increased snowpack accumulations and increase runoff and groundwater levels during freshet. Eliminating forestry development or limiting it to low-impact silvicultural systems, within the Gar Creek drainage will reduce these potential effects.

The potential for wildfires to occur within the Gar Creek drainage could also impact snow accumulation and runoff conditions. Wildfires can increase potential landslide initiation both in the short term (several years) and long term (several decades). The short term effects have been demonstrated locally at the Springer Creek fire (52 km to the southwest) with the occurrence of several debris slides, debris flows, and debris floods (see Nicol et al 2007 and 2009, and Jordan 2012) which resulted in a fatality and at Kuskonook (75 km to the south) where a debris flow in 2004 impacted several houses.

The short-term effects of wildfire can include increased overland flow as a result of forest floor loss and possible creation of water-repellent soil. The long-term effects include an increase in snowmelt generated peak flows due to the loss of forest cover. Short term wildfire effects in Gar Creek drainage are not expected to have a significant influence on the large scale instabilities, since they typically affect only runoff from short duration rainfall. However, an increase in surface water runoff could have an effect on the initiation of small scale landslides and debris flows. The long term effects on snow accumulation could have an effect on subsurface ground water levels thereby potentially influencing the larger scale instabilities if the primary source of groundwater is from the lower elevation tree covered areas. However, as noted earlier, a substantial amount of groundwater may originate from subalpine and alpine areas.

The potential influence of wildfires has been considered in the assessment of the return period landslide magnitude relationship in the assignment of R_u values. If a wildfire were to occur in the Gar Creek drainage a post wildfire risk analyses could be conducted (MFLNRO) to identify any elevated slope hazards caused by the effects of the wildfire.

The effects of climate change are much more difficult to incorporate into a landslide model as it is difficult to estimate the frequency and magnitude of unusual climatological events. Climate change projections for Castlegar have been made (Moore et al 2010) which indicate that the mean annual temperature will increase by 2.1°C by 2050 and 3.9°C by 2080 and the mean annual precipitation will rise by about 5% with even higher increased precipitation occurring during the winter months and lower precipitation (drier) during the summer months. In general there are three ways climate change can affect the landslide assessment:

- Firstly, the frequency of extreme precipitation events can increase which results in an increase in the probability of the anticipated landslide magnitude resulting in a higher hazard.

- Secondly, the magnitude of the extreme runoff events can increase potentially increasing the landslide magnitude and thus increasing the run-out area.

- Thirdly, warmer temperatures increase evapotranspiration, reducing groundwater levels and therefore reducing the hazard.

Data are not available to quantify the effects of any of these outcomes and thus a conservative approach may be warranted when considering the landslide frequency and risk.

The authors of 'Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC (2012) identified the following consequences of climate change on runoff and flood flows in the Kootenays:

- Spring floods associated with seasonal snowmelt may become more severe because of more rapid snowmelt, or when a major warm weather storm occurs over a rapidly melting snowpack. Possible increases in the order 10% in extreme spring flood flows are envisaged.
- Increased likelihood of severe summer convectional showers inducing extreme floods in small to medium drainage basins.
- Increased probability of forest fires due to more intense droughts and more pest-afflicted forests will lead to higher runoff and increase probability of debris floods and debris flows

19. History of Land Development, Land Use, and Regulatory Processes

The 1939 air photos indicate a well-established agricultural based development on the Johnsons Landing bench and by 1945 there was significant development on the Gar Creek fan. RDCK records indicate the original house at the upper Johnsons Landing bench area (Freshe property) was constructed in 1931. A search of the land titles indicates that the most recent subdivision of property on the upper Johnsons Landing bench area occurred in 1988 with the consolidation of two lots to create the lot at 2240 Kootenay Joe Road and the creation of the smaller lot at 2223 Houston Road. Ministry of Environment (MOE[5]) files indicate that a technician visited the site in response to a referral from MOT for the subdivision application to assess the flood hazards. At that time MOE staff were involved in a subdivision referral process whereby staff commented on flooding hazards associated with new subdivisions. MOE staff did not assess properties for landslide hazards except for channelized debris flows. The technician made a comment on file that there was no flood hazard affecting the property and that Gar Creek was contained in a deep valley to the north of the property.

