The Village of Lions Bay:
A Natural Hazards Assessment Area Strategy for Coastal, Creek and Hillslope Hazards.

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1. Introduction

The Village of Lions Bay is a residential community located on the east side of Howe Sound, southwestern British Columbia, approximately 10 km NE of Horseshoe Bay, West Vancouver. It is part of the Metro Vancouver Regional District. The first residences were developed in the 1960s and the Village was formally incorporated in 1971.

The timing of development just precedes the beginnings of landslide hazard/risk management in British Columbia. At Rubble Creek below the Barrier, near Whistler, the Garibaldi Station subdivision expropriation (~1971) and subsequent court case established a precedent for land use decisions based on perceived risk (Berger 1973). At the same time (~1974/75), there was reversal on subdivision approval on Cheekye fan in Squamish; the Cataline subdivision of Lillooet Lake was permitted with conditions with respect to debris flow hazards (Piteau 1976); and Sunset Highlands, West Vancouver, was permitted with conditions specific to rockfall hazard (Piteau 1981).

At Lions Bay, the sidewall of Howe Sound rises steeply from sea-level to the ridge crest at 1500 m elevation, with the highest peaks being Brunswick Mountain at 1788 m and the West Lion at 1646 m. There are several large watersheds which bisect the fjord sidewall and traverse the community, including Magnesia Creek, Alberta Creek and Harvey Creek. Smaller creeks include Battani, Upper Bayview and Rundle creeks.

Given this steep terrain and the coastal maritime setting there are a number of geohazards that may affect the community. These include coastal hazards, creek hazards and hillslope hazards. While there is existing Provincial legislation that gives local government the authority to require geotechnical assessment on a case by case basis when triggered by development proposals, to date, due to establishment of the Village before geohazards were regularly considered in development approvals, the Village of Lions Bay has no overarching hazard and risk management framework that allows a consistent approach to guide land development. This is the first all-hazard (coast, creek & slopes) review for the Village of Lions Bay.

2. The Concept of Hazard & Risk

A hazard is a phenomenon with the potential to cause harm; it is usually represented by a magnitude and recurrence interval (see Table 1). Consequence (Table 2) is a product of factors, including whether a given hazard will reach a site, whether elements at risk (e.g., houses/people) will be present when the site is affected by the hazard, how vulnerable the elements at risk are to the hazard affecting the site, and the value of the elements at risk or the number of persons exposed. The product of the factors Hazard and Consequence equals Risk.

No activity is free of risk, and the concept of safety embodies risk tolerance. In Canada and BC there is no legislated guidance for risk tolerance to geohazards, and the term “safe” has not been defined. In considering risk tolerance, an important concept is that risk of loss of life from natural hazards should not add substantially to those that one is typically subject to (e.g., driving, health, recreation, etc) combined. For reference, the risk of death and injury from driving in Canada is approximately 1:10,000 and 1:1000 per annum, respectively (Transport Canada 2011).

Table 1. Qualitative hazard frequency categories.

Qualitative frequency	Annual return frequency	Probability	Comments
Very high	>1:20	>90% in 50 years	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	40% to 90% in 50 years	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	10% to 40% in 50 years	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	2% to 10% in 50 years	The hazard is of uncertain significance.
Very low	<1:2500	<2% in 50 years	The occurrence of the hazard is remote.

Table 2. Simplified consequence assessment.

Consequence	Description
Very High	Direct impact with extensive structural damage; loss of life & limb.
High	Direct or indirect impact with some potential for structural damage; loss of life & limb.
Moderate	Indirect debris impact. No structural damage but damage to houses and property.
Low	Minor property damage only.
Very Low	Virtually no damage.

3. Project Scope

The purpose of this report is to review geohazards affecting the Village of Lions Bay and to create a Natural Hazards Assessment Area (NHAA) planning framework to provide a consistent basis for managing georisk.

This report will identify potential hazards and assess the potential reach of these hazards. It is beyond the scope of work to assess the frequency of occurrence of identified hazards, as that is typically a very detailed assessment, often requiring subsurface examination, stratigraphic analysis, radiometric dating of soil layers and advanced computer modelling. Thus, this report cannot make judgements on hazard or risk acceptability at any given site. To avoid deeming an area safe, when in fact rare but destructive hazards might affect a site, the Natural Hazards Assessment Areas (NHAA) framework needs to be conservative, erring on the side of caution.

The primary deliverable will be a Natural Hazards Assessment Area (NHAA) framework that will provide a rationale for development based on existing professional guidelines and regulations. The proposed NHAAs are based on review of the geomorphic setting, site-specific geotechnical reports, historic airphotos, high resolution topographic mapping and field observation.

The work was conducted by Pierre Friele, M.Sc., P.Geo., of Cordilleran Geoscience with internal review and technical support provided by Gioachino Roberti, M.Sc.

4. Geomorphic Context

4.1 Bedrock geology

Bedrock geology within Village of Lions Bay consists of lower-Cretaceous Gambier Group marine sedimentary and volcanic rocks (imapbc, https://maps.gov.bc.ca/ess/hm/imap4m/). Outcrops viewed in the field appear primarily to consist of greenish volcanic rock that is highly fractured (decimeter fracture spacing) with red oxidation on exposed surfaces. Upslope, the headwaters of Magnesia, Alberta and Harvey Creeks are underlain by mid-Cretaceous granodiorite of the Coast Plutonic Complex which has intruded into the older Gambier rocks. These plutonic rocks are more competent. Prominent northwest trending faults and jointing creates structural discontinuities that may be source of instability.

4.2 Quaternary history and surficial geology

Surficial geology in the area is a product of Pleistocene glaciation and post-glacial erosional processes (Blais-Stevens 2008). The last, or Fraser, glaciation began 33,500 years ago (all ages converted to calendar from radiocarbon scale) and reached its peak 17,500 years ago. Howe Sound south of Porteau Cove was ice free by 15,000 yr BP (Fairbanks et al. 2005), but ice retreat was delayed several thousand years by grounding, with several minor readvances forming the Porteau end moraine (Friele and Clague 2002). The inner basin of Howe Sound was not ice free until after 12,500 yr BP. According to Jackson et al. (2014), glacial marine sedimentation (mud with stones dropped from icebergs) had ceased by 10,600 yr BP.

The weight of Pleistocene ice depressed the land surface. During deglaciation, the sea flooded the land to a level of up to 220 m higher than today. Sea-level fell rapidly as the land rebounded such that by about 10,000 years ago sea-level had fallen to 10 m below present. By 5700 years ago sea-level had risen to approximately modern levels (Clague et al. 1982).

Morainal materials deposited during the last glaciation are known as Vashon Drift (a complex of till, glaciofluvial and glaciolacustrine sediments) (Photo 1). Glaciofluvial deltaic and glaciomarine sediments were deposited up to an elevation of 220 m (Photo 2). These sediments are known as Capilano Formation. Glaciofluvial deltaic sediments are found in the gravel quarry at Magnesia Creek (120-140 m elevation) and the fan-delta morphology extends upslope to its apex at 280 m elevation, while bouldery fan-delta sediments at Harvey Creek extend up to 220 m elevation. Fine grained marine sediments are typically found on benchlands, such as the east point of Anvil Island where clays were mined for manufacturing of brick.

Following deglaciation, fluvial and mass wasting processes rapidly reworked glacial sediments (Lian and Hickin 1996; Friele et al. 1999). Process rates declined over time such that by no later than 7,500 years ago the landscape was similar to today (the paraglacial paradigm; Church and Ryder 1972). In Howe Sound, in subaqueous fjord settings, Jackson et al. (2014) reported that in areas removed from valley side influence significant deposition had ceased by 10,600 yr BP, but in fjord sidewall areas within influence of debris fan-deltas at Lions Bay significant sedimentation did not cease until 5500 yr BP. While mass movement processes were much more active in the deglacial and immediate post glacial periods owing to the steep relief, these processes are still active today (Jordan and Slaymaker 1991; Friele and Clague 2009), albeit at a much-reduced rate.

Post-glacial sediments, formed in modern colluvial, fluvial and beach environments, are referred to as Salish sediments. In post-glacial time, erosion by streams and mass movement (debris slides, debris flow, rockfall, rock avalanche, snow avalanche) will have continued to rework bedrock and soil mantled slopes. Steep rockfall talus aprons have developed on mid to lower slopes (Photo 3). Magnesia, Alberta and Harvey Creeks have become incised into their respective paraglacial debris cones and inset alluvial fans have formed at their mouths.

4.3 Climate

Howe Sound is subject to a maritime climate with moderated temperature regime and winter precipitation peak driven by cyclonic storms. Climate Normals (Environment Canada, 2017) for a nearby station, Squamish STP at 4 m elevation, are provided in Figure 1. Temperatures are cool from December through February, rising to a peak in July and August. There is a pronounced precipitation peak starting in October and extending through January, diminishing to a low in June through September. At that station, mean annual precipitation is 2230 mm and the extreme recorded daily precipitation was 128 mm/24 hrs on February 1, 1991.

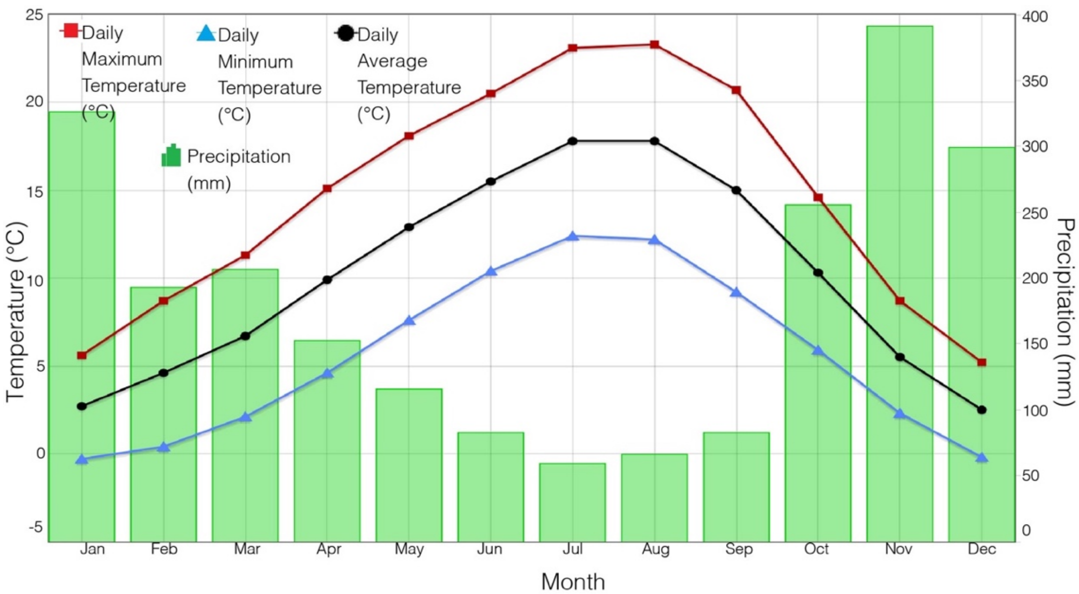


Figure 1. Temperature and Precipitation Graph for 1981 to 2010, Canadian Climate Normals, Squamish STP (4 m elevation).

