Landslide Risk Assessment, Moonshine Bay, Pitt Lake

Report to

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Executive Summary

Moonshine Bay is the site of a cluster of 13 recreational lots on the southwest shore of Pitt Lake, southwestern British Columbia. Previous hazard mapping (Thurber 1994) specific to 10 of the lots that were leasehold tenure indicated that they were vulnerable to a high to very high debris slide, debris flow and/or rockfall hazard. The hazard rating implied a potential annual frequency of occurrence of a damaging or destructive event affecting the lots of >1/100 or even >1/20. Expressed in terms of a human lifetime (50yrs) this is >40% to >92% in 50yrs, respectively. Since this exceeded a low hazard level (1/500, 10% in 50 years), the lots were not sold by the Crown, and were retained as leasehold.

In the fall of 1990 there was a debris slide from an abandoned logging road upslope that caused damage to one cabin (Lot 8) and a near miss on two other lots (Lot 9, 10). Then in late September 2020, a severe rainstorm triggered a debris flow in a steep gully that destroyed one cabin (Lot 7) and damaged two others (Lot 6, 8), one of which was previously damaged in 1990 (Lot 8). Luckily, no fatality occurred in either of these events.

In response to this recent destructive landslide occurrence, MoFLNRORD and Metro Vancouver contracted Cordilleran Geoscience to produce an updated Landslide Risk Assessment pertinent to the slope hazards affecting the 13 lots, with a view to understanding the life-safety risk and any potential risk management options that might be available to mitigate the risk.

The landslide risk assessment was based on field traverses conducted in May 2009, October 2020 and November 2020. The field traverses involved mapping of terrain conditions on and upslope of the subject properties, between the shoreline and 400 m elevation. The location and condition of an old abandoned logging road and the potential rockfall source area were documented, channel assessments of the September 2020 debris flow track and two other gully channels were conducted, and the morphology of valley bottom colluvial (landslide) deposits upon which the lots are situated was mapped. Mapping was based on visual inspection; no subsurface exploration was conducted.

Landslide risk was estimated using a Quantitative Risk Assessment (QRA) approach, estimating the probability of death to an individual (PDI), where PDI is calculated as landslide hazard * landslide spatial impact * occupancy * vulnerability. Landslide hazard rates were taken from studies conducted elsewhere in BC and applied to the terrain affecting the subject properties. Landslide spatial impact was based on expert judgement. Individual exposure pertained to recreational occupancy, assumed to be weekend use. Where a lot was affected, then vulnerability of the occupants was deemed to be very high. Risk was estimated for existing conditions, and modified according to anticipated increase in landslide hazard with future climate change. These risks were then recalculated assuming occupancy was modified by strategic avoidance of weather conditions (heavy rain) associated with landslide triggering.

The estimated landslide risk was evaluated against life-safety policy recently adopted by District of North Vancouver (2009), District of Squamish (2017) and Cowichan Valley Regional District (2019), whereby life-safety risk is unacceptable if PDI >1/10,000, it is tolerable if between 1/10,000 and 1/100,000 and broadly acceptable if <1/100,000. It was found that under existing conditions (present climate, unrestricted weekend use) risks were tolerable to unacceptable, and with future climate change they became unacceptable. However, with weather avoidance, then risks were generally tolerable even with future climate change, that is, excepting those lots that were affected by unstable road conditions upslope. In those cases, risks remained unacceptable.

These results are presented with the caveat that QRA while appearing precise due to its use of numbers, is actually only a tool to aid decision making. Since judgement goes into the formulation of the estimates, the method is semi-quantitative. Nevertheless, given the previous hazard ratings assigned to the lots, and the past occurrences of damaging and destructive landslides affecting the development area, these results appear consistent and reasonable.

Risk management measures might involve passive or structural solutions. As discussed above, a passive measure, strategic avoidance of inclement weather conditions, would appear to be an effective measure in all cases except for lots affected by unstable road conditions upslope. Of course, expunging leases would eliminate the risk altogether. Structural measures would involve building defensive structures on the subject properties or on Crown land upslope. There are pros and cons to all measures; with respect to weather avoidance, the question arises who monitors weather alerts, ensures adherence and assumes liability; expungement of title is likely to be controversial given previous investment; structural measures are invasive and expensive, and require management plans and ongoing maintenance, and issues around assuming responsibility for these may limit their practicability. All potential measures will require consultation between local government and affected leaseholders.

Introduction

Moonshine Bay on on the southwest shore of Pitt Lake, southwestern BC, is home to 13 recreational cabins on lease and private lots. In late September 2020 there was an intense rainstorm fore-warned by Environment Canada on September 23. On returning to their property on the weekend subsequent to the storm, the Lot 7 landowner found their cabin completely destroyed by a debris flow (Photos 1-3). This report was prepared for MoFLNRORD and Metro Vancouver. It provides an assessment of the landslide risk affecting the 13 properties, and provides risk management options for continued safe use.

The Concept of Safety - Hazard & Risk Assessment

A hazard is a phenomenon with the potential to cause harm; it is usually represented by a magnitude and recurrence interval (see Table 1). The Integrated Land Management Bureau uses the following landslide hazard (debris flow/rockfall) frequency categories (MoE 1999)(Table 1).

Table 1. Qualitative landslide hazard frequency categories.

Qualitative frequency	Annual return frequency	Comments
Very high	>1/20	Hazard is well within the lifetime of a person or typical structure. Clear fresh signs of hazard are present.
High	1/100 to 1/20	Hazard could happen within the lifetime of a person or structure. Events are identifiable from deposits and vegetation, but may not appear fresh.
Moderate	1/500 to 1/100	Hazard within a given lifetime is possible, but not likely. Signs of previous events may not be easily noted.
Low	1/2500 to 1/500	The hazard is of uncertain significance.
Very low	<1/2500	The occurrence of the hazard is remote.

The product of the factors *Hazard* and *Consequence* equals *Risk*. Consequence itself is a product of factors, including 1) whether an event will reach a site, 2) whether elements at risk will be present when the site is affected by the hazard, 3) how vulnerable the elements at risk are to the hazard affecting the site, and 4) the value of the elements at risk, or the number of persons exposed.

In Canada and BC there is no legislated guidance for risk tolerance to landslides and associated phenomenon, and the term "safe" has not been legally defined. In considering risk tolerance, an important concept is that risk of loss of life from natural hazards should not add substantially to that from all life's usual factors (driving, health, recreation, etc) combined. For reference, the risk of death while driving is 1/10,000 per annum (Transport Canada, 2011) and this value establishes a threshold level for acceptable risk.

Herein, the definition of safe follows the so-called Hong Kong Landslide Risk Criteria, as adopted by District of North Vancouver (2009) and District of Squamish (2017), whereby landslide risk thresholds are >1/10,000 unacceptable, 1/10,000 to 1/100,000 tolerable, <1/100,000 broadly acceptable (Porter and Morgenstern 2013).

Assessment Area

Table 2 lists lots identified by MoFLNRO as requiring hazard and risk assessment. The lots and the terrain upslope that affects the lots defines the study area (Figure 1).

Table 2. Subject properties assessed in this report, Metro lot numbers, Crown Land File Number, tenure and legal description (see Figures 1 & 3, for locations).

Metro ID	Crown Land File Number	Tenure holder	Legal Description
1	0256021	Greg/Shannon Cooney	DL 7342, Grp 1, NWD
2	0254554	Jane Luke/Grant Stewart	DL 6244, Grp 1, NWD, containing 0.198 ha.
3	0223641	Phil Caloz	Blk A OF DL 6914, Grp 1, NWD
4	0223640	Wayne Wagner/JoAnne Mckay	Blk B, DL 6914, Grp 1, NWD
5	0223639	David Wise	Blk C, DL 6914, Grp 1, NWD
6	0227015	Amanda Kerr	Blk D, DL 6914, Grp 1, NWD
7	0227016	Rick Bindley	Blk E, DL 6914, Grp 1, NWD
8	0227276	Amber Crawford Dale, Conor	Blk G OF DL 6914, Grp 1, NWD
9	0226845	Dan Boiselle & Cathy Kelly	Blk H, DL 6914, Grp 1, NWD
10	Private land	Darrel/Colleen Handley	Blk C, DL 7230, Grp 1, NWD
11	Private Land	Darrel/Colleen Handley	Blk D, DL 7230, Grp 1, NWD
12	0269601	Ray/Deb Kennett	Part of DL 1850, Grp 1, NWD
13	Private Land	James Sheremeta	DL 3137, Grp 1, NWD

Methods

This report is based on review of background material, including previous reports specific to the site by Thurber (2004), Nhc (1995) and Cordilleran (2011), observations collected during three foot traverses of the area, and professional judgement.

The first field traverse was made on May 8, 2009, mapping the colluvial landforms underlying properties 1-8 (Table 2), and documenting terrain conditions up to about 420 m elevation on and in the vicinity of an old logging trail climbing above properties 8-13. On October 3, 2020, in response to the occurrence of the recent landslide, the debris flow track was mapped from the beach to its headscarp in a gully at 410 m elevation. Finally, on November 10, 11, 2020, as part of this assignment, a traverse was conducted of the terrain about the gullies above lots 1-8, and mapping of landforms on the lower slopes bordering the lake, including observations at each identified lot (Table 2).

In the field, observations of slope, parent material, landform type, evidence of geomorphic activity were recorded at specific sites with waypoint locations recorded by handheld GPS unit. A map of observation waypoints is included (Figure 1). A 1:10,000 scale basemap with 10 m contours and a coloured slope theme was prepared from TRIM topographic data using QGIS. A geomorphic map was prepared from field observations, topographic interpretation and Google Earth imagery (Figure 3). Annotated photos are presented in Appendix 1. Appendix 2 present a pictorial summary of the 1990 landslide.

The report describes the geologic/geomorphic setting, assesses the landslide risk and makes recommendations for landslide risk management. The landslide risk assessment follows the general approach laid out by Porter and Morgenstern (2013) and summarised by MoFLNRO (2014).

Background Material

Thurber (2004) provided the following ratings (Table 3) for the properties discussed in this report. See nhc (2005) and Thurber (2004) for more detail regarding their assessment methodology. The summary of hillslope hazard by Thurber (2004) is provided below:

> "This cluster of 10 [lease] lots is located at the foot of steep but variable slopes (see Figure 3 herein). The northern 3 or 4 lots are proximal to the outlets of at least two mountain gullies. In our judgment, these lots are the most exposed to debris floods or debris flows.
>
> There is a distinct cliff line above the 5 or 6 south lots. It is not well defined by base map contours but the cliff base is about 250 m in elevation above the lakeshore. 1996 aerial photos show a debris slide track that originated at the base of the cliffs and reached the shore in the gap between Lots 226845 and 269601. This slide [1990] would have severely damaged or destroyed buildings. [There is] concern about the probability of similar slides and rock fall activity on these lots."

Table 3. Hazard ratings for subject properties (from Thurber 2004).