Although terrain mapping by Kutenai Nature Investigation Ltd (1983) did not indicate the Gar Creek fan was subject to debris flows, the fan was first identified as a potential debris flow fan in a report entitled "Terrain Stability Inventory Alluvial and Debris Torrent Fans Kootenay Region" (Klohn Crippen 1998). This inventory of hazard areas was funded by the Forest Renewal BC Program to inform the forest industry of downslope consequences areas that should be considered while preparing Forest Development Plans. In 1995, Jordan published Reconnaissance Terrain Stability Mapping which depicted the Gar Creek channel above the fan as "a gully or channel likely to experience debris flows".

The Klohn Crippen report georeferenced the apex of fans studied but did not delineate the fan boundaries. This proved cumbersome for the RDCK building inspectors and MOT Subdivision Approval Officers. Consequently, in 2001, the RDCK, with assistance from MOE, retained Carol Wallace Consulting (2001) to delineate fan polygons using air photographs. In 2004, MOE in conjunction with the Fraser Basin Council published Flood Hazard Maps and made them available to local governments and provincial agencies responsible for land use decisions. See http://www.env.gov.bc.ca/wsd/public_safety/flood/fhm-2012/landuse_documents.html. These maps and the information contained in them provide a summary of the flood and debris flow hazards documented in the MOE regional offices up until 2003. A large number of the alluvial and debris flow fans in the Kootenay Region appear as polygons in this map series.

In 2009, the RDCK included the alluvial and debris flow polygons in their floodplain bylaw. The areas, including the Gar Creek fan, were identified as Non-Standard Flood and Erosion Polygon areas in Schedule "C" of the RDCK's 2009 Floodplain Management Bylaw No 2080. This bylaw requires basic floodplain setbacks and increased elevations from the creek and lake but also requires a person wanting to build a house in a Non-Standard Flood and Erosion Polygon to retain the services of a Qualified Professional (QP) to assess the landslide and flood hazard. The maps were also made available to the MOT Provincial Approving Officer and the MOE lands officers who also may require a QP hazard assessment report prior to approving a subdivision

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[5] BC government ministry names change. For simplicity, the following historical names are used: Ministry of Environment (MOE), Ministry of Forests (MOF), and Ministry of Transportation (MOT)

or the sale or lease of crown lands in these areas. In these instances the QP must assess the hazard and in their report state whether or not the land is safe for its intended use.

20. Implications of Local Residential Development and Land Use Planning

Landslide susceptibility zoning involves the classification, area, or volume (magnitude) and spatial distribution of existing and potential landslides in the study area (Fell et al 2008). Landslide hazard zoning takes the outcomes of landslide susceptibility mapping and assigns an estimated frequency to the potential landslides. Landslide risk zoning takes the outcomes of hazard mapping, and assesses the potential damage to persons, property and environmental features for the elements at risk accounting for temporal and spatial probability and vulnerability (Fell et al 2008).

Where zoning is by life loss risk and a study has been done at an intermediate or advanced level (as per this study), it should be possible to delineate land use zones where (a) life loss risk is so low no development controls are necessary; (b) where site-specific assessment of the life loss risk is required prior to approval of development; and (c) where the life loss risk is so high that no development is possible (Fell et al 2008).

In this study, areas have been identified (Figure 36) where the landslide hazard is high or very high and is generally considered to be too high for most residential use. Any further residential development in these above areas should be discouraged. No new building permits should be issued or new subdivisions approved without the support of a comprehensive geotechnical landslide hazard assessment. Such an assessment would consider both the macro and micro topography, any updated landslide and slope monitoring information, and any other new information that supports the development. In areas of high and very high hazard such a study and mitigative works are likely to be cost prohibitive.

In British Columbia, there are several provincial statues that govern residential development. MoTI has historically been the agency responsible for land subdivision approvals (in rural areas) while local governments have been responsible for local zoning and approving and issuing building permits. Section 86 of The Land Title Act allows an application for subdivision to be refused if the Approving officer considers that the land is subject or could reasonably be expected to be subject to landslides.

Specifically Section 86 (1)(c)(v) reads:

> *Without limiting section 85 (3), in considering an application for subdivision approval, the approving officer may... (c) refuse to approve the subdivision plan, if the approving officer considers that ...(v) the land is subject, or could reasonably be expected to be subject, to flooding, erosion, land slip or avalanche.*

Similar wording is also found in the Strata Property Act, Bare Land Strata Regulations 75/78 Section 3(1)e(vi) and (2).