Precipitation is strongly enhanced with elevation as mountain slopes drive air masses upward, a phenomenon known as orographic uplift. Climate statistics (2001-2010) for various elevations were estimated using the web-based tool ClimateBC (http://www.climatewna.com/ClimateBC_Map.aspx) and are presented in Table 3. Annually, approximately 2000 mm precipitation falls at sea-level, increasing to 4000 mm at the ridge crest. Assuming a wet snow density of 50%, then 15 cm of snow, amounting to 5% of winter precipitation, may be experienced at sea-level, increasing to 1 m, or 25% of winter precipitation, at mid elevation and 3 m, or 50% of winter precipitation, at the ridge crest. This indicates that at mid and high elevations, both rain and rain-on-snow are important drivers of winter runoff.

Table 3. Climate statistics for Lions Bay, showing the effect of elevation.

Elevation (m)	Mean annual temperature (C)	Mean annual precipitation (mm)	Mean winter precipitation (mm)	Precipitation as snow (mm water equivalent)
0	9.3	1938	1552	83
500	8.2	2228	1779	158
1000	5.7	3106	2464	635
1500	3.1	3872	3055	1665

Intensity-duration-frequency (IDF) curves were prepared for Metro Vancouver by BGC (2009). Their Zone 8, the North Shore Mountain slope, is most representative of conditions at Lions Bay. The IDF for Zone 8 is provided in Table 4. It indicates that a 24hr rainfall of about 100 mm would be considered a 2-year storm, while a 100 yr storm could deliver upwards of 200 mm/24 hrs.

Table 4. Intensity-duration-frequency data (mm/hr) for Zone 8, Metro Vancouver. Source: BGC 2009.

Duration	2-year	10-year	50-year	200-year
1 hr	14.9	23.2	30.4	36.5
24 hr	3.9	6.2	8.1	9.8
48 hr	2.9	4.6	6.1	7.3
72 hr	2.5	3.9	5.1	6.2

4.4 Hydrology

MacKay Creek in North Vancouver provides a good analog for the hydrologic regime in Lions Bay creeks (Figure 2). From October through April, the hydrologic base level is driven by rain and rain on snow, and sustained from May through June by a snowmelt freshet. Instantaneous storm peaks may occur in any season, but typically in the fall and early winter, from October through December.

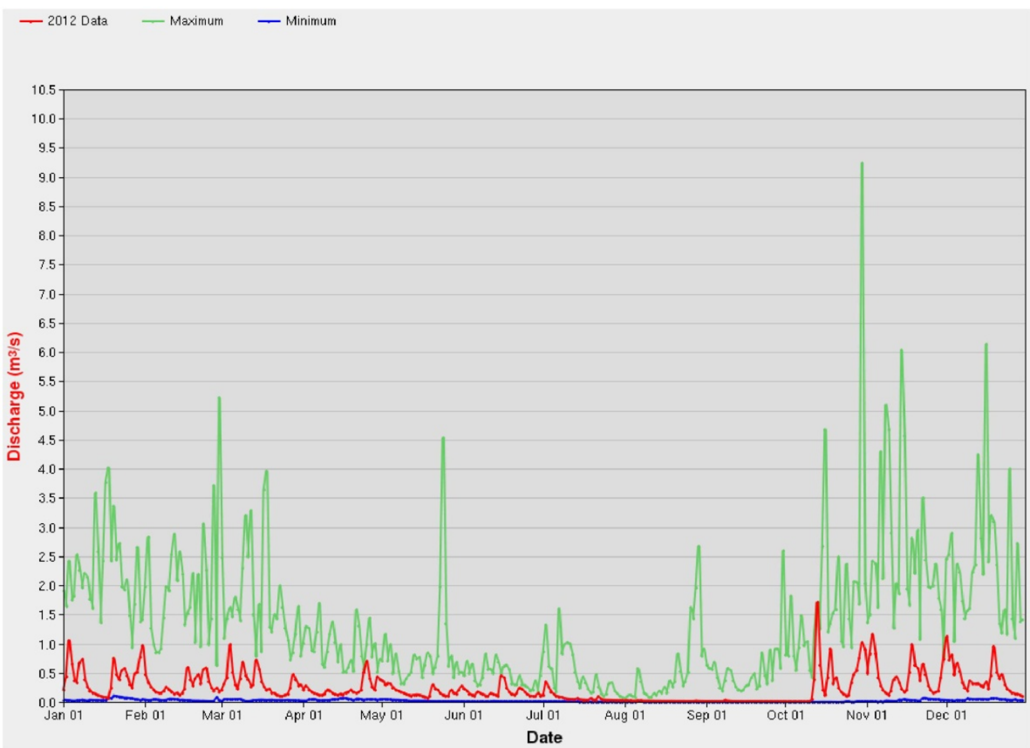


Figure 2. Daily discharge Mackay Creek at Montroyal Boulevard (08GA061), 1970-2012. Basin area is 3.63 km^2, compared to 7, 1.2 and 4.7 km^2 for Harvey, Alberta and Magnesia creeks respectively.

5. Methods and Materials

5.1 Background review

A list of background documents provided by the Village of Lions Bay have been reviewed and summarised below and in Appendix 1.

5.2 Airphoto review

Table 5 provides a list of airphotos reviewed for this project. The area includes Lions Bay and areas to the north including M-Creek. Airphoto flight lines include the years 1939, 1946, 1957, 1968, 1979, 1982, 1992, 1996 and 2004.

Table 5. Airphotos reviewed in this study.

SRS6935:70-64	BCB92019:109-105	BC87066:154-152	BC79194:62-59
BCC96124:108-99	BCB92019:38-40	BC82058:70-75	BC79193:246-249
BCC96078:104-106	BC87066:31-33	BC82060:125-122	BC7116:105-101
BCB92019:111-115	BC87066:90-88	BC79194:80-83	BC7177:214-218
BC7177:190-186	BC2349:51-49	BC134:84-80	
BC7115:227-229	A10398:93-91	BC143:79-82	
BC2348:85-78	A10398:114-116	BC143:77-75	
BC2349:18-25	A10396:44-40		

These airphotos have been reviewed many times by previous authors to identify landslide events affecting torrents channels. In this study, we applied a new photogrammetric technique, Structure from Motion (SfM), to generate orthophotos and Digital Elevation Models (DEMs) for subsequent photo years. The intent was to provide a chronology of land development from orthophoto observations, and, following the methods outlined by Roberti et al. (2017), to test if DEMs could be differenced to identify areas of slope movement. The orthophoto analysis provided valid information but the topographic differencing did not provide good results. Due to poor photo quality, and tree cover in areas of interest, the required DEM accuracy could not be achieved. Orthophotos and DEMs are provided for use of Village of Lions Bay.

5.3 LIDAR base map

In 2012, airborne LIDAR was flown for Lions Bay. Various products including hillshade, slope thematic and high resolution (e.g., 1 m contour interval) topographic mapping were derived from the LIDAR. The hillshade model shows ground surface expression in great detail and is utilised to map specific landforms and structural features. Slope thematic mapping is useful in delineating areas with different landslide susceptibilities, as slope is characteristic of certain landform types, like fans, talus or ravine slopes, and is one of the primary factors governing stability. Slope classes used include 0-30%, gentle terrain including debris fans; 30-50%, moderate sloping terrain with variable cover; 50-60% and 60-70%, moderately steep terrain with variable cover; and 70-90% for steep terrain, typically rock covered with till and colluvial veneer; and >90% slopes typically bedrock outcrop. Topographic maps are similarly useful. All derived map bases are georeferenced and are used within Tablet devices for field mapping. The Geomorphic

Map and Natural Hazard Assessment Area Maps that accompany this report are presented at 1:10,000 scale, with 5 m contours, hillshade and slope theming. For final presentation, slope theming is averaged over 10 m pixels to smooth anthropogenically terraced topography.

5.4 Cadastral data

The Village of Lions Bay has provided shapefiles delineating lots and spreadsheets with various information for each.

5.5 Field traverses (Map 1)

Field traverse conducted by Cordilleran in Lions Bay include:

- On November 9, 2011, the terrain in the vicinity of the water tank near Rundle Creek was examined.
- On April 26 and May 8-9, 2012, Cordilleran traversed slopes between Alberta and Magnesia Creek to assess terrain potentially affected by the old logging road, now the Harvey Trail.
- On July 6, 2012, the vicinity of Rundle Creek was traversed to examine the potential consequence of windthrow.
- On October 26, 2014, Cordilleran conducted a review of a small landslide that occurred directly upslope the Harvey Creek water intake.
- On June 9, 2016, Cordilleran conducted a review of the terrain within and downslope of the newly identified potential rock avalanche scarp.
- In 2017, as part of this project, field traverses were conducted on October 17, 25, and November 2, 8, 9 & 29.

5.6 Maps and Appendices

All observation sites from traverses indicated have been plotted on the appended Map 1 to provide an indication of the level of ground truthing. Map 2 provides an overview of Geomorphic Features. Maps 3-9 delineate Natural Hazard Assessment Areas (NHAAs).