Metro Lot #	Crown Land File Number	Hazard[1]	Comment
1	0256021	VH	Debris flood/flow; with proximity to large creek debris cone.
2	0254554	VH	Debris flood/flow.
3	0223641	VH	Debris flood/flow, with channel behind building.
4	0223640	H	Debris flood/flow, possible debris slide, low debris flow hazard.
5	0223639	H	Debris slide hazard, low debris flow hazard.
6	0227015	VH	Debris slide, possible slide path but low debris flow hazard on north side of lot.
7	0227016	VH	Debris slide, possible rockfall.
8	0227276	VH	Debris slide, with previous building damage (1990).
9	0226845	VH	Rockfall and debris slide. Note building on rockfall debris and debris slide (1990) each side of lot.
10	Private land	..	Not assessed.
11	Private Land	..	Not assessed.
12	0269601	VH	Debris flood/flow and debris slide.
13	Private Land	..	Not assessed.

[1] See Table 1.

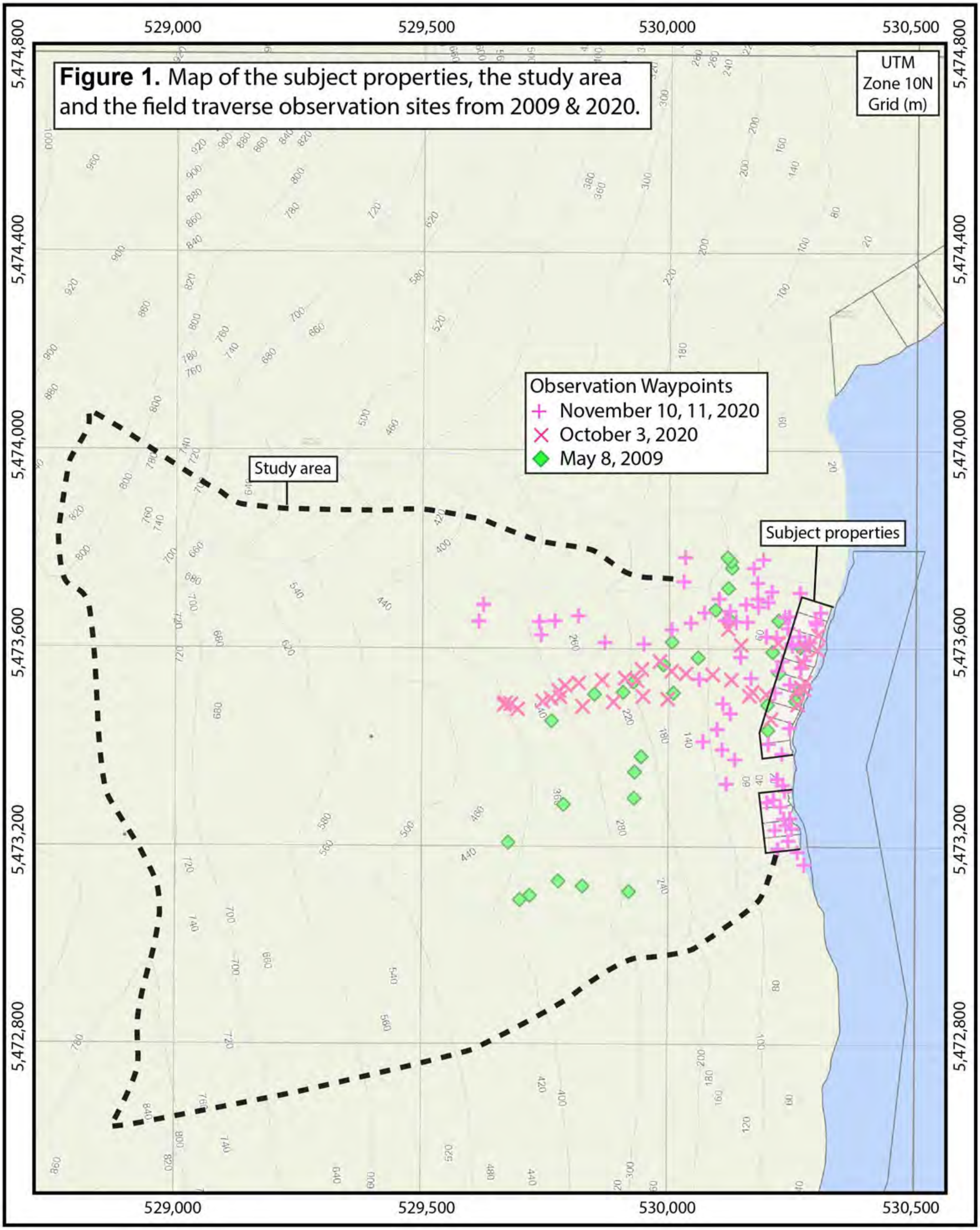


Figure 1. Map of the subject properties, the study area and the field traverse observation sites from 2009 & 2020.

Gemorphic Overview

Climate and physiography

The study area (Figure 1) is located on the southwest shore of Pitt Lake. The climate at 700 m elevation above the subject properties was provided by Climate BC (http://www.climatewna.com). The climate is cool and wet (Figure 2). The mean annual temperature is 7.6 °C, with average monthly temperartures of 1-2 °C in winter months rising to 16 °C in July/August. The area is seasonally very wet, with a mean annual precipitation of 3452 mm, with the wettest months (>200 mm) extending from October through April. About 15-20% of winter precipitation falls as snow.

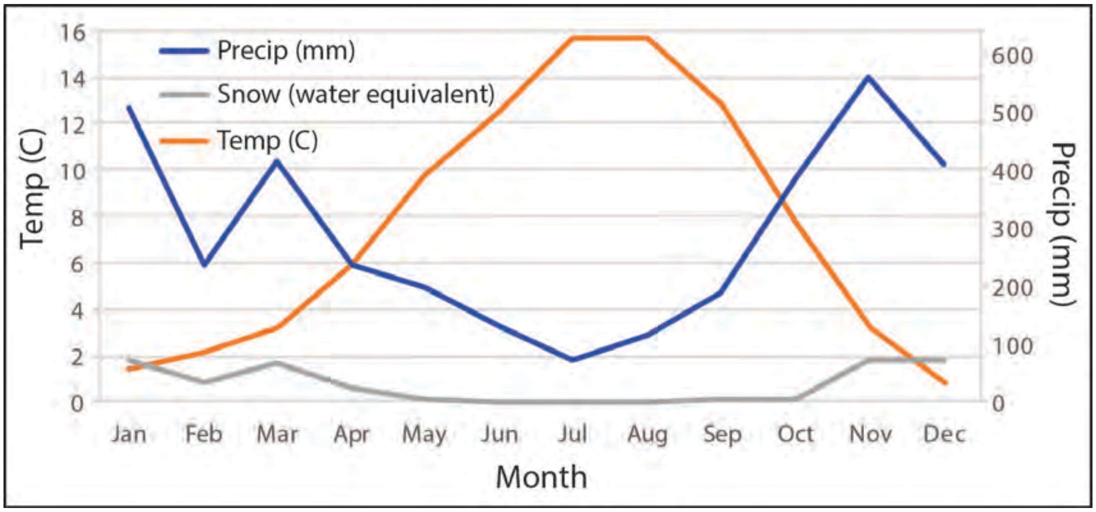


Figure 2. Climate in the study area at 700 m elevation.

Bedrock underlying the hillslope is competent intrusive plutonic rock (diorite). The terrain above the lots rises from lake level at ~2 m elevation to the ridge crest at 860 m elevation, with an average slope of 56%. The north/south length of the study area at water level is about 575 m distance, but at the height of land it is about 1500 m, indicating considerable horizontal convergence (Figure 3).

This hillslope area is underlain by four subbasins and one open-slope area situated between subbasins 3 and 4 (Figure 3). The subbasins are small (7-60 ha.), steep (Melton's ruggedness ratio = relief/basin area$^{0.5}$; 1.0-1.7), and based on Melton's ratio (debris flow threshold >60%), they are debris flow prone (Wilford et al 2005; Table 4).

Table 4. Basin and hillslope morphometrics and hazard assessment.

Subbasin	Area (km^2)	Top (m)	Bottom (m)	Ruggedness	Hazard at base of slope
1	0.30	850	140	1.30	Debris flow
2	0.20	790	100	1.55	Debris flow
3	0.07	560	120	1.67	Debris flow
Open-slope	0.13	500	50	>0.7[1]	Debris slide, rockfall
4	0.58	870	40	1.09	Debris flow