The Local Government Act allows local government to establish a Development Permit Area to protect the development from hazardous conditions Sections 919.1 and 920 as shown below:

> *919.1 (1) An official community plan may designate development permit areas for one or more of the following purposes:*
> *(b) protection of development from hazardous conditions;*
> *(2) With respect to areas designated under subsection (1), the official community plan must*
> *(a) describe the special conditions or objectives that justify the designation, and*
> *(b) specify guidelines respecting the manner by which the special conditions or objectives will be addressed.*
> *(3) As an exception to subsection (2) (b), the guidelines referred to in that subsection may be specified by zoning bylaw but, in this case, the designation is not effective until the zoning bylaw has been adopted.*
> *(4) If an official community plan designates areas under subsection (1), the plan or a zoning bylaw may, with respect to those areas, specify conditions under which a development permit under section 920 (1) would not be required.*
>
> *920(5) If the land was designated under section 919.1 (1) (b), the conditions and requirements referred to in subsection (7.1) of this section may vary that use or density, but only as they relate to health, safety or protection of property from damage.*
>
> *920 (7.1) For land designated under section 919.1 (1) (b), a development permit may do one or more of the following a) specify areas of land that may be subject to flooding, mud flows, torrents of debris, erosion, land slip, rock falls, subsidence, tsunami, avalanche or wildfire, or to another hazard if this other hazard is specified under section 919.1 (1) (b), as areas that must remain free of development, except in accordance with any conditions contained in the permit.*
>
> *920(11) Before issuing a development permit under this section, a local government may require the applicant to provide, at the applicant's expense, a report, certified by a professional engineer with experience relevant to the applicable matter, to assist the local government in determining what conditions or requirements under subsection (7.1) it will impose in the permit.*

The Community Charter (Section 56) can allow local government to refuse a building permit if a building inspector considers that construction would be on land that is likely to be subject to debris flows, land slips, avalanches. The building inspector may require a certified report by a

Professional Engineer or Geoscientist stating that the land may be used safely for the use intended. Section 56 is attached below:

> *56 (1) For the purposes of this section:*
> *"construction" means*
> *(a) the new construction of a building or other structure, or*
> *(b) the structural alteration of or addition to an existing building or other structure,*
> *but does not include the repair of an existing building or other structure;*
> *"qualified professional" means*
> *(a) a professional engineer, or*
> *(b) a professional geoscientist*
> *with experience or training in geotechnical study and geohazard assessments.*
> *(2) If*
> *(a) a bylaw regulating the construction of buildings or other structures is in effect, and*
> *(b) a building inspector considers that construction would be on land that is subject to or is likely to be subject to flooding, mud flows, debris flows, debris torrents, erosion, land slip, rockfalls, subsidence or avalanche,*
> *the building inspector may require the owner of land to provide the building inspector with a report certified by a qualified professional that the land may be used safely for the use intended.*
> *(3) If a qualified professional determines that the land may not be used safely for the use intended, a building inspector must not issue a building permit.*
> *(4) A building inspector may issue a building permit in accordance with subsection (5) if a qualified professional certifies that the land may be used safely for the use intended if the land is used in accordance with the conditions specified in the professional's report.*
> *(5) A building permit under subsection (4) may only be issued on the following conditions:*
> *(a) the owner of the land covenants with the municipality to use the land only in the manner certified by the qualified professional as enabling the safe use of the land for the use intended;*
> *(b) the covenant contains conditions respecting reimbursement by the owner for any expenses that may be incurred by the municipality as a result of a breach of a covenant under paragraph (a);*
> *I the covenant is registered under section 219 of the* Land Title Act.
> *(6) If a building inspector is authorized to issue a building permit under subsection (4) but refuses to do so, the council may, on application of the owner, direct the building inspector to issue the building permit subject to the requirements of subsection (5).*

In RDCK's Floodplain Management Bylaw, the Non-Standard Flooding and Erosion Ratings (NSFER) were assigned to several alluvial and debris flow prone fans. The RDCK considers these areas subject to or likely subject to erosion and landslides and thus any development within or on a fan rated as F or E requires a report completed by a Professional Engineer or Geoscientist with site specific recommendations if the professional considers the site appropriate for development. The report is registered on the title of the property. If the report determines that the land may not be used safely for the use intended, the Building Official is required to refuse to issue a building permit.

The mapping and identification of NSFER areas has greatly assisted local governments in identifying sites that require additional review before development is allowed when considering debris flow and flooding hazards. However, there is presently no systematic mapping program to identify other natural hazards including debris slides, debris avalanches, rock slides, and snow avalanches and there is no central repository for the known hazard information.