Appendix 1 provides summaries of site specific reports. Appendix 2 gives a list, gleaned from Septer (2006), of geohazards affecting east side of Howe Sound near Lions Bay. Appendix 3 presents annotated photos from select field observation sites discussed in the report text.

6. Background Reports

6.1 Channelised torrents and highway cut rockfalls, Howe Sound

Since the development of the highway in the 1960s and the occurrence of numerous destructive debris torrents on steep creeks in the early 1980s, rockfalls and channelized debris flows affecting the highway, and mitigation of both, have featured in numerous reports.

Reports by Hungr and Morgan (1984), Hungr et al. (1984), Lister et al. (1984), VanDine (1985) and Bovis and Dagg (1987) describe the steep creek debris flow, or “torrent” phenomenon and provide methodologies to identify, assess magnitude and frequency, and design remedial measures. Such measures were implemented in Lions Bay in 1985 and 1987 on Magnesia, Alberta and Harvey Creeks, and on other steep channels affecting Highway 99 along Howe Sound.

Reports by Bunce et al. (1997) and Hungr et al. (1999) document the rockfall hazard affecting highway and railway corridors in BC with special attention to Highway 99.

Eisbacher (1983), Evans and Savigny (1994) and Couture and VanDine (2004) (and others) are field trip guidebooks that draw from earlier reports to present useful summaries of the hazards in the region. Earle (2003) provides a very nice collection of photos documenting the damages caused by the 1980s debris flows and the construction of remedial measures.

The Septer (2006) and Blais-Stevens (2008) reports are catalogues of flood and landslide hazard events collated from media and other reports. The Septer (2006) document was scanned using the keywords Lions Bay, Magnesia, Alberta, and Harvey to create a list of hazards that have affected the Lions Bay area in historic time (Appendix 2). Aside from the well-known creek and rockfall hazards that have affected the Lions Bay area, some useful insight into the Upper Bayview area was gained, documenting the timing of the diversion of Upper Bayview toward Alberta Creek and subsequent slope instabilities that resulted in 1972 affecting several properties.

6.2 Site-specific reports in Lions Bay

Several site-specific reports conducted within Village of Lions Bay were reviewed for this project. Short summaries of each are provided in the Appendix 1. Overall, the reports provide an indication of the types of hazard issues affecting Lions Bay, including rockfall (Golder 1989; Fieber Rock Engineering Services, 2011; Geopacific 2016); open-slope slides (Cordilleran 2014a; BGC 2012/2013); road stability and associated downslope risks (Golder 2006; Cordilleran 2011; Cordilleran 2012b, 2013); creek hazards (Hungr 2007; BGC 2012/2013; Cordilleran 2012a, 2012b, 2014b); and coastal processes (Westmar 2005).

7. Development History

The 1939 airphotos show bright scour on Alberta Creek channel, implying a recent scouring flood or debris flow. In addition, there appeared to be some near shore clearings on Harvey Creek fan, south of the creek mouth. These could be old camps, as extensive logging had converted most forest within the future Village boundaries to younger seral age stands. A private dock is apparent on the south end of Harvey Creek fan, and hydro right-of-way has also been cleared. On the 1946 photos there is little change. By 1957, there was extensive construction in the railway and highway corridors, mining of the Magnesia Creek raised delta deposit, and there was the development of logging roads up onto midslopes between Magnesia and Alberta creek, with some large fill/spoil sites evident with sidecast directly into Alberta Creek. The logging road did not cross Alberta Creek. By 1968 the subdivisions at Brunswick Beach and on the Harvey/Alberta Creek fans below the highway were well established, and there was one tier of subdivision road above the highway. Also by 1968, the high elevation logging road system and associated clearcuts were pushed into Magnesia and Harvey Creeks. By 1979 the existing subdivision road network was near completion, with only the uppermost length of Oceanview Road pioneered but not finished. In 1982, the Kelvin Grove subdivision above and below the highway was under construction. Also, notably, Harvey Creek was heavily scoured and bright. The 1992 airphotos show the extant subdivision with protective structures completed on Magnesia, Alberta and Harvey Creeks. No substantial change was noted on 1996 and 2004 airphotos.

8. Hazard Identification and Analysis (Map 2)

Geohazards addressed in this framework include coastal zone hazards; creek hazards and hillslope hazards, as discussed in the subheadings that follow. During the discussion refer to the Geomorphic Features map, attached as Map 2.

8.1 Coastal zone hazards

Coastal hazards include flooding from a combination of processes including tides, storm surge and wave action. Landslide or earthquake induced tsunami waves are also important coastal hazards in some areas. Also important in some settings is coastal shoreline erosion.

Climate change science indicates that sea-level rise is currently occurring and that the rate is expected to increase in the near future (e.g., 20-years) (Englander 2014). Sea level rise increases the vulnerability of littoral elements at risk to coastal flooding and erosion.

8.1.1 Coastal zone flooding

Coastal flooding is the product of a number of contributing factors, including astronomically forced tidal cycles, storm surge, wind/wave setup, wave run-up onshore, sea-level rise, and possible tsunami.

Astronomic tide

Tide cycles are driven by the gravitational forces of astronomical bodies, with repetition over 19-year periods. Coastal BC experiences a mixed semidiurnal tidal regime, with two high and two low tides per day, with unequal levels for the successive highs and lows. Further, the tide amplitude varies month to month, with the deepest cycles in summer and winter. The highest tides are usually experienced in the winter. The tide level recommended for assessment of coastal zone flooding is the Higher High Water, Large Tide (HHWLT), the average of the 19 annual highest high waters, or 2.05 m CGD[1].

Atmospheric (storm) surge

Storm surge is caused by rising of the water level during intense low pressure storm systems. In the past two decades, the annual maximum storm surge at Point Atkinson exceeds 0.3 m, while the maximum experienced was about 1 m. For Howe Sound, the predicted 1:200-year and 1:500-year storm surge values are 1.2 and 1.3 m (Ausenco Sandwell, 2011).

Wave effects

Just as low pressure allows water surface to rise, the drag by wind can also cause the local water surface to rise, and this is called wind setup. This can be further augmented by wave action, or wave setup. In protected waters wind setup is typically small and subsumed with wave setup.

When waves meet the shoreline they typically break, and rush onshore. Wave runup is the vertical reach of the break. Wave runup varies greatly with orientation to the wind, subtidal water depth, shoreline slope and roughness, and is a value requiring site-specific assessment.

In the Salish Sea area, these combined wave effects may vary greatly from near zero in protected settings to >1 m in exposed sites.

Sea-level rise

Global sea-level rise (SLR) allowances are suggested for the 2100 and 2200-year planning horizons (+1.0 m and +2.0 m, respectively)(Ausenco Sandwell, 2011). However, for structures with a short to medium-term design life, a reduced SLR allowance of +0.5 m was suggested for consideration. Typically, residential houses would represent a medium to long-term design life (50 to 100 years), and 1 m SLR allowance is recommended.

Englander (2014) cautions that the Intergovernmental Panel on Climate Change (IPCC) only sanctions predictions affirmed by complete scientific consensus, that their predicted rate for this century is actually less than observed, and that should tipping point scenarios arise like collapse of the Arctic and Antarctic ice shelves, and other factors, coastal sea-level rise will be more rapid and severe than reckoned. This

[1]CGD, all elevations are referenced to Canadian Geodetic Datum.

century could see double the rate advocated by IPCC and BC provincial guidelines (Ausenco Sandwell, 2011; APEBC, 2017). With this in mind, coastal communities are advised to practice adaptive management for Coastal Land-use Planning.

Tsunami

Clague et al. (2003) conclude that megathrust triggered tsunami would attenuate to less than 1 m before reaching Georgia Straight. They also concluded that tsunami induced by landslides or delta foreslope slumps within coastal inlets could reach 2 m, but there is no evidence for them in the late Holocene, and therefore they are considered extremely rare. These conclusions were reiterated by Clague and Orwin (2005). Jackson et al. (2014) attempted to locate large rockslide deposits on the floor of Howe Sound that might be responsible for generating tsunami waves. They identified only one rockslide, located off the northwest side of Bowen Island, and determined that no evidence exists for such events in the late Holocene. After Clague et al. (2003), Westmar (2005) concluded the maximum credible tsunami in Howe Sound was cited as 2 m with a return period of 100-1000 years. Their conclusion is based on judgment, and in light of lack of tsunami evidence reported by Clague et al. (1993) and Jackson et al. (2014), the frequency appears somewhat conservative. Nevertheless, given a 4-5 m tidal range, such an event would have to be coincident with HHW to cause damage, resulting in a very low probability of severe consequence occurring. On this basis, local sea-level Flood Construction Level (FCL) estimates do not factor in tsunami.

Combining factors to set the shoreline FCL

Various future sea-level scenarios may be contemplated using different sea-level rise values, storm surge return frequencies, and site-specific estimates of wave setup and runup. Several available studies (e.g., Ausenco Sandwell, 2011; NHC 2014; KWL 2014, 2016) appear to settle on the use of the base variables, as such:

Higher High Tide:	2.05 m CGD;
500-year Storm Surge:	1.3 m CGD;
Global Sea Level Rise to 2100:	1.0 m;
Total base estimate:	**4.35 m CGD.**

Yet, factors such as wave setup/runup allowance and freeboard are varied according to location exposure and uncertainty tolerance, to yield a range of estimates, as such:

Wave setup/runup Allowance:	0.0 m, 0.3 m, 0.65 m, 1.2 m;
Freeboard Allowance:	0.3 m, 0.6 m, 1.0 m;
Final FCL range (average)	**4.65-6.55 m (5.6 m) CGD.**

Furthermore, accounting for an additional 1 m sea-level rise allowance to year 2200 provides a planning elevation for assessment of 7.55 m CGD, which is rounded up to 8 m.

8.1.2 Coastal zone erosion

Where coastlines are composed of unconsolidated sediment, coastal erosion may be a serious problem. This may be severely aggravated by sea-level rise. At Lions Bay, shoreline materials may be of several types, including bedrock, fillslope materials, blocky talus, bouldery debris flow colluvium and beach gravel. Erodibility will be in part a function of the material calibre (size of clasts), but will also depend on steepness of the shore and exposure to wave and current. Natural colluvium, such as boulder debris and talus are reasonably resistant to erosion. Fillslope materials may be oversteepened and vulnerable to erosion. Highly erodible are beach gravels, especially landforms formed by sediment transport (Photo 4).