[1] slopes ~70-90% with rock bluffs

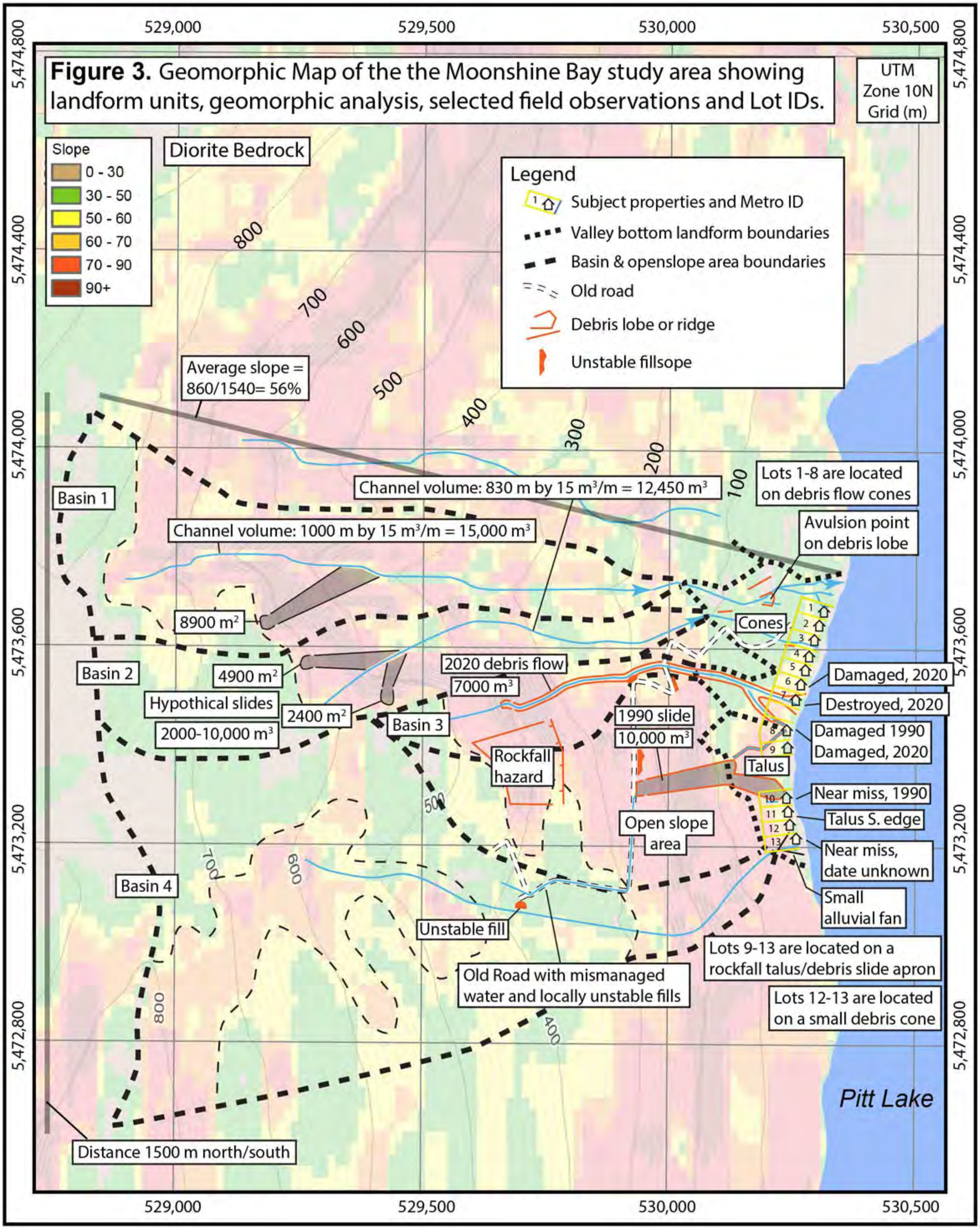


Figure 3. Geomorphic Map of the the Moonshine Bay study area showing landform units, geomorphic analysis, selected field observations and Lot IDs.
UTM Zone 10N Grid (m)
529,000
529,500
530,000
530,500
5,474,800
5,474,400
5,474,000
5,473,600
5,473,200
5,472,800
Slope
0 - 30
30 - 50
50 - 60
60 - 70
70 - 90
90+
Diorite Bedrock
Legend
Subject properties and Metro ID
Valley bottom landform boundaries
Basin & openslope area boundaries
Old road
Debris lobe or ridge
Unstable fillslope
Average slope = 860/1540= 56%
800
700
600
500
400
300
200
100
Channel volume: 830 m by 15 m³/m = 12,450 m³
Channel volume: 1000 m by 15 m³/m = 15,000 m³
Lots 1-8 are located on debris flow cones
Avulsion point on debris lobe
Basin 1
Basin 2
Basin 3
Basin 4
8900 m²
4900 m²
2400 m²
Hypothical slides
2000-10,000 m³
Cones
2020 debris flow
7000 m³
Damaged, 2020
Destroyed, 2020
Damaged 1990
Damaged, 2020
1990 slide
10,000 m³
Rockfall hazard
Talus
Near miss, 1990
Talus S. edge
Open slope area
Near miss, date unknown
Small alluvial fan
Unstable fill
Lots 9-13 are located on a rockfall talus/debris slide apron
Old Road with mismanaged water and locally unstable fills
Lots 12-13 are located on a small debris cone
Pitt Lake
Distance 1500 m north/south

Basins 1-3 and their debris cones

Basins 1-3 affect Lots 1-8. The materials within the lower to mid slopes of Basins 1-3 consist of till blanket up to several metres thick. Upper slopes of the basins support till and colluvial veneer on rock. Colluvium from rockfall and weathered/eroded till have been conveyed and deposited on the debris cones at the mouths of the basins.

At the base of slope, Lots 1-8 are located on bouldery debris cones issued from Basins 1-3. Basins 1-2 form a composite cone with average slope of 30-40%. The modern active part of the Basin 1 cone is north of Lot 1. Here the cone surface follows a consistent grade to the shoreline. However, starting from Lot 1 and extending south to Lot 8, the shoreline (littoral) margin of the cone is truncated by wave action, forming a short steep (60-70%) slope rising 5-10 m up from the beach before breaking back to the cone surface. This truncated margin would indicate that in the distant past the sediment delivery to these cones was much higher than in the present, allowing them to build out farther into the lake. But with sediment yield diminished, shoreward erosion has become dominant, allowing erosion of the cone toe. Another indication of reduced sediment yield relative to erosion rate is the incised channel condition of the Basin 1-3 creeks where they cross their respective cone surfaces (Tables 5-7).

These observations are consistent with the "paraglacial model" of cone formation (Church and Ryder 1972). By this model, the typical time frame for cone building would be 10,000-7,000 years ago, and for diminished debris yield would be 7000 years onward. This is not to say there is no hazard; just that the hazard today is reduced from what it was in the early post glacial period.

Table 5. Basin 1 cone channel. Downstream trend in channel condition.

		AC	Freeboard		
WP	Grad. (%)	Width (m)	LB (m)	RB (m)	Comment
150	+50, -30	..	15+	4	Creek on boulder bed, confined, rock sidewalls LB, cone apex RB
151	+30, -15	4-5	2-3	4	Top end active cone, unconfined over last century
152	..	4-5	1.5	1.5	Boulder step pool
153	±20	..	..	..	Channel starting to braid, aggradation around mature cedars.
175	±30	..	0	0	No freeboard. Potential avulsion right along black line (Fig 3).
171	±30	4	0	0	5 m tall by 20 m wide debris aggradation behind coarse wood, historic as water pipe tangled up in debris.
169	..	..	..	..	Toe of blocky lobe, creek braids over it
167	±35	..	2-3	4	Cobble boulder gravel aggradations behind wood

Basin 1 has built a steep (20-30% slope) bouldery debris cone with an area of 24,500 m^2. At the apex the creek channel is 4-5 m wide and incised 2-4 m (WPs151, 152; Table 5). However, between 60-70 m elevation there is evidence of debris deposition with aggradation behind wood and boulder jams (WPs 169, 171, 175; Table 5). At this site, there is no freeboard and southward avulsion is possible, affecting Lot 1-3. The lower reaches of the channel are braided (WP167; Table 5).

Basin 2 has built a steep (20-45%) debris cone with an area of 19,000 m^2. At the apex of the Basin 2 cone (WP189; Table 6) the stream is incised in a trapezoidal channel 3-5 m wide at the base and incised to 3-5 m depth. This cross-sectional area is sufficient to confine the 200 yr flood with room for debris flood bulking. However, the degree of freeboard is not constant along the length of the channel on the cone. There are three locations (WP214, 182, 67; Table 6) where there is low (<2 m) freeboard on the channel, and these sites create a potential flood and avulsion hazard affecting adjacent properties. For example, at WP214 several boulders have lodged in the channel creating a sediment wedge to form upstream. At this location, there is only 1-2 m of freeboard and a channel avulsion here would be possible, directing debris flows or floods onto the cone surface and possibly affecting the subject properties. In particular, the old logging road switches near the apex (WP189; Table 6), and would direct overland flow to Lots 4-6. Farther downstream, the old logging road crosses the creek, locally reducing freeboard to 1-2 m. At the channel mouth (WP66, 67; Table 6), freeboard is about 2 m.

Table 6. Basin 2 cone channel. Downstream trend in channel condition.

		AC	Freeboard		
WP	Grad. (%)	Width (m)	LB (m)	RB (m)	Comment
125	..	3-5	4	2.5	Abrupt step to rock upstream.
189	..	3	..	..	Apex. Very rough step pool and full of CWD. Old road goes straight up cone and switches south at apex of cone.
124	±20	5	..	5	Ephemeral, lose confinement 10m downstream.
214	±25	4-5	2	2	Bouldery sediment wedge creates local zero freeboard location. Potential avulsion point.
179	+20, -40	12	1-2	2	Creek braided locally
180	..	..	5	3	4-5 m step down, plunge pool in channel, freeboard increases.
181	+45, -25	4	3-4	3-4	Bouldery cone
182	..	..	1.0	2	Old road grade crossing
183	+40, -25	..	2-3	4	RB underlain by bouldery debris lobe, 20 m long by 5-10 m wide, with one 3-4 m dia clast on creek edge; 35% sloping cone surface. Photo of house downstream LB.
212	..	..	..	..	10m up from shore. View to mouth.
184	+40, -30	..	1.5	1.5	
66		4	2	2	Ephemeral
67	..	..	..	..	Lot 3. At mouth, debris from creek stuffed under lake edge patio

Basin 3 has built a steep (35-45% slope) debris cone with an area of 17,000 m^2. The apex of the debris cone is at 120 m elevation on the south side (WP40; Table 7), but perhaps 70 m elevation on the north side (WP36; Table 7). The north side of the cone is truncated by the Basin 2 debris cone, suggesting that Basin 2 is more active than Basin 3. Basin 3 is the smallest basin area, and early Holocene sediment exhaustion (before the larger Basin 2) fits with the paraglacial model discussed above.

There is evidence for early Holocene sedimentation (WPs 34, 84; Table 7) exposed by the 2020 debris flow. In this section an eroded trench reveals unweathered slope-parallel dipping, stratified sandy gravel, overlain by a humic stained and weathered, unsorted debris flow diamicton that thickens from 1-2 m upslope to several metres downslope toward the beach. Charcoal samples (WPs 84, 85; Table 7) were located from the base of the humic/weathered debris and radiocarbon dating could provide some indication of chronology of debris flow activity. Samples have not been submitted for dating, as the cost was out of scope of the contract.

Table 7. Basin 3 cone channel. Downstream trend in channel condition.

		AC	Freeboard		
WP	Grad. (%)	Width (m)	LB (m)	RB (m)	Comment
40	+45, -50	4	6	7	Apex RB
85	..	..	..	..	Charcoal sample from just above rock floor channel base (C14, Pitt 2).
39	+55, -30	5	4.5	3	Lower end bedrock floored channel.
38	+45, -35	4-5	5	0	Top end avulsion, above cedars, local break in slope and loss of confinement.
36	40	..	2	0	Avulsion RB. Track 50 m wide at avulsion, split by rise with cluster of three cedars. Dmm till, compact. Potential avulsion LB, 40% slope to Lot 5 cabin. Top end of unconfined channel, above this 5-6 m channel confinement.
34	45	..	..	..	Damage corridor. Track 30 m wide, scoured 1 m weathered colluvium down to glaciocolluvial cone delta gravels. Creek has eroded 4-6 m deep by 3-4 m wide trench in gravel exposing dipping beds, top of 20 m long nick point is here.
84	..	4	3-4	3-4	Charcoal sample from wedge Holocene cone. 50cm above bed of creek, 1.5 m down from cone surface. See photos, old deglacial cone is steeper than modern cone which forms thickening wedge of debris into lake.
32	..	..	..	..	Lot 6. Porch ripped off front of cabin.
33	..	..	..	..	Lot 7. Cabin destroyed by boulder lobe.
31	..	..	..	..	Debris flow impact at lake, 2 m incision of colluvium on shoreline.

The steep open-slope area

The open-slope area above Lots 9-13 is steep (70-90% with bluffs >90% slope) and prone to debris slides and rockfall. Materials consist of till and colluvial veneer on rock.