There is no local legislation restricting the use of land that is subject to landslides that has already been developed other than through evacuation orders under the Emergency Program Act or through expropriation under the Expropriation Act.

In summary the estimated hazard from landslides (as per the Hazard Zoning Map) for some lots is such that any further development should be restricted unless a subsequent landslide hazard and risk assessment is conducted that considers both the macro and micro topography, any updated landslide and slope monitoring information, and any other new information that supports the development. In areas of high and very high hazard such a study and mitigative works are likely to be cost prohibitive.

21. Conclusions and Recommendations

A review of the landslide characteristics, local surficial and subsurface geology, and local weather conditions leading up to the event combined with the application of slope stability analyses, landslide run-out modelling, and judgement led to the following observations and conclusions:

- Record June rainfall and late snowmelt saturated the soils on the slope above the community and triggered the landslide.
- A landslide of similar size has not occurred in this area since deglaciation (last 12,000 years).
- Previous (before 2012) reviews and observations of the area:
    - The Gar Creek fan (lower landslide deposit adjacent to Kootenay Lake) was mapped as a potential debris flow area. The province provided the maps and files to the RDCK. The area is noted in the RDCK Floodplain Bylaw 2080 to have a Non Standard Flood and Erosion Rating.
    - Terrain mapping and site assessments in the Gar Creek drainage in 1983, 1994, 2001, and 2003 did not indicate the possible occurrence of a landslide large enough to travel onto the Johnsons Landing bench (Figure 2).
    - Local residents observed very high creek flows, high turbidity, changing flow patterns, high bed-load and debris blockages weeks and days before the landslide event.

- There is potential for future landslides in the Gar Creek drainage. The landslide likelihood estimates given below are approximate and could change in the future if more information on landslide movement becomes available.
    - The likelihood of a landslide and debris flow that is contained within the Gar Creek channel flowing over the Gar Creek fan and into Kootenay Lake is estimated at 1:10 per year.
    - The likelihood of a landslide of sufficient volume to travel onto and near the downslope end of the Johnsons Landing bench is estimated at 1:1,000 per year (see Figure 36).
    - The likelihood of a landslide of sufficient volume to travel onto the Johnsons Landing bench and continue to Kootenay Lake is estimated at 1:10,000 per year (see Figure 36).

The recommendations that follow are based on field reviews, numerical modelling, experience and judgement. The results of the landslide assessments and risk analyses indicate that some residents, users of the Argenta-Johnsons Landing and Houston Roads, users of the Community Hall, and users of the beach area are exposed to continued landslide and debris flow hazards.

The following is a list of site specific recommendations intended to reduce the risk of loss of life:

1. **Notify local residents of the estimated hazard and risk.** Some properties are large with portions of the properties straddling different hazard areas allowing for the potential to rebuild or relocate houses to safer areas.
2. **Restrict further land/house development in the areas identified as having a moderate, high, or very high hazard unless subsequent geotechnical investigations are conducted that supports the development, recommends protective works, and/or reduces the assessed hazard.** The investigations would need to consider the macro and micro topography, any updated landslide modelling and slope monitoring information, and any other new or existing information. It is likely that in areas identified as having a high or very high hazard that such an investigation and/or works would be cost prohibitive.
3. **Establish and maintain a minimum 5 m channel bottom to top of channel bank height at the 70° bend (elevation 750 m) in Gar Creek.** The landslide hazard map was produced from modelling that included 4 m height differential at this bend and significant changes to this height (through creek deposition of sediments and debris) may extend landslide and snow avalanche hazard boundaries downslope. Upon review of the landslide run-out modelling and risk analyses it may be determined that it is

advantageous to construct and maintain additional channel bank height. Any changes to the bank height, including the temporary berm, must consider private land ownership, berm maintenance, and downslope impacts.

4. **Establish a simple landslide monitoring program.** Landslide monitoring and further site observations over the next several years will provide additional information on the hazard and may allow for a refinement or modification to the estimated likelihood of landslide occurrence. Monitoring and site observations may include the collection of information related to slope movements, rainfall and snowpack accumulation and melt, inventory of and changes to the location and volume of springs and seeps, and appearance of any new tension cracks, shear zones, scarps or the extension of existing scarps. The degree to which monitoring will be implemented will ultimately depend on land use decisions.

5. **Establish communication plans and protocols to update residents and visitors of local conditions during periods of potential increased landslide hazard.** While some local residents are familiar with the signs of increased landslide hazard (example: high creek turbidity), the recognition of landslide early warning signs should be communicated in a formal manner to all those present or accessing the area (including visitors).