8.2 Creek hazards

The main creeks crossing Village of Lions Bay include Magnesia, Alberta and Harvey Creeks. These have large steep watersheds with known debris flow hazard and have been mitigated by use of catchment basins or flumes to direct debris to the sea. Other smaller creeks are Battani, School Yard, Upper Bayview and Rundle. These smaller creeks drain the mountain face between the divides of the larger watersheds.

8.2.1 Harvey, Alberta and Magnesia Creeks

Debris flow is the rapid movement of rock, debris and water down a steep confined channel. In the study area, historic debris flows have ranged from 1000s m^3 to several 10,000s m^3 in volumes. Velocity of debris along its path varies from 3-10 m/s and higher. Due to the large volumes, boulder material with logs and high impact velocities, debris flows are very destructive phenomenon (Table 6).

Table 6. Landslide size class ratings describing impacts for each class (Jakob 2005). Size classes are within the range expected for the Village of Lions Bay.

Class	Volume (m^3)	Peak discharge (m^3/s)	Potential consequences
1	<10^2	<5	Very localized damage, known to have killed 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 buildings, destroy sections of infrastructure corridor, damage bridges and block creeks.
5	10^5-10^6	1500-12,000	Destroy camps and forest up to 2 km^2 in area, block creeks and small rivers.

Design of mitigation for Harvey, Alberta and Magnesia (Photo 5) creek hazards in the 1980s was based on the Design Event (Table 7). Since there was no data available to prepare a debris flow frequency analysis, the Design Event was based on the “largest volume that could reasonably occur during the life of the structure” (Hungr et al. 1984). The method assigned an estimated channel yield rate (m^3/m) to the total channel length in the watershed; 10% might have been added to account for point sources. The storage structure volume was then made 15-25% larger than the design debris flow (Table 7). The channel works downstream of catchments were sized to accommodate twice the design event.

Note that these design criteria were judgment-based, following a Probable Maximum Magnitude (PMM) approach (Morgan et al. 1992). The design events and the design storage capacities were not based on estimated return periods; therefore, it was not possible to assign return period safety levels to the mitigation works. This is critical to understand when considering the residual risk affecting residential development at Village of Lions Bay because landslide safety evaluation criteria (Cave 1993; DNV 2009) make explicit reference to return periods ≥500-years.

Multiple failure mechanisms could lead to larger design events than estimated by the method outlined by Hungr et al. (1984). Primarily, significant point source volumes, >10% of overall channel yield, could be added. Potential triggering for a large point failure could be an earthquake, or simply could be the combined effect of climate/weather, chemical weathering, time and gravity. Thus, larger, more rare events, should be accounted for in the full spectrum of debris flow hazards on Harvey, Alberta and Magnesia Creeks.

A few local examples were examined to assess debris flow frequency-magnitude from similarly sized basins. Charles Creek, with a 1.8 km^2 watershed area, is the most active of the Highway 99 mitigated creek channels (Figure 3). Morgan et al. (1992) presented a reanalysis of Charles Creek data (n=10 events) using probabilistic methods and judgment. They estimated the 500-year event to have a volume on the order of 50,000 m^3, somewhat exceeding the former design event of 29,000 m^3. Jakob (2012) again reanalysed Charles Creek (n= 19 events) by fitting and evaluating multiple probability distributions, and concluded the 1000-year return event might have a volume on the order of 50,000-60,000 m^3, but with the uncertainty ranging from 20,000 to 300,000 m^3. The caveat was provided that this includes only debris flows from mobilised talus, and not large point source events. Jakob (2012) also reported on Jones Creek, with a 6.8 km^2 watershed area, located in the Cascade Mountains, Washington State. Based on analysis of data derived from test pitting and radiocarbon dated stratigraphy, Jakob estimated volumes for the 500-year and 2500-year events of 100,000 m^3 and 200,000 m^3, respectively. This review suggests that small steep watersheds with areas of 1-7 km^2 could have 500-year to 2500-year return period volumes that exceed the design volumes of 15,500 m^3 to 62,500 m^3 for Harvey, Alberta and Magnesia creeks.

Table 7. Geomorphic character and design details for Harvey, Alberta and Magnesia Creeks. After Couture and VanDine 2004.

Item	Harvey	Alberta	Magnesia
Event record	1969 (debris flood), 1972, 1973, 1981 (floods)	1982, 1983 (debris flows)	1960 (flood), 1962, 1981 (debris flows)
Debris flow probability	Moderately high	High	Very high
Elements at risk	Multiple residences, subdivision roads, highway and railway	Multiple residences, subdivision roads, highway and railway	Multiple residences, access roads, highway and railway
Drainage area	7 km^2	1.2 km^2	4.7 km^2
Ruggedness	50%	110%	65%
Creek length	5.25 km	2.6 km	4.7 km
Process Domain	Debris flood	Debris flow	Debris flow
Design debris flow	62,500 m^3	15,500 m^3	44,500 m^3
Design debris discharge	500 m^3/s	350 m^3/s	400 m^3/s
200-year flood	107 m^3/s	22.7 m^3/s	75.7 m^3/s
Debris control measure	Debris basin, barrier and downstream channelization completed in 1985.	800 m long flume to sea, completed in 1988.	Debris basin and barrier, completed in 1985.
Design storage volume	77,500 m^3	n/a	51,500 m^3
Spillway design capacity	1000 m^3/s	n/a	800 m^3/s

Figure 3. Charles Creek retention structure with debris flow infill. Downloaded from internet (https://www.flickr.com/photos/tranbc/8510095573).

Present day standards for residential development would have to consider 500-year and perhaps more rare event scenarios (e.g., 1:2500), especially given potential earthquake triggering. Thus, it is concluded that the degree of safety provided by the mitigation structures at Lions Bay is unknown, and they may be undersized when considering modern safety criteria. If this is the case, there will be some unknown level of residual risk affecting fan areas. As channels are highly confined upstream of the structures, the residual risk only presents on terrain downslope of the catch basins, where channels lose the confinement of deep rock gullies and incised raised fan deposits.

Water flood and debris flood hazard may present downstream of catchment structures as well. Where an engineered flume is present it has more than enough capacity to accommodate water floods and bulked debris floods. However, it was noted that for example on Harvey Creek, the engineered flume does not extend right to the beach, so in that area lots may be vulnerable to floods and debris floods (Photo 6).

8.2.2 Other creeks

Other creeks in the Village of Lions Bay include Battani Creek, tributary to Magnesia Creek at the highway; Schoolyard Creek discharging from municipal drainage below Bayview Road and flowing north of the school; Upper Bayview, diverted into Alberta Creek just above upper Bayview Road; and Rundle Creek, tributary to the sea. Each of these creeks have smaller catchments, <1 km^2, and based on other NHAA frameworks reviewed (e.g., Roberts Creek; District of North Vancouver), such small basins are not often not formally recognised as creeks for NHAA designation. Despite this, they may be prone to local flooding and debris flow. Battani and Rundle creeks flow within ravines and are captured within the NHAA framework on that basis. Upper Bayview supports an identified hazard and its fan is allocated a NHAA. Schoolyard Creek is not specifically included in the NHAA framework. In addition, there may be other non-identified drainages that affect properties and need assessment at the site-specific level. These latter would be accounted for in assessments required in other NHAAs.

Flooding and or avulsion may occur at road crossings or other places where drainages are intercepted by pipes (i.e., culverts and bridge openings) due to insufficient conveyance of creek flow, or blockage (Photo 7). Avulsion at road crossings can often result in unexpected overland flooding, as roads and roadside ditches tend to convey floodwaters quickly and often directly to driveways and developments. An evaluation of the conveyance capacity of all creek crossings is beyond the scope of this project.

8.3 Hillslope hazards

Hillslope hazards include any non-channelised mass movements events such as snow avalanche, open-slope debris slides, rockfall or rock avalanche. Also included are structural features, such as terrain with lineaments, that might indicate a deep-seated bedrock instability.

8.3.1 Snow avalanche

Snow avalanche, the rapid movement of snow on steep slopes, occurs primarily within alpine terrain during fall, winter and spring months, but may reach down into forested terrain along well defined tracks in the timber. While snows avalanches occur in headwater areas in Magnesia, Alberta and Harvey Creeks, and may contribute to channelized hazards in those creek basins, the hillslope areas within Village of Lions Bay are not considered vulnerable snow avalanche activity.

8.3.2 Open-slope debris slides

Open-slope landslides typically involve fragmented bedrock, organic debris, and mineral sediment (Photo 8). A typical slide is triggered by rockfall from a bluff, by windthrow of large trees on a steep slope, or by slab failure of a weathered soil veneer. The headscarp failure plane is typically >60%, but sometimes as low as 40%, or less.

Typical, or generic steep terrain where landslide initiation is most likely has 60-120% slope, and is overlain by a veneer/blanket of till/colluvium (e.g., see Rollerson et al. 2001, 2005). Natural factors that contribute to the failure rate are wetter climate, higher frequency of extreme rainfall, gullied or escarpment landforms, increasing soil moisture, aspect, and fine grained sediments (Rollerson et al. 2001). Regional storms with severe localised precipitation cells may trigger numerous events (Guthrie and Evans 2004).

The initial slip then impacts timber downslope clearing a swath through the forest, and may be very destructive to infrastructure (Table 6). Slide types may be differentiated as open-slope, gullied types (headwall, sidewall, channel), road-related, or single track versus multiple track events (Fannin and Rollerson 1993).

Volume and damage potential

Open slope landslides in Coastal BC typically have headscarp dimensions that are 10-50 m wide by 0.5-1.0 m thick. At Lions Bay slope length of steep slope segments above residential areas range from 150-600 m long, and longer. If these track dimensions are applied to steep slope lengths, where scour and entrainment is predicted, and used to estimate potential slide volumes, then slide volumes affecting residential areas may be on the order of 750 m^3 to 30,000 m^3, or Class 2 to 4 events (Table 6).