The most important aspect of the open slope area in an old logging trail that climbs from the Basin 1-2 debris cone surface, across the lower face between Basins 2 and 3, crossing Basin 3 channel at 150 m elev., and then carries on across the steep open slope. The road was built long before Forest Practices Code road-building standards, and has been abandoned. A length of about 300 m of unstable fillslope was identified (Figure 3). The evidence of instability consists of 0.5-1.0 of fillslope settlement and areas with open tension cracks (Photos 4-8). There is both misaligned water and unstable fills, combined with steep sidehill, on this road (WPs 192-198; Table 8).

All lots downslope of the potential road related slide hazard, that is lots 8-13, are considered to be subject to VERY HIGH road-related debris slide hazard.

Table 8. Notes on legacy road crossing open slope area. Traverse proceeds to bushside.

WP	Comment
192	Basin 3 creek crossing. Start of unstable fill to south. Open tension cracks, 1-2m settlement.
193	3rd switch. Unstable fill on outside of switch on 70% slope into creek. Extends 30 m north of WP. Fresh open T/C and 1-2m settlement. Vol: 5 x 2 x 30m.
194	4th switch. Outside corner, crib construction on 70-90% to Basin 3 creek. Cribs completely rotted with settlement noted. 1-2 inset. This material was scoured out by the 2020 debris flow. Fillslope inside switch, rocky fill supported by cribs 1-2m tall. T/C in road fits shovel handle. Houses downslope.
195	10 x 10m brush opening on unstable, failed fill on 70% slope.
196	T/C 1m settlement, 2m offset from shoulder, on 80% slope.
197	1990 Slide headscarp 20-25m wide. Reached beach. Just missed houses on Lots 8 and 10. Erosion channel on road grade into headscarp.
198	Failing wood box culvert. Water diverted from this creek, caused failure at WP197.
199	5th switch. Up to WP198 grade 30-40%. After 198 gains bench: fillslope away from break and stable grade diminishes.
200	WPs 199-200 road goes straight up hill (45%). Parallel to creek which is 20m to south.
201	Road washout from small tributary creek. Road could capture creek.
202	6th switch. WPs 201-202 road washed out by trib. WP202 road captures trib.
203	End landing on left bank Basin 4 creek. Gully sidewall. 10 x 10 x 2 on unstable fill held by CWD. Sidewall 10-15m long at 60-70%.
204	7th switch. Cuts back south. WP202-204 Road continuation carries flow that washed out WPs 202-203.

There is a steep rock cliff above the subject properties delineated by WPs 205-206 (Figure 3; Photo 3). The cliff is 50 m tall and 200 m wide. At the foot of the cliff there is a large detachment forming a 5-7 m tall uphill facing scarp (Figure 3), and displaying near vertical, open joints and detached blocks (Photo 9). This site is a prehistoric and future potential rockfall source area.

In the steep rock terrain below this cliff area there are other potential rockfall source areas. On the foot traverses (May 2009; Oct 2020) descending from the base of cliff to the foot of slope several sites were noted with fresh rockfall scars on trees. Small fragmental rockfall is an active process on these slopes.

At the foot of slope there are scattered rockfall blocks ranging in size from blocks (angular <4 m dia) to megablocks (angular 4-10 m dia)(WP86; Photo 10). Of note, the cabin on Lot 9 is built on a very large rockfall block (Photo 11) located directly below the rockfall source area (Figure 3).

Basin 4 debris cone

The south end of the open-slope area is crossed by Basin 4 creek. The creek pours off a steep rockface, and then spreads on a small cone. According to the appearance of the cabin and the property, and confirmed by the owner of Lot 5, this cabin is abandoned. The Lot 5 owner stated that creek flows have flooded this cabin at times. Indeed, very fresh braiding and erosion parallel the south wall of the cabin (WP112; Table 9).

Table 9. Basin 4 cone channel. Downstream trend in channel condition.

WP	Comment
110	Apex small cone at base of creek pouring off rock hillslope
111	RB edge cone, very active braiding flow.
112	Back of Lot 13 cabin, appears abandoned, on active cone, recent scour missed house by 1 m, no freeboard.
113	LB edge cone, south side Lot 12 cabin.

1990 open-slope debris slide

In the fall of 1990 a debris slide was reported to have affected Lot 8, knocking trailer off its crib support. This event is documented by the photo montage included in Appendix 2. This event was reported by Thurber (2004) & Nhc (2005) who indicated that the slide was visible on 1996 air photos. They had no other information. Field examination by Cordilleran in 2009 indicated that the slide originated as a road fill failure from the old road crossing above the site at 230 m elevation (WP197; Table 8). The slide was apparently triggered by misaligned water coming from farther upgrade on the road (WPs198, & WPs 199-204; Table 8).

The slide traveled 300 m to the lake (Figs. 1&2) causing damage to a trailer on Lot 8 and just missing the cabin on Lot 10. Had the slide not jammed and deflected by wood and rough talus surface, the cabin on Lot 9 could have been affected. The slide track covers an area of 1.5ha. If 0.5m of debris were entrained per square metre then the side would have had a volume of 7500 m^3. This is a class 3 debris slide (Table 13).

September 23-24, 2020 debris flow

Environment Canada issued a rainfall warning for south coast areas, including the Lower Mainland, on September 23, 2020. Rainfall data was collected from four available stations (Table 10). Daily rainfall amounts peaked on September 23rd with values between 40-80 mm; while 48 hr values peaked September 24th with values of 70-136 mm (Table 11). Note that these are all low elevation sites, and that values may have been much higher on montane sites at 500-800 m elevation. The late September 2020 debris flow was likely triggered by this storm event.

Table 10. Lower Mainland weather stations referred to in Table 11.

Site	Elev (m)	Latitude (°N)	Longitude (°W)
Alvin	61	49.61	122.63
Pitt	3	49.22	122.71
Port Moody	130	49.28	122.88
West Vancouver	170	49.35	123.19

Table 11. Rainfall amounts (24 hr, 48 hr) for Lower Mainland Stations, September 23-26, 2020 storm.

	West Vancouver		Port Moody		Pitt Meadows		Alvin	
Date	24 hr	48 hr	24 hr	48 hr	24 hr	48 hr	24 hr	48 hr
2020-09-21	0.2		1.7		0.0		0.5	
2020-09-22	1.5	1.7	5.3	7.0	0.4	0.4	9.9	10.4
2020-09-23	59.9	61.4	79.4	84.7	40.7	41.1	61.5	71.4
2020-09-24	24.3	84.2	34.0	113.4	28.4	69.1	74.4	135.9
2020-09-25	30.9	55.2	11.6	45.6	23.8	52.2	43.4	117.9
2020-09-26	1.9	32.8	4.0	15.6	2.1	25.9	11.7	55.1
2020-09-27	0.0	1.9	0.0	4.0	0.0	2.1	0.8	12.4
Totals	117		129		95		191	

On October 3, 2020, the debris flow track was traversed from the lake edge to the headscarp at ~410 m elevation (Photos 12-18). It was found that the debris flow initiated as a channel fill failure near the downslope end of a steep sided rock canyon (Photo 12, 13). No point source sidewall failures contributed to the debris flow.

At select stations along the path, the cross-sectional area within the trimline of the event was measured (Photos 14-15). Using the cross-section perimeter scoured and an estimate of the depth of scour (0.25-1 m), a representative scour area could be estimated. This area was multiplied by the length of each channel segment between observation points; and then all segments added to provide an estimate of the debris flow volume, which was found to be between 2866-11,462 m^3, most likely about 7164 m^3 (Table 12). The average apparent channel yield was 15 m^3/m.

Table 12. Estimated debris flow volume and average channel yield from post event channel assessment and estimate of scour.

Waypoint #	Scour perimeter (m)	Segment length (m)	Cross section area (m^2)	Cross section area (m^2)	Segment volume (m^3)	Segment volume (m^3)
			Scour 0.25 m	Scour 1 m	Scour 0.25 m	Scour 1 m
54	11	33	2.8	11	90.8	363
50	21	62	5.3	21	325.5	1302
47	23	67	5.8	23	385.3	1541
45	28	62	7.0	28	434.0	1736
44	22	44	5.5	22	242.0	968
43	33	39	8.3	33	321.8	1287
42	28	35	7.0	28	245.0	980
41	28	30	7.0	28	210.0	840
40	21	41	5.3	21	215.3	861
39	24	66	6.0	24	396.0	1584
Totals		477			2866	11,462
					Average volume = 7164 m^3	
					Average channel yield = 15 m^3/m	

Hazard Assessment

Catastrophic landslide (>0.5 Mm^3)

There is no evidence of tension cracking or slope sagging that would suggest the potential for a large (>0.5 M m^3) catastrophic landslide. The hazard is not considered credible at this site.

Debris slides and flows

The primary, potentially lethal, hazards affecting the subject properties includes debris flow from steep Basins (1-4) and debris slides from the open slope terrain between Basin 3 & 4. Past events described above indicates Class 3 and Class 4 events (Table 13) have directly affected cabins at Moonshine Bay. Debris flows may initiate, as did the 2020 event, from failure of material stored within the channel, or they may be triggered by open slope failures on the basin sidewalls, converging on and travelling down the channel. Sketched scenarios on Figure 3 suggest open slope slides with volumes of 2000-10,000 m are reasonable; and channel length and the yield estimated for the 2020 debris flow, then future channel scour debris flows along Basins 1 & 2 could have volumes of 10,000-15,000 m^3 (Figure 3). The destructive potential for debris flows has been compiled by Jakob (2005)(Table 13).

During the 2020 debris flow, the Basin 3 channel was scoured down to bedrock (Photos 14, 15), so another channel scour event is not possible until such time as debris accumulates along the channel in sufficient quantity to fail again. This process of gradual channel recharge may take centuries (Jakob et al., 2011).

Table 13. Landslide size class ratings describing impacts for each class (Jakob 2005).

Class	Volume (m^3)	Peak discharge (m^3/s)	Potential consequences
1	$<10^2$	<5	Very localized damage, known to have killed forestry workers in small gullies and damaged small buildings.
2	10^2-10^3	5-30	Bury cars, destroy small wooden buildings, break trees, block culverts, and damage heavy machinery.
3	10^3-10^4	30-200	Destroy larger buildings, damage concrete structures, damage roads and pipelines, and block creeks.
4	10^4-10^5	200-1500	Destroy several houses, destroy sections of infrastructure corridor, damage bridges and block creeks.
5	10^5-10^6	1500-12,000	Destroy small villages and forest up to $2km^2$ in area, block creeks and small rivers.

The frequency of landslide occurrence is required to be able to estimate and evaluate landslide risk by quantitative means, as conducted in the subsequent section “QRA.” Since there is no landslide frequency data for the study area, hazard probabilities are taken from post-logging landslide hazard studies in the Coast Region of BC (see references for Rollerson, Millard, JMRATA). Landslide rates have been expressed as Landslides/hectare/year (L/ha/yr) for slopes <60% (III, Low, 0.0005) and >60% (IV, Moderate, 0.0013)(Table 14).