6. **Establish a watershed plan for resource management and development on crown land within the Gar Creek watershed.** The plan may outline allowable and restricted watershed activities such as the harvesting of timber or road construction.

7. **The Ministry of Transportation and Infrastructure should evaluate opportunities to reduce landslide risk to the travelling public in areas potentially impacted by future landslide events in the Johnsons Landing area.**

8. **To document lessons learned from this tragic event, Government agencies should review the following suggestions intended to improve public safety relating to landslide events:**

   a. **Increase public awareness of when and how to report signs of unusual creek activity and slope instability.** There were signs of unusual creek activity (high flows, high turbidity, and small debris/erosion events) in the days before the Johnsons Landing 2012 landslide event that did not get reported to the local government or EMBC.

   b. **Enhance the accessibility of landslide hazard maps and reports to regulatory bodies, qualified professionals, property owners and the public.** A map identifying the Gar Creek fan as a potentially hazardous area was available in 1998. However, some residents, with property on the fan, were not aware that this information existed. There were other landslide hazard maps and reports available but were not easily accessible. There are other areas in the Kootenays where landslide hazards have been identified and the general public and landowners may not be aware of this information (mainly in the form of maps appended to the RDCK Floodplain Management Bylaw and MFLNRO Flood Hazard Maps). Residents and the general public should be made aware of and/or understand how to access existing landslide hazard information, new landslide reports and new landslide hazard maps.

c. **Raise awareness of the benefits of LIDAR (Light Detection and Ranging) for professionals, government agencies, and private companies in areas of known or expected landslide hazard located above areas with significant values.** The use of LIDAR mapping at Johnsons Landing provided a better definition of the previous landslide activity that was not evident in air photos or on the ground.

d. **Establish uniform and consistent landslide risk tolerance/acceptability criteria to be applied throughout the Regional District for assessment of landslide risk relating to land development, building permitting, and existing residences.** The criteria will help avoid potential confusion with respect to what is considered "safe".

e. **Maintain robust emergency communications with consistent protocols for all emergency response personnel responding to landslide events.** The second landslide that occurred on the morning of July 13th, 2012, came very close to impacting several people in the area. It is important that during post landslide response that adequate consideration be given to the potential of secondary landslide activities. Rapid geotechnical assessments are often required with ongoing spotting requirements and attention to precipitation and snowmelt levels in order to minimize hazards to responders.

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Michele Ihas
Glenn Olleck
Frances Maika

Field
Duncan Lake

22. Closure and Report Limitations

This report was prepared for the exclusive use of the Regional District of Central Kootenay. The material in it reflects the authors' best judgment and professional opinion in light of the information available to them at the time of preparation. Any use which a third party makes of this report or any reliance on or decision to be made based on it are the responsibility of such third parties. The authors accept no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based, or lack thereof, on this report. No other warranty is made, either expressed or implied.

This report and assessment have been carried out in accordance with generally accepted practice. The study methods used and tasks performed to complete the scope of work are consistent with the Association of Professional Engineers and Geoscientists of BC (APEGBC 2010) Guidelines for Legislated Landslide Assessments for Residential Development. Conclusions and recommendations presented herein are based on visual site inspections, data collected, limited subsurface investigation, and analyses. Significant professional judgement has been applied in developing the conclusions and recommendations. No other warranty is made, either expressed or implied.

This report is submitted for the RDCK who may distribute this report as reasonably required for evaluation, implementation and approvals.

This report does not quantify all conceivable risks due to landslide events in the Gar Creek drainage as it does not attempt to estimate the number and location of all people or resources at any one time in the drainage, on the Johnsons Landing bench or Gar Creek fan.

The report only considers landslides originating in the watershed due to natural causes. It does not include any artificial watershed changes such as road building, mining or forest harvesting. The estimation of landslide magnitude, likelihood of occurrence, type of event, and run-out location can change immediately following a landslide event.

Estimating landslide potential and run-out location is not a precise science and requires significant professional judgement, experience, and interpretation.

We trust that this report meets your current requirements. If you have any questions or comments please contact the undersigned.

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24. Glossary

Following are definitions for some technical terms used in this report.

Ablation till: Material deposited as the glacial ice around it melts away.

Acceptable risk[6]: A risk for which, for the purposes of life or work, we are prepared to take pretty well as is with no regard to its management. Society does not generally consider expenditure in further reducing such risks justifiable.

Aeolian: Deposited by the wind.