Frequency

No data on open-slope landslide density is available for Lions Bay or Howe Sound. While historic open-slope failures are known from within valleys tributary to the sound (e.g., M Creek, Bovis and Dagg, 1987; Magnesia, Harvey, Alberta and others, e.g., Jakob and Weatherly 2003), historic landslides on the valley sidewall or fjord “face units” are not evident.

Thus, the landslide rate for slopes directly upslope of Lions Bay housing is not known, but appears to be less than 1:100-years based on airphoto inventory, Google Earth review and personal observation. This is a poor minimum estimate, as a 100-year return is a high to moderate hazard (Table 1), when in fact the hazard may be moderate (<1:100 per annum) to Low (<1:500 per annum), or less.

In lieu of known landslide frequency, regional landslide density may be used to approximate frequency (Catani et al. 2016). Post logging landslide densities have been studied in Coastal British Columbia. Since the slopes above Lions Bay have been logged, this data provides an analog for the present study. Regional landslide mapping in the Coast Mountains conducted within a window of 20 years since logging (Rollerson et al. 2001) indicates densities on steep terrain of 0.015-0.035 slides/hectare (sl/ha); while this doubles to 0.03-0.06 sl/ha for Cascade Mountains near Chilliwack (Millard et al. 2002), perhaps owing to poorer rock types.

As a first approximation, one can take the low range of the landslide density, or 0.015-0.035 sl/ha/20-years (Rollerson 2001), and apply this to Village of Lions Bay. For example, above the Village, between Magnesia and Alberta Creek there is 40 ha of steep terrain that could generate open-slope landslides. This ground occupies a belt about 1000 m wide across the slope and 400 m horizontal distance along the fall line. Assuming a slide width of 20-50 m, then there are 20-50 independent paths. Thus, 0.015-0.035 sl/ha/20yrs reduces to 0.03-0.07 slides per annum for a 40 hectare area. This then needs to be allocated to 20-50 independent slide tracks, suggesting there is a 1:500 to 1:1000 per annum hazard for a landslide in any given track.

Only detailed subsurface testing could reveal actual landslide rates for the study area. An example of a prehistoric debris slide is provided from excavation conducted at Ansel Place exit, Sunset Highlands, West Vancouver. At that site, excavation on the east abutment of the overpass exhumed two Douglas fir logs buried by slide debris. Radiocarbon dating gave ages of 1090±50 (GSC-6574) and 1060±50 (GSC-6573) C^{14} yr BP, or 965 calendar years BP for the landslide that buried the trees (Cordilleran, 2001). Note, this age appears consistent with the Low frequency (Table 1) estimated above.

Landslide runout or travel angle

Landslides will typically travel to the base of slope, with the deposition zone being a 50-200 m wide belt of terrain less than 30% slope (Fannin and Rollerson 1993). Travel angle, H/L, or ratio of total drop to total horizontal length of the landslide is widely used to characterise travel distance (Corominas 1996), and this measure can be used in terrain hazard mapping as a first order estimate of potential impact areas.

No landslide travel data exists for the southern windward Coast Mountains. For open-slope slides with similar length and volume characteristics to potential open-slope slides at Lions Bay, two data sets were examined: one collected from Google Earth review for 70 landslides near Bella Bella by Cordilleran (unpublished), and a second from Horel (2007) for a sample of 33 landslides on Northern Vancouver Island (Table 8). Measured travel angles for each slide were binned in 10 percentile categories and cumulative frequencies “farther than” were tallied. Qualitative hazard categories extend from Very High to Very Low with cumulative frequency probability in 20 percentile categories: Very low=0-20%; Low=20-40%; Moderate=40-60%; High=60-80%; and Very high=80-100%)(Table 8).

Table 8. Travel angle (H/L) vs frequency of occurrence, cumulative frequency and qualitative hazard affecting. Data for Bella Bella and Northern Vancouver Island.

Bella Bella (n=70) (Cordilleran)			Northern Vancouver Island (n=33) (Horel)		
Travel angle (m/m)	Cum. Freq. (probability)	Qualitative $P_{S:H}$	Travel angle (m/m)	Cum. Freq. (probability)	Qualitative $P_{S:H}$
0.11-0.2	0.04	Very low	0.11-0.2	0.00	Very low
0.21-0.3	0.10	Very Low	0.21-0.3	0.09	Very Low
0.31-0.4	0.24	Low	0.31-0.4	0.55	Moderate
0.41-0.5	0.41	Moderate	0.41-0.5	0.76	High
0.51-0.6	0.71	High	0.51-0.6	0.88	Very high
0.61-0.7	0.80	Very high	0.61-0.7	0.94	Very high
0.71-0.8	0.96	Very high	0.71-0.8	0.97	Very high
0.81-0.9	0.99	Very high	0.81-0.9	0.97	Very high
0.91-1.0	0.99	Very high	0.91-1.0	0.97	Very high
1.01-1.1	1.00	Very high	1.01-1.1	1.00	Very high

A Quantitative Risk Assessment (QRA) is applied as a sensitivity analysis to determine a reasonable shadow angle for setting the Open-slope Hazard Area boundary. QRA requires estimates of probabilities of the hazard and the consequence to estimate risk, as per the formula below:

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

- P_H=probability of design event hazard occurring, open-slope landslide;
- $P_{S:H}$ = probability of spatial affect given the hazard, landslide travel category;
- $P_{S:T}$ = probability of temporal effect given spatial effect, occupancy;
- V = vulnerability of structure and risk of loss of life to person most at risk in the home; high;
- E = elements at risk = 1

Since there is no landslide travel data for Howe Sound, probabilities for various reach angles were assigned from regional data (Table 8), as such: VH, $P_{S:H}$=0.9, H/L>50% slope; H, $P_{S:H}$=0.7, H/L is 40-50% slope; M, $P_{S:H}$=0.5, H/L is 30-40% slope; L, $P_{S:H}$=0.3, H/L is 20-30% slope; and VL, $P_{S:H}$=0.1, H/L<20% slope.

The sensitivity analysis (Table 9) applies three likely hazard (P_H) scenarios to the five reach classes ($P_{S:H}$), with 50% building occupancy ($P_{T:S}$) and high vulnerability (V=1). Then for any single damage corridor, the individual risk is tolerable (i.e., <1:10,000) only for Very Low landslide reach probability, or for increasing reach probability (Low to Very High) with increasingly reduced landslide frequency. The risk is only acceptable (i.e., <1:100,000) with VL reach probability with P_H at 1:5000, or less.

Table 9. QRA sensitivity analysis to validate choice of landslide reach category used to establish NHAA.

Damage corridor hazard frequencies (per annum) applied in sensitivity analysis			Reach category					Risk Estimates for a range of hazard levels		
								R1	R2	R3
1:500	1:2500	1:5000	Qualitative	$P_{S:H}$	$P_{T:S}$	V	E	1:500	1:2500	1:5000
0.002	0.0004	0.0002	VH	0.9	0.5	1	1	1111	5556	11111
0.002	0.0004	0.0002	H	0.7	0.5	1	1	1429	7143	14286
0.002	0.0004	0.0002	M	0.5	0.5	1	1	2000	10000	20000
0.002	0.0004	0.0002	L	0.3	0.5	1	1	3333	16667	33333
0.002	0.0004	0.0002	VL	0.1	0.5	1	1	10000	50000	100000

On the basis of the analysis above, to reduce the probability to no less than tolerable (1:10,000 per annum) of Type 1 error, that is, declaring a site free of hazard when in fact hazard exists, it was determined that the lower boundary for the open-slope NHAA 3A should be established using the lower limit of the Low reach probability category, equating to an H/L of 20% (11^0). Projecting this slope from some potential start zone high on the slope above the subject property captures essentially the entire municipality (Figure 4).

It was judged that reach would be reduced by travel obstructions. Road benches tend to mitigate open-slope landslide travel distance (Guthrie et al. 2010). For any given landslide path in Village of Lions Bay there are multiple road crossings (range is 2-8) and the Highway 99 road bench. Given the highway is a four-lane highway, divided and bounded by no-post barriers, it was judged these multiple road obstructions will limit reach. The outside edge of Highway 99 was used to truncate the runout, with the NHAA extending upslope of the highway.

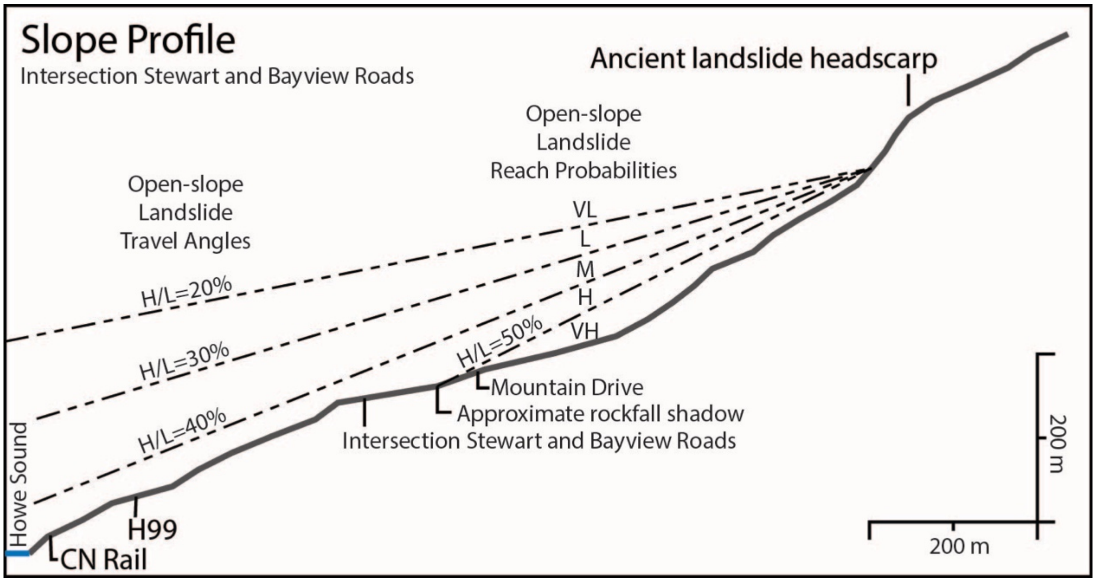


Figure 4. Topographic slope profile through the intersection of Stewart and Bayview Roads. Open-slope travel angles are plotted from a hypothetical start zone on the slope below the cliff and show that runouts can extend very far down the slope.