It is widely recognized that within 5-30 years after logging there is a 10 times higher landslide rate than compared to unlogged areas. The slopes above the site were logged before the 1990s and support mature conifer forest 60-70 years old. Thus, the post logging factors that increase landslide hazard (loss of rooting strength, water diversions, road fillslopes) have recovered. On this basis, the post-logging landslide rates are factored down by 10 to represent “natural” conditions (Table 14). The exception is the Open Slope area above Lots 8-13. In this area, a road-related hazard is also factored into the total risk.

Table 14. Landslide rates ($landslides/km^2/yr$) from formerly logged terrain, British Columbia. Average excludes Haida Gwaii. Reduced by a factor of 10 to represent mature stand (natural) conditions.

Slope (%)	Haida Gwaii	WC VI	Phillips	Capilano	Coast Mtns	Average
35-60	0.0030	0.0028	0.0005	…	0.0005	0.0012
60-100	0.0267	0.0076	0.0060	0.0084	0.0013	0.0058

Since landslide rates are expressed as Landslides/hectare/year (L/ha/yr) the area contributing to the hazard is important. The debris flow prone basins 1-3 flow from steep-sided deep gullies with 100-300 m long steep (>70% slope) sidewalls. This convergence contributes considerable source area to the feeder channel. Debris flows are landslide flowing along steep confined channels. If fed by open-slope sidewall slides, then the debris flow frequency at Basins 1-3 debris cone apices is proportional to the contributing areas of steep terrain in the gullies (Figure 3). The frequency for each basin and the open slope area has been tallied (Table 15).

Table 15. Debris flow frequency for Moonshine Bay basins cone apex or open slope area. Estimated from terrain attribute data (Average frequencies, Table 14).

Subbasin	Area (km^2)	Steep area (km^2)	Probability	Return Interval (yrs)	Climate change (+300%)
1	0.30	0.23	0.0013	760	253
2	0.20	0.11	0.0006	1596	532
3	0.07	0.06	0.0003	2961	987
OS		0.13	0.0008	1302	434
4	0.58	0.21	0.0012	803	268

These hazard frequencies are applied in the Quantitative Risk Assessment below. Note that the landslide rates are reasonable, but not precise measures of hazard. They provide a consistent measure of base hazard, to which other hazards must be considered and added to arrive at total risk.

Debris flooding, avulsion and erosion

As described in the Geomorphic Overview, the channels are reasonably deep and confined, sufficient for much of their length to contain a 200-year flood, but bulking by debris could result in localised rapid aggradation and lateral shifts, or avulsion. There are localised low freeboard areas that would allow for avulsion of debris flow and sediment laded flood flows. Given a debris flow/flood, this hazard is very high (Table 1) affecting Lots 1-3 and Lot 13. This risk factors into the judgement applied in the QRA and Conclusions.

Rockfall

A large area of bluffs lies between 300-500 m elevation directly upslope of Lots 8-11 (Figure 3; Photos 9,10). The lower slopes are formed by a coarse blocky apron extending at 40-60% slope into the lake, and formed of 2-10 m dia rockfall blocks (Photo 10). The bluffs display unfavourable jointing and present point source locations for large rockfall events. As the talus extends to the lake (Photo 11), all shoreline cabins below the bluffs are vulnerable to rockfall. There is no evidence available to quantify rockfall frequency at the shoreline. This risk factors into the judgement applied in the QRA and Conclusions.

Lake flooding

The subject properties are on the shore of Pitt Lake (Photos 1-3). On the lake the average high water during the freshet is about 2.1 m geodetic. The 200year return FCL for the lake is taken to be 5.3 m geodetic (nhc 2005). The elevations of the habitable space within the cabins are not known. No incidence of flooding from Pitt Lake has been reported to Cordilleran Geoscience. The Pitt Lake flood hazard affecting residential space is judged to be LOW. The 200yr return flood elevation needs to be verified/established by survey on the subject properties.

Quantitative Risk Assessment (QRA), Moonshine Bay, Pitt lake

Method and result table

The georisk affecting each lot has been estimated by a Quantitative Risk Assessment (QRA) method. Herein, the risk that is considered is risk to life and limb, *not* property damage. This is an essential point to keep in mind when interpreting results.

QRA requires estimates of probabilities of the hazard and the consequence to estimate risk, as per the formula for individual risk below:

Individual risk = $P_H * P_{S:H} * P_{S:T} * V * E$, where

The risk probability (Table 16) is then estimated for each Lot, as follows:

- P_H - Hazard at cone apex or for open-slope area (Table 15)
- $P_{SHrunout}$ - Spatial affect: slope runout proportion of cone/slope length (0.8-1)
- $P_{SHwidth}$ - Spatial affect: ratio of damage/consulting zone width (0.3-0.8)
- P_{TS} - Temporal exposure: weekends, =2/7, 0.29
- V - Vulnerability: lethal, 1
- E - Individual: 1

A QRA was carried for each lot, as per the following rationale:

- Most lots are affected by two basins, or by an open slope and basin. A very high road fill risk was added to Lots 8-10. The all-hazards risk is the sum of the specific risks.
- The present risk was factored by 300% to represent future landslide risk under climate change, as per the recent report for landslide rate under climate change in Metro Watersheds (BGC 2020).
- Finally, the risk is reduced by 90% to show how mitigating exposure by adhering to weather warning would affect risk tolerance. Restricting visits to only low rain months would include the ratio =7/12, (0.58). However, it is judged that hazard in winter is much higher than summer, so avoidance of winter months is weighted more heavily (0.1).
- Risk probabilities are expressed as the inverse to represent a hazard annual return interval (1/n years). The results are presented in Table 16 below.

The landslide risk is evaluated against Hong Kong Criteria, as applied by District of North Vancouver (2009) and District of Squamish (2017). The life-safety landslide risk criteria for Probability of Death to an Individual (PDI), as follows:

- Unacceptable (red) Individual risk >1/10,000 per annum;
- Tolerable (orange) Individual risk between 1/10,000 - 1/100,000 per annum;
- Broadly acceptable (green) Individual risk <1/100,000

It cannot be over emphasized that Quantitative Risk Assessment, while giving the impression of being precise, is solely a “Bayesian” tool for aiding decision making. Since the input parameters are based on estimates derived from expert judgement, so too are the outcomes. It is best to view the numbers as numerical rankings as opposed to actual risks. The final interpretations need to be further weighted by expert judgement.

Table 16. Preliminary Quantitative Risk Assessment, Moonshine Bay, Lots 1-13. Final results (Table 17) are modified by judgement and will include rockfall for lots 8-11.

Hazard at							Partial Risk	Final Risk Estimate as Annual Return Interval			
								Weekend recreation		Weather Avoidance	
Lot	Hazard	PH	PSHD	PSHW	PTS	V	R	Present	Future CC	Present	Future CC
B1	760	0.0013	0.8	0.8	0.29	1	0.00024				
B2	1596	0.0006	0.8	0.2	0.29	1	0.00003				
L1							0.00027	3716	1239	37158	12386
B1	760	0.0013	0.8	0.5	0.29	1	0.00015				
B2	1596	0.0006	0.8	0.5	0.29	1	0.00007				
L2							0.00022	4506	1502	45063	15021
B1	760	0.0013	0.8	0.3	0.29	1	0.00009				
B2	1596	0.0006	0.8	1	0.29	1	0.00014				
L3							0.00023	4284	1428	42843	14281
B2	1596	0.0006	0.8	0.8	0.29	1	0.00011				
B3	2961	0.0003	0.8	0.1	0.29	1	0.00001				
L4							0.00012	8176	2725	81763	27254
B2	1596	0.0006	0.8	0.3	0.29	1	0.00004				
B3	2961	0.0003	1	0.3	0.29	1	0.00003				
L5							0.00007	13905	4635	139048	46349
B2	1596	0.0006	0.8	0.1	0.29	1	0.00001				
B3	2961	0.0003	1	0.8	0.29	1	0.00008				
L6							0.00009	10927	3642	109267	36422
L7	2961	0.0003	1	1	0.29	1	0.00010	10363	3454	103633	34544
B3	2961	0.0003	0.8	0.7	0.29	1	0.00005				
OS	1302	0.0008	1	0.5	0.29	1	0.00011				
L8							0.00017	6046	2015	60458	20153
RF	100	0.0100	1	0.5	0.29	1	0.00145				
L8							0.00162	619	206	6190	2063
OS	1302	0.0008	1	0.3	0.29	1	0.00007	14966	4989	149655	49885
RF	100	0.0100	1	0.5	0.29	1	0.00145				
9							0.00152	659	220	6593	2198
OS	1302	0.0008	1	0.3	0.29	1	0.00007	14966	4989	149655	49885
RF	100	0.0100	1	0.5	0.29	1	0.00145				
10							0.00152	659	220	6593	2198
11	1302	0.0008	1	0.3	0.29	1	0.00007	14966	4989	149655	49885
OS	1302	0.0008	1	0.2	0.29	1	0.00004				
B4	803	0.0012	1	0.2	0.29	1	0.00007				
12							0.00012	8565	2855	85652	28551
OS	1302	0.0008	1	0.2	0.29	1	0.00004				
B4	803	0.0012	1	1	0.29	1	0.00036				
13							0.00041	2466	822	24657	8219
RF	100	0.0100	1	0.7	0.29	1	0.00203				
13							0.00244	411	137	4106	1369

Hazard codes: B1, Basin 1; B2, Basin 2; B3, Basin 3; B4, Basin 4; OS, Open-slope; RF, Road fill.

Lot 1 (Photo 20).

This lot is located on the composite Basin 1 & Basin 2 cone, adjacent to the active northern portion of Basin 1 cone area. There is an identified avulsion location directly upslope of the cabin (Photos 20, 21; WPs 168, 171).

It is assumed that given a debris flow on either cone, there is an 80% chance the debris would reach the cone margin at Pitt Lake. Further, based on damage width and proximity, there is a 80% of impact from Basin 1 and a 20% chance of impact from Basin 2. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present and future risk is unacceptable; while
- With weather avoidance, present and future risk is tolerable.

Lot 2 (Missing photo)

This lot is located on the composite Basin 1 & Basin 2 cone, removed from the active channel of either cone. There is an identified avulsion location (Photo 21, WP171) directly upslope of the cabin.

It is assumed that given a debris flow on either cone, there is an 80% chance the debris would reach the cone margin at Pitt Lake. Further, based on damage width and proximity, there is a 50% of impact from either cone. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present and future risk is unacceptable; while
- With weather avoidance, present and future risk is tolerable.

Lot 3 (Photos 22, 23)

This lot is located on the composite Basin 1 & Basin 2 cone, adjacent to the Basin 2 channel, and affected by the identified avulsion location on Basin 1 creek.