Basal till: Material deposited at the base of a glacier.

Colluvium: Unconsolidated sediments that have been deposited at the base of slopes by mass movement processes such as landslides, ravel, or creep.

Consequence[7]: The effect on human well-being, property, the environment, or other things of value; or a combination of these. Conceptually, consequence is the change, loss, or damage to the elements caused by the landslide.

Debris avalanche: An extremely rapid, partly or fully saturated landslide on a steep slope, not confined in an established channel.

Debris Flow[8]: Debris flow is a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel"

DEM: Acronym for Digital Elevation Model; a three-dimensional representation of the land surface, created from terrain elevation data.

Diamicton: Nonsorted to poorly sorted sediment, typically gravel and sand suspended in a fine textured matrix.

Elements at Risk[9]: Things of social, environmental and economic value, including human well-being and property that may be affected by a landslide.

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[6] From Fell and Hartford 1997 – Landslide risk management

[7] Adopted from LMH 56 Landslide Risk Case Studies in Forest Development Planning and Operations 2004 MOFR.

[8] Modified from Hungr et al 2001.

[9] From APEGBC 2010. Association of Professional Engineers and Geoscientists of British Columbia 2010. Guidelines for Legislated Landslide Assessments for Proposed Residential Development in British Columbia.

Failure plane: The sliding surface between two layers of soil or rock.

Fan: A cone-shaped deposit of sediment constructed by streamflow (fluvial) or debris flows (colluvial).

Fluvial: The processes associated with rivers and streams and the deposits and landforms created by them.

FSR: Acronym for Forest Service Road.

Glacial till: Material deposited directly by glacial ice.

Glacio-fluvial: Refers to material deposited by running water downstream or adjacent to a melting glacier.

Glacio-lacustrine: Refers to sediment deposited in lakes formed below or adjacent to a melting glacier.

Hazard[7]: A source of potential harm, or a situation with a potential for causing harm, in terms of human injury; damage to property, the environment, and other things of value; or some combination of these.

Individual Risk[6]: The risk to any identifiable (named) individual who lives within the zone impacted by the slope failure; or who follows a particular pattern of life that might subject him or her to consequences of slope failure.

Karst: A landscape feature formed when water dissolves including limestone, dolomite and gypsum, characterized by sinkholes, caves, and underground drainage systems.

Landslide[7]: A movement of rock, debris or earth down a slope. Includes debris flows, debris slides and rockfalls and other types of mass movement.

Levee: An elongated ridge formed by debris flows or streams.

LIDAR: Acronym for Light Detection and Ranging – a technology for producing very accurate digital elevation models from airborne radar instruments.

Morainal: Refers to material deposited by glacier ice; glacial till.

Morphometric: The process or technique of measuring the external form of an object, in this case watersheds.

Orthophoto: A mosaic of aerial photographs geometrically corrected so that it can be used to measure true distances.

Photogrammetry: The practice of determining the geometric properties (elevation, distance, slope) of terrain from aerial photographs.

Piezometric Pressure: Subsurface water pressure.

Pleistocene: Geological epoch which lasted from about 2,500,000 to 11,700 years ago, spanning the world's recent period of repeated glaciations.

Ravel: The rolling, bouncing, and sliding of individual particles down a slope.

Rheology: The study of the flow of matter, primarily in liquid state, but also applies to substances such as muds, sludges, suspensions which are `soft` solids; also refers to a mathematical model or formula describing liquid or plastic flow.

Risk[7]: The chance of injury or loss as defined as a measure of the probability and the consequence of an adverse effect to health, property, the environment, or other things of value.

Risk Analysis[7]: The systematic use of information to identify hazards and to estimate the chance for, and severity of, injury or loss to individuals or populations, property, the environment, or other things of value.

Risk Assessment[7]: An assessment that combines risk analysis and risk evaluation to determine if a risk is acceptable or tolerable.

Scarp: A vertical or near-vertical soil or rock exposure at the head (top) of a landslide that separates the earth mass that has slid from the mass that has not.

Societal Risk[6]: The risk to society as a whole: one where society would have to carry the burden of a landslide accident causing a number of deaths, injuries, financial, environmental and other losses.

Superelevation: The difference in elevation (height) between the two edges of a landslide or debris flow.

TRIM: Acronym for Terrain Resource Information Management (the full name is seldom used) – refers to the 1:20,000 topographic maps produced by the province of British Columbia.

Varve: A layer of glacio-lacustrine sediment deposited in a single year.