8.3.3 Rockfall

Rockfall is the falling, bouncing and rolling of detached rock fragments from cliffs and steep slopes. Over time, rockfall material may form a veneer/blanket or apron of material below a source bluff. These deposits are known as scree or talus. Volumes can range from individual blocks to 100s of cubic metres.

Natural rockfall source areas are readily identified by slope thematic mapping, keying into slope areas with 70-90% slopes, and especially bluffs with slopes >90%. A number of steep rock areas were visited in the field to confirm rock condition.

The Gambier Group rocks within the Village of Lions Bay are typically highly fractured, with fracture spacing of decimeters to meters, with multiple orientations in any rock mass, including steeply dipping sets allowing topple, slide and wedge type failure (Photo 9). Field inspection indicates that many bluff areas support surfaces with open joints. Thus, in steep terrain, rockfall presents as a common hazard affecting downslope areas. The 50-100 m tall cliff above Mountain Drive is a significant rockfall source area (Photos 10, 11). Rockfall debris is very common on the slopes above Mountain Drive and Timbertop Road (Photos 12, 13), and a long-time local resident has reported that on two occasions in the last 20-30 years rockfall has affected developed lots (295 Mountain Drive and 415 Timbertop Drive). Klohn Leonoff (1992) identified an “ancient slide” of about 5000 m^3 volume located “about 400 m south of Kelvin Grove Way.” No further details were provided, but the slopes directly above the highway are mantled with rockfall colluvium (Photo 3) derived in part from an apparent wedge failure (WP 240, 2017) in the bluff spanning Lots 48, 60 & 61, Kelvin Grove Way.

A method of identifying areas vulnerable to rockfall is the shadow zone concept introduced by Hungr and Evans (1993), whereby an angle of 27.5^0 is plotted from the top of a talus slope and extended down to where the angle intersects natural ground, typically somewhat beyond the toe of the talus slope. Hungr and Evans (1993) demonstrated that in most cases, 99.9% of rockfall will not exceed this angle of travel. However, there are special site conditions that can lead to excess travel, and the method must be used with caution.

Artificial rockcuts may be especially vulnerable to rockfall. This is evident from the large number of rockfalls that have affected Highway 99 and other road systems throughout BC.

8.3.4 Rock avalanche

Rock avalanches are large fragmental rock failures originating in bedrock and traveling rapidly downslope as an unsorted mass. Several large rock avalanche deposits are known from Howe Sound. Eisbacher (1983) mapped a rock avalanche deposit, with a volume of 300,000-400,000 m^3, draping the benchland underlying the Sunset Highland subdivision, West Vancouver. The rockslide originated from the collapse of a rock spur at 600 m elevation below Black Mountain on the Howe Sound Crest. The landslide has not been dated, but Piteau (1981) attributed a paraglacial age. Jackson et al. (2014) document rockslide deposits on the sea floor off the northwest side of Gambier Island, with radiocarbon ages indicating an early paraglacial age.

At Lions Bay, on the hillshade rendering derived from the recently acquired LIDAR, a prominent cliff located north of Alberta Creek has been identified as a potential rockslide scarp by BGC (2012/2013):

> "A landform that may be a large rock slide is visible on the slope to the north of Alberta Creek. Several [house] structures are located on or near the toe of this feature, but apparently no ground movement in the area has been reported. It is possible that this suspected rock slide occurred as the slope was debuttressed during glacial retreat and that it is not currently active; however, further investigation of this feature may be warranted.

In 2016 and for this project, Cordilleran traversed the headscarp crest and terrain below to look for evidence of ongoing and potential instability. The headscarp is 600 m long and southwest facing, with the crest between 550-650 m elevation with cliffs between 30-110 m tall (see Map 2, Geomorphic Features). The crest does not show evidence of sackung, but there are sites of open and unfavourable jointing with several identified rockfall sources of 10s m^3 to 1000s m^3 volume.

The slopes below the large landslide scar (see Map 2) are divided into the north half and the south half. On the north half, there are 150-300 m long, 60-80% slopes of rubble talus, extending from 450 m elevation to a concave break at 200-300 m elevation. The subdivision is on the benchland at the toe, extending from 80-250 m elevation. This area is predominantly rock outcrop with lows covered with till and glaciofluvial veneer; only areas fringe to the slope above support fragmental rockfall. There is no extensive rockslide deposit.

Below the south end of the landslide scarp is a distressed slope area, 300 m wide by 300 m long, with the irregularly sloped surface between 370-540 m. The mass consists of fragmented rock with three extensional horst and graben structures and a lateral boulder levee on the south margin (see Map 2, Geomorphic Map). The thickness of the mass is unknown, but could be on the order of 10-20 m. Thus, the total volume estimate is 1-2 M m^3.

On the basis that the lower slopes below about 150 m elevation are largely rock with partial till veneer, it was judged that the rockslide was likely a deglacial event that deposited partially onto the receding ice sheet. Only point source rockfall is expected from the modern headscarp. The distressed area in the south is interpreted as a failed rock mass, arrested on the slope during initial failure. Its present state of stability is not known, and the hazard/risk the feature presents is uncertain.

8.3.5 Deep-seated bedrock instability

Deep seated bedrock instabilities are locations where gravitational stresses have caused or continue to drive slow failure in bedrock slopes. The slopes are said to be sagging, and these areas are referred to by the german word "sackung." Sackung are typically identified by extensive areas of linear tension cracks and uphill facing scarps. There are many such features throughout the Coast Mountains. Jackson et al. (2014) recently identified an extensive area of sackung on Bowen Island, with a small part of the slope having failed into the sea during the deglacial period.

Sackung slopes exists in the Britannia Creek watershed within Jane Basin. Both these examples are in Gambier Group rock similar to Lions Bay.

The 1-2 Mm^3 arrested rock mass below the Lions Bay headscarp displays structural features typical of sackung. In its case, the tectonic structures formed during initial collapse. However, it is not known if there is ongoing, or perhaps intermittent slow mass movement of this feature.

Another potential bedrock weakness is an open-downward, horseshoe-shaped headscarp located on the divide between Upper Bayview and Harvey Creek (see Map 2, Geomorphic Map). This feature is 250 m wide and extends from its crown at 880 m elevation downslope about 150 m distance. The stability of this feature is unknown.

Just 100 m south of the Village of Lions Bay, the whole slope from sea level to 1100 m elevation shows signs of weakness. The area is sided by two linear depressions defining an area about 500 m width and delimitated by a horseshoes-shaped headscarp at the top and by a convex toe at sea level (Figure 5). The convex toe dictates the highway path. The stability of this feature is unknown. This area is outside the LIDAR coverage but it has been recognized and mapped on the historic orthophotos. In personal communication, this area was previously identified to Cordilleran Geoscience by Karen Savage, P.Eng., of Horizon Engineering. Even if this feature might not directly affect Village of Lions Bay, it affects the highway and may pose significant hazard to the access to the Village of Lions Bay.

These examples of potential deep-seated instability require characterisation and assessment by a qualified geological engineer.

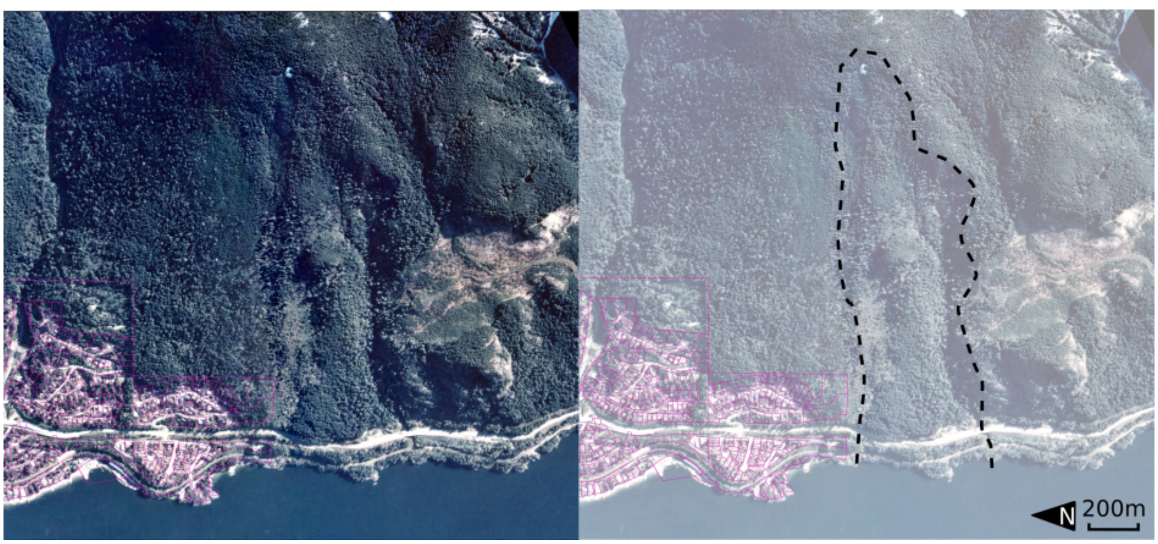


Figure 5. Potential sackung slope identified just south of Village of Lions Bay.

8.3.6 Seismic slope instability

The study area is vulnerable to seismicity from a Cascadia subduction zone earthquake as well as more frequently-occurring crustal earthquakes. The National Building Code (2005) and the BC Building Code (2012) require building design to conform to the 2% in 50-year return period event (~1:2500 per annum)(Table 1). This standard is also referenced by EGBC (2010).

EGBC (2010) states:

> "earthquakes can destabilize slopes leading to landslides, can cause liquefaction leading to landslides and/or can cause slope displacements. Therefore, seismic slope stability analysis, or seismic slope displacement analysis (collectively referred to as seismic slope analysis) may be required as part of the landslide analysis."