It is assumed that given a debris flow on either cone, there is an 80% chance the debris would reach the cone margin at Pitt Lake. Further, based on damage width and proximity, there is only a 30% of impact from Basin 1 and a 100% chance of impact from Basin 2. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present and future risk is unacceptable; while
- With weather avoidance, present and future risk is tolerable.

Lot 4 (Photo 24)

This lot is located on the Basin 2 cone, south of the channel. It is also possible that there is a slight risk of impact from Basin 3. It is assumed that given a debris flow on either cone, there is an 80% chance the debris would reach the cone margin at Pitt Lake. Further, based on damage width and proximity, there is an 80% of impact from Basin 2 and a 10% chance of impact from Basin 3. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present and future risk is unacceptable; while
- With weather avoidance, present and future risk is tolerable.

Lot 5 (Photos 25, 26)

This lot is located on the Basin 2 cone, south of the channel. It is also possible that there is a risk of impact from Basin 3.

It is assumed that given a debris flow on Basin 2, there is an 80% chance the debris would reach the cone margin at Pitt Lake; while on Basin 3 the debris would reach the lake. Further, based on damage width and proximity, there is only a 30% of impact from either basin. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present risk is tolerable but future risk is unacceptable; while
- With weather avoidance, present risk is acceptable and future risk is tolerable.

Lot 6 (Photo 28)

This lot is located on the Basin 3 debris cone, north of the channel, and is vulnerable to debris flow. This cabin was damaged during the 2020 debris flow, having its porch ripped off. Otherwise, the main building appears fine. Erosion of the scoured shore-front gravels may lead to future undermining of the foundations, unless bank reinforcement is undertaken. It is also possible that there is a slight risk of impact from Basin 2.

It is assumed that given a debris flow on Basin 2, there is an 80% chance the debris would reach the cone margin at Pitt Lake; while on Basin 3 the debris would reach the lake. Further, based on damage width and proximity, there is only a 10% of impact from Basin 2 and a 80% chance of impact from Basin 3. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present risk is tolerable but future risk is unacceptable; while
- With weather avoidance, present risk is acceptable and future risk is tolerable.

Lot 7 (Photo 29)

This lot is located on the Basin 3 debris cone, on the south side of the channel. The cabin was destroyed in late September 2020 by a debris flow.

It is assumed that given a debris flow on Basin 3, there is an 100% chance the debris would reach the cone margin at Pitt Lake. Further, based on damage width and proximity, there is a 100% of impact from Basin 3. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present risk is tolerable but future risk is unacceptable; while
- With weather avoidance, present risk is acceptable and future risk is tolerable.
- These conclusions may seem unreasonable given the recent destruction of the cabin, and its proximity to the channel. The first thing to note is that risk is estimated as risk to life, not risk of property damage. Further, the apparent lower risk at this site, reflects the hazard level, P_H, which is the lowest of all the basins due to the smaller basin size hence smaller aggregate area contributing to the hazard at the mouth of the basin. Despite the recent occurrence, the long term average hazard remains unchanged. Also note that the regionalised hazard estimate used in this study may not reflect site specific conditions. Judgement is required to further evaluate the risk.

Lot 8 (Photo 30)

This lot is located on the south edge of the Basin 3 debris cone, and is vulnerable to debris flow, open slope slides and rockfall from the steep slope directly above. The building was knocked off its foundation in the 1990 road fill landslide, and later repositioned (see Appendix 2). Then in the late September 2020 debris flow, an avulsion lobe stopped just uphill of the building (WP8) and a small slurry of afterflow debris accumulated to a metre depth along the cabin backwall (Photo 30).

It is assumed that open-slope slides would reach the beach, with 50% chance of impact given damage width; considering a debris flow on Basin 3, there is an 80% chance the debris would reach the cone margin at Pitt Lake. Further, based on damage width and proximity, there is a 70% of impact. A roadfill slide was also considered with high frequency (0.01) and 50% impact by width. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present and future risk unacceptable;
- If road hazard removed then present and future risk remain unacceptable;
- With weather avoidance, present and future risk remain unacceptable;
- With both weather avoidance and road hazard removed then present and future risk are tolerable;

Lot 9 (Photo 31)

This lot is located on blocky talus below the identified rockfall hazard cliffs, and is vulnerable to both open slope slides and rockfall. The left/front of 1990 open-slope slide jammed against mature cedar trees and stopped directly upslope of this cabin (WP91), with the main force veering south toward Lot 10, and a narrow tongue veering northerly to follow the north side of the rockfall cone (WP96) directly to Lot 9. The Lot 9 cabin was encircled by the 1990 slide. This was a near miss.

It is assumed that an open-slope slides would reach the beach, with a 30% chance of impact considering damage width. A roadfill slide was also considered with high frequency (0.01) and 50% impact by width. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present and future risk is unacceptable;
- If road hazard removed then present risk is tolerable and future risk is unacceptable;
- With weather avoidance, present and future risk is unacceptable;
- With weather avoidance and if road hazard removed, then present risk is acceptable and future risk is tolerable;
- Site specific conditions, including very rough blocky surface and shape of the talus cone, may tend to reduce travel to the lowest slopes, or deflect some slides away. But this cannot be quantified at this level of review. Also note that the regionalised hazard estimate used in this study may not reflect site specific conditions. Finally, rockfall hazard was not built into the aggregate risk. Judgement is required to further evaluate the risk.

Lot 10 (Photo 32)

This lot is located amongst blocky talus below the identified rockfall hazard cliffs, and is vulnerable to both open slope slides and rockfall. The 1990 open-slope slide jammed and veered south toward lot 10, with the south margin of the debris lobe reaching the beach within 10 m of the cabin. This was a near miss.

It is assumed that an open-slope slides would reach the beach, with a 30% chance of impact considering damage width. A roadfill slide was also considered with high frequency (0.01) and 50% impact by width. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present and future risk is unacceptable;
- If road hazard removed then present risk is tolerable and future risk is unacceptable;
- With weather avoidance, present and future risk is unacceptable;
- With weather avoidance and if road hazard removed, then present risk is acceptable and future risk is tolerable;
- Site specific conditions may tend to reduce travel to the lowest slopes, or deflect slides, but this cannot be quantified at this level of review. Rockfall hazard was not built into the aggregate risk. Judgement is required to further evaluate the risk.

Lot 11 (Photo 33)

This lot is located amongst blocky talus below the identified rockfall hazard cliffs, and is vulnerable to both open slope slides and rockfall. Although the old road crosses above, no unstable fill was mapped. Legacy road was not factored in to the risk estimate.

It is assumed that open-slope slides would reach the beach, with a 30% chance of impact considering damage width. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present risk is tolerable and future risk is unacceptable; while
- With weather avoidance, present risk is acceptable and future risk is tolerable.

Lot 12 (Photo 34)

This lot is located at the base of the steep open-slope area, and lies on the north edge of the Basin 4 alluvial cone. It is vulnerable to open slope slides, rockfall and debris flow from Basin 4 creek. Although the old road crosses above, no unstable fill was mapped. Legacy road was not factored in to the risk estimate.

It is assumed that open-slope slides would reach the beach, with a 30% chance of impact considering damage width. The debris flow would reach the beach, but risk is 20% based on damage width. Results are presented in Table 16, and summarized/discussed below:

- Under existing management, present and future risk is unacceptable; while
- With weather avoidance, present and future risk is tolerable.

Lot 13 (Photo 35, 36)

This lot is located at the base of the steep open-slope area, and lies on the center of the Basin 4 alluvial cone. It is vulnerable to open slope slides, rockfall and debris flow from Basin 4 creek. The old road crosses above, and one location of unstable fill was mapped on the outside of a switchback (WP203). The legacy road was factored in to the risk estimate.

It is assumed that open-slope slides would reach the beach, with a 20% chance of impact considering damage width. The Basin 4 debris flow would reach the beach, with certain impact. The roadfill debris flow would reach the beach, with 70% chance of impact at the cabin (e.g., smaller event). Results are presented in Table 16, and summarized/discussed below:

- Under existing and future climate conditions, risk is unacceptable;
- If road hazard removed then with weather avoidance present risk is tolerable and future risk is unacceptable;

Risk Management

Risk can be managed by

- complete avoidance (expunge title)
- strategic avoidance (control exposure)
- controlling runout (structural measures)

Structural

Park issues. All land surrounding the Lots is within Pinecone Burke Provincial Park. Any protection works may need to be located on Park Lands. Park authority would be responsible for approvals.

Deflection structures. These are invasive, expensive, and require a management plan and maintenance. Questions arise over authority/responsibility. Deflection structures are typically excavated diversion berms, they require forest removal and ground shaping. It is uncertain that they would be permitted within a park.

Landslide netting. These are less invasive, less expensive, and require management plan and maintenance. Questions arise over authority/responsibility. Geobrugg & Maccaferri are local suppliers that specialize in rockfall and debris flow netting solutions (www.geobrugg.com; www.maccaferri.com) They or other suppliers can be approached for budget estimates.

Figure 4. Debris fencing installed to protect Highway 1 just east of Lytton.

Passive

Complete avoidance. No recreational cabin use. This solution implies expungement of title. Legal advice required. Clearly this solution may be of interest to some title holders and not to others. Discussion with land owners is required.

Strategic avoidance. This can be accomplished by reducing the exposure to the hazard. Open-slope landslides and debris flow are strongly associated with rainfall, and typically occur during fall/winter storms. Avoiding these periods, by observing warnings, substantially reduces the exposure to risk, more than just by the ratio of days avoided (=5/12, 0.42), but also recognizing landslides are triggered by fall/winter storms, and by avoiding these then landslide risk can largely be avoided.

Environment Canada monitors weather and storm tracking and posts rainfall warnings for South Coastal regions[1]. The warnings are based on forecast values of 25-50mm/24 hrs based on season and other conditions. These warnings are broadcast on all media channels including CBC, Global, CTV, and others. The rainfall warning thresholds are well below what would be used in industrial resource operations in very wet terrain in Coastal BC (Statlu 2018), which would indicate a shutdown with 100 mm/24 hr, 150 mm/48 hr, or 200 mm/72 hrs. If tenure holders abided by the September 23, 2020 warning then no persons would have been exposed to the landslide risk. By monitoring Environment Canada or these media outlets, cabin use during periods of elevated hazard can be effectively avoided. The QRA supports this conclusion.

The problem with this measure lies with responsibility. As there is no effective way to ensure cabin owners will monitor warnings nor follow avoidance protocol, then the measure relies on the honour system, and the continuing awareness of future lease holders. One measure to ensure continued awareness is to ensure lease documents carry appropriate language describing monitoring and avoidance protocols, and save harmless clauses. Then the responsibility falls to the tenure holders to abide, and the liability shifts to them. Legal advice is required to verify this opinion.

Residual risk

The landslide risk assessment is reasonable, but is a simplification. Firstly, it is assumed to be risk to life, rather than to property. Thus, destruction of a cabin is considered acceptable risk, as long as it was not occupied. There are other residual risks to consider. Rockfall may not be fully captured by rainfall warning as frost days also a factor. However, if rockfall hazard frequency at the lakeshore is low to start, then the residual risk is low in comparison. Post-fire landslide rates may be greatly increased within 3-10 yrs of a severe burn. The occurrence of fire will temporarily increase landslide risk, as would renewed logging. These are short terms (1-10 yr) elevated risks, which would gradually lapse to long-term background.

[1] https://www.canada.ca/en/environment-climate-change/services/types-weather-forecasts-use/public/criteria-alerts.html#rainfall

Conclusions

- Previous overview geohazard studies have documented very high to moderate hazard levels (Table 1) affecting cabins at Moonshine Bay. Previously identified hazards included debris flow, debris slide, mountain stream avulsion, flooding and erosion and rockfall.
- In the historic period there have been two landslides causing damage or destruction to recreational cabins, the fall of 1990 open-slope slide from unstable road fill, and the Sept 2020 natural gully channel initiated debris flow. Neither event caused fatality. These two events highlight and support the previous conclusions.
- In light of the recent destruction of the cabin on Lot 7 and damages to cabins on Lot 6 and Lot 8, a review of the landslide risk affecting all lots was undertaken.
- Hazard was estimated using landslide rates from terrain attribute studies conducted elsewhere in Coastal BC. When used to compare risk across basins, this measure allows a repeatable methodology. The hazard levels may not represent actual hazard at any specific site, nor was rockfall hazard able to be explicitely incorporated. Thus outcomes from the analysis (Table 17) have been weighted using professional judgement.
- Note that risk is estimated as life-loss, not property damage. Life-risk exposure assumed recreational use, restricted to weekends only. Estimated risks were then factored to account for climate change, and for mitigation by strategic avoidance. Note that if risk exposure assumed residential occupancy, then landslide risk would be unacceptable across the board.
- The results from the QRA and judgment combined are expressed in Table 17.

Table 17. Life-loss risk from QRA, adjusted by judgement. CC is climate change.

	Weekend use, unrestricted		Weather Avoidance		
Lot	Present	Future CC	Present	Future CC	Comment
1	Unacceptable	Unacceptable	Tolerable	Tolerable	
2	Unacceptable	Unacceptable	Tolerable	Tolerable	
3	Unacceptable	Unacceptable	Tolerable	Tolerable	
4	Unacceptable	Unacceptable	Tolerable	Tolerable	
5	Tolerable	Unacceptable	Tolerable	Tolerable	
6	Tolerable	Unacceptable	Tolerable	Tolerable	Damaged 2020
7	Tolerable	Unacceptable	Tolerable	Tolerable	Destroyed 2020
8	Unacceptable	Unacceptable	Tolerable	Tolerable	Damaged 2020
8	Unacceptable; roadfill		Unacceptable; roadfill		Damaged 1990
9	Tolerable	Unacceptable	Tolerable	Tolerable	
9	Unacceptable; roadfill		Unacceptable; roadfill		Near miss 1990
10	Tolerable	Unacceptable	Tolerable	Tolerable	
10	Unacceptable; roadfill		Unacceptable; roadfill		Near miss 1990
11	Tolerable	Unacceptable	Tolerable	Tolerable	
12	Unacceptable	Unacceptable	Tolerable	Tolerable	
13	Unacceptable	Unacceptable	Tolerable	Unacceptable	Flood damage,
13	Unacceptable; roadfill		Unacceptable; roadfill		date unknown

- This report was conducted to aid land managers with decisions about how to ensure public safety. Structural measures may be employed, but the presence of Park Land and the associated cost may limit the opportunity for extensive earthen deflective berms. Less invasive structures such as rockfall and debris flow netting might be considered. The problem with any structural measure is who holds responsibility for monitoring and maintenance. That may be a hurdle that prevents this option.
- Passive measures rely on forms of avoidance. Complete avoidance, implying expungement of tenure, eliminates the risk; it may also eliminate safe and enjoyable use during dry summer season months. Since the intended use is recreational, this option appears to be too extreme. Nevertheless, it deserves discussion, and may find acceptance with some tenure holders.
- Strategic avoidance, by voluntarily monitoring Environment Canada warnings and avoiding occupancy when warnings are posted, will reduce life-loss risk to tolerable levels in most cases. The exception is for sites where legacy roads with identified fillslope instabilities exist above cabins. In these cases, when the roadfill hazard is factored in, the risk becomes unacceptable. The issue with this measure is the responsibility lies with the tenure holder, and the Crown will require a mechanism that renders them "Save harmless."

Caveat

This report is for risk management decision making purposes only. It is not to be used to evaluate future building permit approvals. An independent assessment by a qualified professional will be required to assess any specific building proposals.

References

BGC, 2019. Metro Vancouver projected climate change effects on landslides in Metro Vancouver watersheds. Report to Metro Vancouver.

Jakob, M., 2005. A size classification for debris flows. Engineering Geology, 79: 151-161.

Jakob, M., Bovis, M., and Oden, M., 2005. The significance of channel recharge rates for estimating debris-flow magnitude and frequency. Earth Surface Processes and Landforms, 30, 755–766.DOI: 10.1002/esp.1188

JMRATA, 1999. Annex to GVRD Watershed Analysis Report February 1999. *In* Acres International, 1999. GVRD Watershed Ecological Inventory Program, Annex to the Analysis Report. Watershed Management Plan #5, Volume I. Prepared by Acres International, B. Thompson, B.A. Blackwell and Associates, J.M. Ryder and Associates Terrain Analysis, Northwest Hydraulic Consultants Limited, Oikos Ecological Services Ltd., Phero Tech Inc., Timberline Forest inventory Consultants. 268 pp

Gariano, S.L., and Guzzetti, F., 2016. Landslides in a changing climate. Earth-Science Reviews, 162: 227-252.

Hungr, O., Morgan, G.C., and Kellerhals, R.S., 1984. Quantitative analysis of debris torrent hazards for design of remedial measures. Canadian Geotechnical Journal, 21, pp. 663-677.

Lian, O., and Hickin, E.J., 1991; Early Postglacial Sedimentation of Lower Seymour Valley, southwestern British Columbia. Géographie physique et Quaternaire, 1996, 50(1): 95-102.
Millard, Rollerson & Thomson 2002, Post Logging landslide rates in the Cascade Mountains, SW BC, MoF technical report TR-023.
Millard, T.H., D.J. Wilford and M.E. Oden. 2006. Coastal fan destabilization and forest management. Res. Sec., Coast For. Reg., BC Min. For., Nanaimo, BC. Tec. Rep. TR-034/ 2006.
MOTI (Ministry of Transportation and Infrastructure). 2009, revised 2013 and 2015. Subdivision Preliminary Layout Review – Natural Hazard Risk, internal document, March 13, 2009
MoE, 1999. Terrain stability mapping, Landslides, hazards, consequences and risks, Ministry of the Environment, Lands and Parks, Victoria, BC, Canada.
MoFLNRO, 2014. Land Procedure Landslide Risk Management. Assistant Deputy Minister, Tenures, Competitiveness and Innovation, Ministry of Forests, Lands and Natural Resource Operations, Victoria, BC.
Porter & Morgenstern 2013. Landslide Risk Evaluation – Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction; GSC, Open File 7312, 21 p.
Nhc 2005. Harrison and Pitt lakes shoreline hazards: hydrogeomorphic hazard assessment. Report to Pottinger Gaherty Environmental Consultants Ltd.
Rollerson, 1992. Relationships between landscape attributes and landslide frequencies after logging - Skidegate Plateau, Queen Charlotte Islands. Land Management Report No. 76. Ministry of Forests, Victoria, BC, Canada. 11 p.
Rollerson, Thomson and Millard 1998. Post-logging terrain stability in Clayoquot & Barkley Sound. In Proceedings of the 12th Annual Vancouver Geotechnical Society Symposium on Site Characterization. Vancouver Geotechnical Society, Vancouver, BC. 13 p.
Rollerson, Jones, Trainor, Thomson 2001. Predicting post-logging landslide activity using terrain attributes: Coast Mountains, BC, MoF technical report TR-011
Rollerson, Millard & Thomson 2002, Using terrain attributes to predict post Logging landslide rates SW Vancouver Island, BC, MoF technical report TR-015.
Rollerson, Maynard, Higman, & Ortmayr 2005. Phillips River landslide hazard mapping project. In Landslide Risk Management, Hungr, Fell Couture (eds), Taylor Francis Group, London.
Statlu 2018. Wet weather shutdown criteria harmonization, BCTS Chinook and Strait of Georgia Business Areas. BC Timber Sales, Strait of Georgia Business Area, Campbell River, BC.
Thurber Engineering Ltd., 2004. Crown lease lots on Pitt and Harrison lakes, BC: reconnaissance level geological slope hazard assessment. Report to nhc.
Wilford, D.J., Sakals, M.E., Grainger, W.W., Millard, T.H., and Giles, T.R., 2005. Managing forested watersheds for hydrogeomorphic risk on cones, Land Management Handbook 61. BC Ministry of Forests and Range, Victoria.
Wilford, Sakals and Innes, 2005. Forest management on cones: hydrogeomorphic hazards and general prescriptions. MoF Land Management Handbook 57

Closure

This report was prepared for use by MoFLNRO, Metro Vancouver and tenure holders identified in this report, including distribution as required for purposes for which the report was commissioned. The report cannot be distributed to other third parties without prior written consent by Cordilleran Geoscience. The work has been carried out in accordance with generally accepted geoscience practice. Judgment has been applied in developing the conclusions stated herein. No other warranty is made, either expressed or implied to our clients, third parties, and any regulatory agencies affected by the conclusions.

If you have any questions please call,

Pierre Friele, M.Sc., P.Geo.