It must be emphasized that the seismic slope stability analysis applies to the design of foundations and engineered slopes (Photos 14-16). The assessment of natural landslides potentially affecting a site considers the frequency and magnitude of historic and prehistoric landslides, as revealed through the historic record, peer-reviewed publications, anecdotal evidence and geologic fieldwork. The historical record extends back thousands of years and over many earthquake cycles, thereby implicitly including seismicity as a triggering agent. Nevertheless, when considering future triggering of landslides, for example within Magnesia, Alberta, Upper Bayview and Harvey catchments, or rockfall, then seismic shaking at potential start zones should be considered.

9. Recommended NHAA Framework

9.1 Overview

The goal of the NHAA boundary delineation is to categorise natural hazards by landform type and/or process domain. The likelihood or magnitude of possible hazards is not explicitly estimated, as that is the role and responsibility of site specific studies or recommended further work.

The following sections outline the proposed Natural Hazard Assessment Area (NHAA) framework for natural hazard areas in the Village of Lions Bay, based on the hazards identified and assessed in the previous section. A generalized, process-based approach to NHAA delineation is proposed, with three main categories:

NHAA 1, Coastal Zone Hazards (flooding and erosion);
NHAA 2, Creek Hazards (alluvial fans; ravines, small creeks); and
NHAA 3, Slope Hazards (Open-slope failures, rockfall, and seismic slope stability).

9.2 Uncertainty

In determining the NHAA boundaries for the hazard categories, it is recognized that there is inherent uncertainty in the frequency-magnitude data upon which the NHAA categories have been based, as well as uncertainty in the extent of influence of possible hazards. Therefore, NHAA boundaries were drawn conservatively so as not to exclude terrain that could be affected by the range of magnitudes considered within future studies. While boundaries are drawn from the high-resolution LIDAR-derived mapping products, for proposed development purposes, surveys and professional assessment(s) may be needed to confirm lot layout, natural features, and setback determination on a site-specific basis (e.g., top of ravine vs. setbacks).

9.3 Legislated authority

By authority vested from the Crown, The Village of Lions Bay may require a Natural Hazard Assessment Area Assessment on lands identified as being within various NHAAs for the following activities:

1. Subdivision as defined in the Land Title Act and Strata Property Act;
2. Building Permit under the Community Charter; and
3. Land alteration, which includes, but is not limited to the removal and deposition of soils and aggregates, construction of retaining walls, paving, and removal of trees.

9.4 Georisk evaluation criteria

The Engineers and Geoscientists of British Columbia are clear that defining levels of geohazard safety is "not the role of a Professional Engineer or Professional Geoscientist." Rather, acceptable risk must be "established and adopted by the local government or provincial government after considering a range of social values" (EGBC 2010, 2012).

Therefore, it is the responsibility of the Village of Lions Bay to establish levels of acceptable risk for development approval process, and then for each hazard being considered, the qualified professional is responsible for estimating the hazard/risk affecting the proposed development, and then comparing this estimated hazard/risk against the established safety criteria.

9.4.1 Traditional hazard-based geo-safety management in British Columbia

In British Columbia, geohazards have traditionally been managed using a hazard based approach. For hydrologic floods an event with a 200-year return interval is used as the safety level (WLAP 2004). This relatively low level is used because floods can usually be forecast, allowing residents to prepare by evacuation or other means, and also because flooding is less life threatening than other geohazards.

Floods carrying high volumes of gravel are termed debris floods. These can be more damaging, and therefore, some agencies have used a 500-year return interval as the safety level for these events (Cave 1993; MoTI 2009). More recently, EGBC (2012) recommended consideration of the 1:2500 year return debris flood and debris flow event, where feasible[2]. Reference to the 1:2500 year return event is based on National Building Code (NBCC 2005), including the requirement to design for earthquake hazards, and recognizing the potential for earthquake induced landslides.

Large landslides with the potential to destroy extensive areas and cause loss of life, were originally considered by Justice Berger (1973), ruling on the risk of landslide from the Rubble Creek Barrier. Justice Berger opined that where even a low risk of death might exist, then that risk was deemed unacceptable; he recommended that the hazard assessment review geologic evidence extending back over the 10,000-year length of the post glacial period. That notion was subsequently interpreted and applied by Cave (1993) and more recently by MoTI (2009) and Clague et al. (2014) to imply that where major catastrophic or life threatening events affect a site/community, then the design criteria should reference the 1:10,000 per annum event.

A summary of hazard criteria currently applied in British Columbia was provided by Clague et al. (2015) who reviewed global and regional hazard safety thresholds for the purpose of risk management within District of Squamish. They found that 1:500-year, 1:2500-year and 1:10,000-year landslide events should be considered (Table 10).

Cordilleran is of the opinion that for most sites the application hazard acceptability criteria that cite very remote hazard thresholds, like 1:10,000 per annum, are not feasible for both scientific and practicable reasons. Stationarity of the process mechanism is a requirement of most statistical analyses; the decline of sediment yield through the paraglacial period (Church and Ryder 1972) and natural climate change are factors which result in non-stationarity over the 10,000 years of the non-glacial period. While human induced climate change is altering future landslide probabilities (Jakob and Lambert 2009). Further, for statistical frequency-magnitude analysis, a data set of sufficient size and confidence is required for statistical treatment; while for most landslide assessments it is rarely possible as this requires extensive subsurface examination, stratigraphic analysis, radiometric dating; and is conditioned on the sedimentary archive being available and complete, when in most cases it is inaccessible or fragmentary. In this context, the uncertainty in frequency-magnitude estimates for extremely rare events may vary over

[2] EGBC (2010) makes no recommendations regarding use of various hazard criteria.

several orders of magnitude. All these issues make inclusion of the 1:10,000 year return period event highly problematic, except for a few exceptional data-rich settings (e.g., Jakob and Friele 2010).

Table 10. Event frequencies that should be considered in landslide risk assessments, as recommended by the Cheekye Expert Panel (Clague et al. 2015).

Event frequencies used in georisk assessment in BC	**Rationale**
10,000-year return period event	Rubble Creek (Berger 1973)* Regional District of Fraser Valley (Cave 1993), District of Squamish (2009), MOTI (2009 revised 2015)
2,500-year return period event	EGBC (2012) (for debris flows and debris floods) NBCC (2005) (for earthquakes)
500-year return period event	MOTI (1993, 2009 revised 2013)

* Berger actually recommended consideration of a 10,000 year (e.g., Holocene) sample time frame, not a return period event.

9.4.2 Recommended risk assessment, after District of North Vancouver

Risk Assessment is a relatively recent approach to landslide safety assessment in BC. Whereas hazard-based methods rely on somewhat arbitrarily selected hazard thresholds, risk-based methods incorporate consequences and are therefore more sensitive (Jakob and Holm 2012), especially when considering increases in residential density. The District of North Vancouver (DNV) has adopted a Risk Assessment approach to assess development following the 2006 Berkley landslide fatality on Riverside Drive in that municipality. The adopted DNV (2009) policy recommendation is located at https://www.dnv.org/programs-and-services/risk-tolerance).

Assuming a good planning model, consistency in georisk management policy among communities is a preferred planning outcome. District of North Vancouver presents a modern and tried framework for managing georisk, and has set a bar that should be emulated. For all creek and hillslope hazards, it is recommended that the Village of Lions Bay adopt a georisk safety policy consistent with the District of North Vancouver. With respect to risk tolerance, the District of North Vancouver (2009) report to council provided the following discussion and policy:

> "Areas of potential landslide hazard can be assessed using a risk-based approach or by means of a factor-of-safety approach. The EGBC Guidelines (2010) state that "the decision whether to carry out and report the results of a landslide analysis quantitatively or qualitatively depends on how the adopted level of landslide safety is expressed, and/or the requirements of the Approving Authority." A qualitative hazard assessment or partial risk analysis should be performed by a Qualified Professional as an initial step in estimating whether a landslide hazard may be present for areas identified on the slope hazard map. If these preliminary analyses demonstrate that risks to life are likely broadly acceptable, then further risk assessment may not be required.
>
> Where a qualitative hazard assessment and/or partial risk analysis demonstrates that risks to life are likely tolerable or possibly unacceptable, the District requires that a more detailed risk assessment be performed. Where a detailed landslide risk assessment is required by the District, the Qualified Professional shall determine which approach is most appropriate for the local site conditions, based on the nature of the potential landslide hazard and its location relative to the area of existing development, re-development, or proposed new

development. It is recognized that landslide hazard and risk assessment is not an exact science and that some factors in the risk estimation process are subjective by nature.

Tolerable and acceptable risks are somewhat different: tolerable risks can be tolerated in order to realize some benefit, but they are not negligible, and should be kept under review and reduced further if possible. In contrast, acceptable risks are considered broadly acceptable to the public and efforts to further reduce risks are not warranted.

The "as low as reasonably practicable (ALARP)" principle applies to risks within the tolerable range. Under the common-law system, risk reduction should be achieved if reasonable opportunities exist. For a risk to be ALARP it must be possible to demonstrate that the cost involved in reducing the risk further would be grossly disproportionate to the benefit gained.

Society is generally less accepting of risks today as in the past. The proposed risk tolerance criteria takes this into consideration by proposing two-tiered criteria, with more stringent criteria for new development. Table 11 below illustrates the application of the proposed policy on risk tolerance criteria."

Table 11. Landslide risk policy, District of North Vancouver.

Type of Application	1:10,000 + ALARP	1:100,000	FOS >1.3 (static)	FOS >1.5 (static)
Building Permit (<25% increase to gross floor area)	X		X	
Building Permit (>25% increase to gross floor area and/or retaining walls >1.2m)		X		X
Re-zoning		X		X
Sub-division		X		X
New Development		X		X

The link to their geohazard DPA Bylaw 7900 (Part 4) is provided for reference[3]. The method employs Risk Assessment, indicating consideration of both hazard and consequence. In the Village of Lions Bay, risk is assessed for ocean, creek and hillslope hazards potentially affecting a site, and seismic slope stability for foundation soils, engineered slopes and adjacent slopes as determined relevant by the qualified professional. The varied tasks encountered in georisk analysis and design of protective measures require both P.Geo. and P.Eng. qualifications and experience, with specialist skill sets required for specific tasks. Risk assessments may be quantitative or qualitative, with the understanding that, as EGBC (2010, Section 3.4.2) notes,

Quantitative estimates use numerical values or ranges of values, while qualitative estimates use relative terms such as high, moderate and low. Both quantitative and qualitative estimates can be based on either objective (statistical or mathematical) estimates or subjective (professional judgmental or assumptive) estimates, or some combination of both.