Professional Geoscientist

Annotated Photos

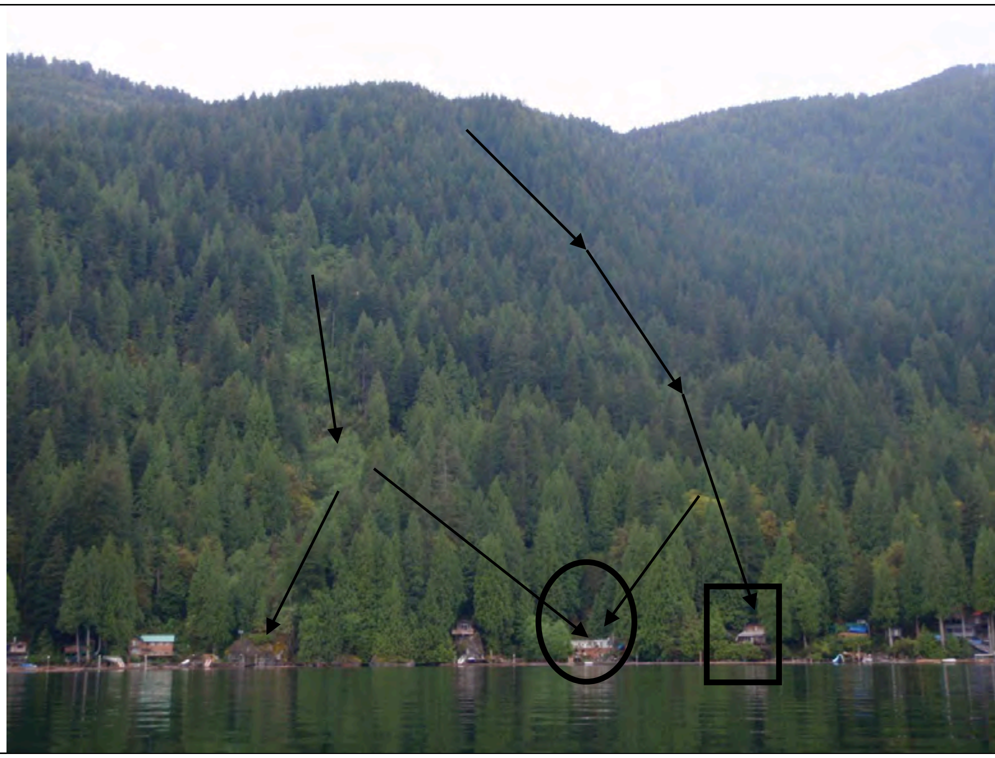


Photo 1. View west showing slopes above Lots 5-10. On left (south) the black arrows identify the 1990 debris slide track. The circled cabin is on Lot 8. On the right (north) the black arrow is the 2020 track. The destroyed cabin on Lot 7 is shown by the black rectangle.

Photo 2. Lots 3-7. 2009. View west. Structures with the red roofs are Lot 5 cabins. The destroyed lot 7 cabin is far left with green roof.

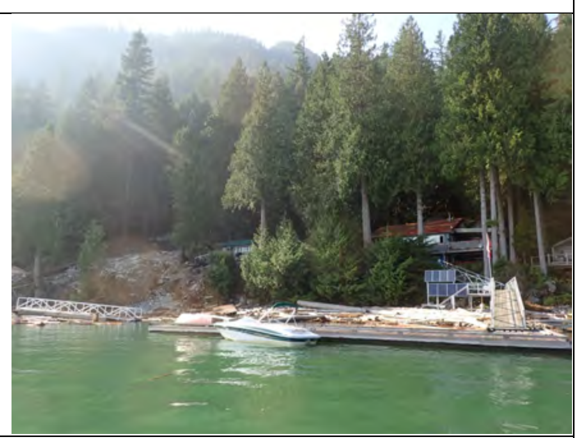


Photo 3. Lots 5-7. 2020. View southwest. Structures with the red roof is Lot 5 cabin. The destroyed lot 7 cabin was far left.

Photo 4. Zone of fillslope failures start 30m south of Waypoint 192. View south.

Photo 5. Fillslope failure at WP193. View north.

Photo 6. Fillslope failure at WP193. View south.

Photo 7. Unstable fillslope at WP194. View south. Note shovel stuffed into tension crack.

Photo 8. Unstable fillslope at WP196. View south. Note the shovel for scale.

Photo 9. Rockfall source area in the vicinity of Waypoints 205-206.

WP10. View south showing rockfall cone. Note 10 m diameter megablocks.

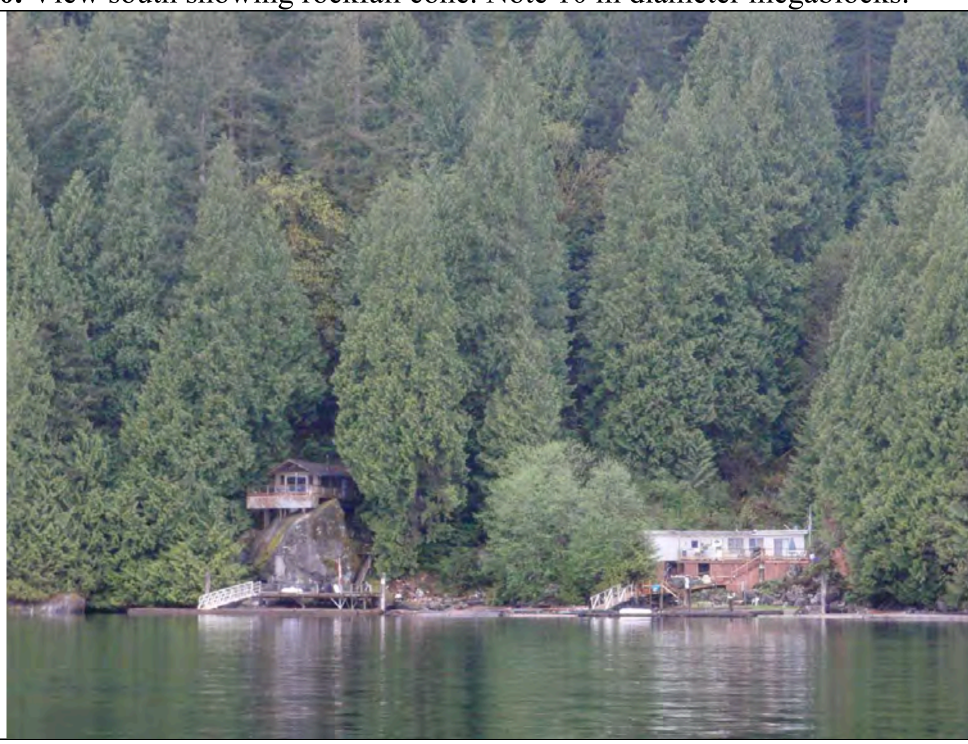


Photo 11. Lot 9 Cabin (left) built on large rockfall block below rockfall source area (Waypoints 205-206). Lot 8 cabin (right) was knocked off its foundation by 1990 debris slide. Lot 9 experienced a near miss, and was not affected because trees caused a jam and diverted the landslide toward Lot 8.

Photo 12. WP54. View up into rock slot canyon from headscarp in channel.

Photo 13. WP54. View down from headscarp in channel.

Photo 14. WP 51. view down upper reach of debris flow track. Note scoured rock channel.

Photo 15. WP41. Note thick till deposits. Assume 0.25-1 m scour across scoured perimeter.

Photo 16. WP36. Lot 7. Cedar clump split debris flow causing avulsion to south.

Photo 17. WP34. Basin 3. Debris cone left bank section in cone deposits. From lower left: grey, slope-parallel bedded paraglacial cone delta gravels; onlapped from center to right, by downslope thickening wedge of humic-stained Holocene debris flow diamict.

Photo 18. WP33-34. View east along lower track to Lot 6 (left)(near miss) and Lot 7 (right)(destroyed house not visible as it had been burnt during cleanup).

WP19. Avulsion lobe stopped short of Lot 8 cabin. Afterflow slurry ponded against cabin wall (Photo 30).

Photo 20. WP168. Cabin on Lot 1. The south edge of the active braided creek channel from Basin 1 adjacent with the north side of the lot.

Photo 21. WP171, wood and boulder jam above Lots 1-3, potential avulsion point.

Photo 22. WP185. Cabin on Lot 3. View south to back wall. Note large angular block at SW corner.

Photo 23. WP185. Cabin on Lot 3. View east down Basin 2 creek. Note only 2 m relief to south side of cabin on left bank.

Photo 24. WP74. Lot 4. View northeast. Cabin notched into top of foreshore slope representing truncated cone toe.

Photo 25. WP75. Lot 5. View SE to cabin built at crest of foreshore slope.

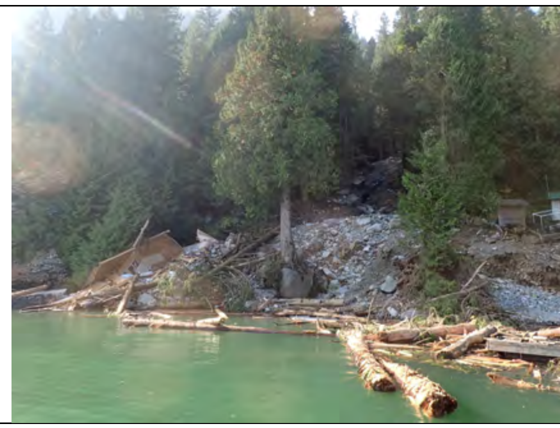
	
Photo 26. WP75. Lot 5. View east to cluster of accessory cabins. South edge of 30% sloping Basin 2 creek debris cone.	**Photo 27.** WP32. Lot 6. View west showing north (right) edge of debris flow track which tore porch off cabin. Cabin otherwise intact.
	
Photo 28. WP32. Lot 6. View down along lower north side of 2020 track, just missing cabin and accessory building.	**Photo 29.** WP32. Lot 7. View east to south (left) edge of 2020 debris flow track and destroyed cabin, since burnt as part of cleanup activity on the lot.

Photo 30. WP97. Lot 8. Back of cabin affected by 2020 afterflow slurry, accumulated to 1 m depth. In 1990, this cabin was knocked off its foundation and then reset in its present position (see Appendix 2)

Photo 31. WP99. Cabin on Lot 9. House built on talus, aCk, 60%, 5-10 m sized blocks

Photo 32. Cabin on Lot 10. The 1990 debris flow just missed (<10 m) the north (right) side of this building. Note the box culvert & creek beneath the cabin.

Photo 33. Lot 11. South edge of rockfall talus at beach. Cabin tucked into steep slope.

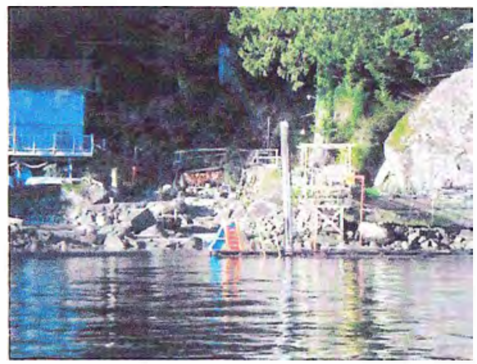
Photo 34. Lot 12. Cabin tucked into foot of steep hill. Back of cabin is a small creek/ncd diverted by concrete flume. Note littoral is armoured by boulders and vulnerable to wave attack.

Photo 35. Lot 13. Note creek passes directly beside south wall of cabin.

Photo 36. Lot 13. View from debris jam at head of small cone. Note tarped roof visible to left of channel downstream..

Appendix 2. Slide that hit Moonshine Bay in 1990

These are photos of the area that was hit by a large slide in the fall of 1990 the slide hit lots G of DL 6914 and separated and went around Lot and hit Lot of Moonshine Bay



App 2, cont'd. Slide that hit Moonshine Bay in 1990

The photo on the top left shows the trailer on Lot G DL 6914 before the slide. The photos on the top right and bottom left show being hit by the slide and the photo on the bottom middle is after the slide and the trailer place on cribbing again **Note trailer is level**. The photo on the bottom right is of the trailer in 2001 when I purchased it. **Note it has settled on the left end** due to unstable soil conditions.