Quantitative estimates may be no more accurate than qualitative estimates. The accuracy of an estimate does not depend on the use of numbers. Rather, it depends on whether the components of landslide hazard and landslide risk analyses have been appropriately considered; and on the availability, quality and reliability of required data.

[3] http://www.dnv.org/sites/default/files/bylaws/Bylaw%207900.pdf#page=203

Further, debris flood and debris flow risk assessment should be based on a minimum 500-year return period and include higher (1:2500 year) return periods where appropriate and practicable. Cordilleran judges that it is unreasonable to expect estimation of a 1:10,000-year event as required by District of Squamish (2017), Fraser Valley Regional District or MoTI. Flood construction levels should be clearly defined with appropriate freeboard to reflect analysis uncertainties and potential channel bed aggradation.

9.5 Expectations for professional scope and reporting

All professional assessments pertaining to Natural Hazard Assessment Areas should be consistent with applicable professional practice guidelines and their various report requirements; and provincial regulations, including but not exclusive to the list below:

i. Flood Hazard Area Land Use Management Guidelines (WLAP 2004),
ii. Guidelines for Legislated Landslide Assessments for Residential Developments in BC (2008, 2010),
iii. Guidelines for Legislated Flood Assessments in a Changing Climate in BC (2012, 2017),
iv. Riparian Areas Regulation,
v. BC Building Code, and
vi. Worksafe BC.

FVRD, District of North Vancouver and District of Squamish are jurisdictions that have experience requiring and reviewing geotechnical hazard reports. In all cases, these jurisdictions have developed specific standards for geotechnical report content (e.g., District of Squamish 2017). Based on their experience, where applicable, a report by a qualified professional should include the following:

1. Report name and date;
2. Client information;
3. Qualified professional information (training, experience, insurance);
4. Property information (legal and civic);
5. Description of development proposal;
6. Review of relevant local bylaws and other statutory requirements;
7. Review of background information (site-specific and overview archived & provided by Lions Bay and others);
8. Description of geologic and geomorphic setting;
9. Description of field work conducted on and, if required, beyond the proposed development;
10. Identification of natural hazards or other hazards identified in background reports and field work. Includes also a description of all potential hazards and rationale for excluding some;
11. For all hazards, separate and in aggregate, analyses georisk affecting the proposed development and evaluates against the Village of Lions Bay safety policy;
12. Discusses the effect of changed conditions to slope stability caused by the project, by future potential natural factors or land-use (fire, forestry) or climate change;
13. Discusses uncertainties and describes any residual risk that would remain;
14. If applicable, states that “the land may be used safely for the use intended” with siting constraints, protective measures or restrictive covenant, as stipulated in the report.
15. Provides technically justified siting constraints or protective measures, as required;
16. Provides implementation steps for the identified structural mitigation works (in terms of design, construction and approval).
17. Provides site plan and other mapping required to show hazards affecting, minimum scale 1:5000;
18. Provides maps, illustrations and diagrams to illustrate risk scenarios referred to in the Report;
19. Recommends restrictive covenants registered against the property title that pertain to geo-hazards, as required;
20. Provides permission to Village of Lions Bay to include the Report in the online geo-hazard report library (as background information, not for other parties to rely on);
21. Provides time limitation or condition statement to describe extent the Village of Lions Bay may rely on the Report for development approvals, and when resubmittal is recommended;

22. Provides an assurance statement (after EGBC 2010, 2012);
23. Signed and sealed by coordinating qualified professional.

9.6 NHAA 1 - Ocean hazards (Map 3)

Ocean hazards include flooding of low-lying terrain, and erosion and instability of oceanfront slopes. NHAA 1 extends from the existing natural boundary of the sea to the 8 m contour line. The 8 m level is conservatively selected to represent the future FCL. This captures all lots fronting the sea within the Village of Lions Bay. The NHAA is intended to identify any sites that should be assessed by a qualified professional to address coastal flood hazards, but does not preclude development. For Ocean Hazards, site specific factors including wave effects, year 2100 HWM, shoreline erosion, shoreface stability and associated setbacks.

At Village of Lions Bay, many steep slopes into the sea are rock controlled or are fillslopes below the railway line. These are not a stability concern for residential development. Most lots on surficial materials are located on bouldery debris fan deposits of Magnesia, Alberta and Harvey Creeks, and while the shorefronts may be steepened to 70-80% by wave attack, the sea scarp is not tall (<6 m) and materials are coarse and relatively resistant to erosion at the timescale of the life of a structure (e.g., 100-years).

The sites most vulnerable to erosion are those low-lying areas at the south end of Brunswick Beach Road, where housing has been developed on a gravel tombolo that has linked a small rock outcrop with the mainland (Photo 5). The beach gravels forming the tombolo stand just above the HWM, being formed by storm waves, and the terrain between the north and south facing beaches is slightly lower, just at the HWM. Future breaching and erosion of these beach ridges places all these low-lying areas at risk.

Within NHAA 1, building siting would require that development applications include a coastal flood hazard assessment to define the year 2100 shoreline position and the derived flood construction level and appropriate setback. Provincial guidance refers to a 15 m ocean setback, while Village of Lions Bay applies a 7.5 m coastal setback. Siting could be further constrained by consideration of potential erosion. A factor of safety analysis may also be required to support foundation design and determine building setbacks from escarpment crests.

Some lots do not have allowable room to accommodate houses under these future conditions. In these cases, setback constraints might be exempted, or in other cases land may be deemed non-developable. This will need to be determined on a site by site basis, and reports by qualified engineering and/or environmental professionals (QPs) would be required to support any exemption and/or variance.

Note that Englander (2014) cautioned that IPCC projections are low. Nhc (2014) noted that the predicted global sea-level estimates may change with time and similarly, they did not factor in potential climate change induced changes in storm intensity and frequency. Accordingly, they recommended adaptive management for coastal zone flood planning, with consideration given to potential future increases in the estimates of sea-level rise and changes in storm intensity and frequency.

9.7 NHAA 2 - Creek hazards (Maps 4, 5 & 6)

In the Village of Lions Bay, NHAA 2, Creek Hazards includes consideration of flooding, debris flooding and debris flow from both large creeks with existing debris flow hazard mitigation, hazards from unmitigated creeks and ravine escarpment slope stability. The debris flow mitigated channels (Magnesia, Alberta and Harvey) each have unique site conditions (watershed area, ruggedness, geomorphic condition) and are best treated individually. Similarly, the smaller unmitigated channels cannot be treated in a uniform way as in some cases their natural channels are within ravines (parts of Battani and Rundle), or in contrast may be unconfined by ravines and completely diverted from their natural course to bypass residences (lower Upper Bayview) or captured in part by the residential drainage network of ditches, culverts and storm sewers (upper School Yard Creek).

After District of North Vancouver (Bylaw 7900, Part 4, DPA 2A & DPA 3A), the Creek Natural Hazard Assessment Area is established to address the following objectives:

1. minimize the risk to people and property from creek and slope hazards;
2. encourage safety in the construction, location and manner of development;
3. minimize development in high hazard areas due to debris flow, debris flood areas;
4. mitigate the impacts of flooding within areas already developed;
5. avoid increasing the hazard to or vulnerability of others on the floodplain; and
6. maintain a natural riverine and floodplain regime.
7. develop safely and minimize the impacts on or near steeply sloped lands, including the potential run out area below steep slopes;
8. reduce slope hazards and landslide risk to people and property by carefully managing development and construction practices on or near steeply sloped lands;
9. avoid alteration of steeply sloped lands that may cause increased instability of the land or adjacent areas;
10. encourage professional design of structures and mitigative works and to ensure field review during construction and post-construction certification; and
11. encourage ongoing maintenance and monitoring of steeply sloped lands.

An example list of guidelines to meet these objectives are provided in DNV Bylaw 7900, Part 4, DPA 2C & DPA 3C.

DNV Bylaw 7900, Part 2B sets out a list of exemptions. These were recently updated (amended October 13, 2017) reflecting 8-years of experience with their Risk Management system. Most are directly applicable and Village of Lions Bay could decide to use in whole or in part (the Village of Lions Bay must consider legal third party reliance issues).

Bylaw 7900, Part 2B, Exemption 2, which pertains to the reference plane for the flood construction level for habitable space, should be deleted, as for all recognised creeks within Village of Lions Bay, including Battani, Magnesia, School Yard, Alberta, Upper Bayview, Harvey, Rundle, and other smaller non-identified creeks intercepted by residential development (upper School Yard), the FCL should be determined by a qualified professional(s) based on consideration of the risk presented by all hazards (flood, debris flood and debris flow). Specialist, multi-disciplinary skill sets may be required, with either or both P.Geo./P.Eng.

The list of exemptions does not include the “25% rule” which nevertheless is included in adopted (DNV 2009) Risk Tolerance criteria (Table 11). To be consistent with many community bylaws in BC, the 25% rule should be taken into account in the DP guidelines.

9.7.1 NHAA 2A - Mitigated debris fans (Map 4)

Without more detailed assessment of debris flow hazard, the level of safety offered by existing mitigation is unknown, as is the tolerability of residual risk. Thus, NHAA 2A is drawn to capture the inset fan surface that extends up to the catchment basin on Magnesia and Harvey creeks, or on Alberta Creek, up to where ravine confinement exists.

For residential developments, the 1:500-year and 1:2500-year return period events need to be considered when evaluating life safety. Thus, NHAA 2A captures terrain that could be affected should existing mitigation structures become overwhelmed by a large, moderate to low hazard event.

Note that, consistent with flood-proofing principles for floodplain areas, since the presence of diking (in this case partial debris flow mitigation) does not guarantee safety, all residential development within mitigated areas must still be supplied with appropriate flood proofing as additional protection and/or failsafe protection. This principle should be applied within alluvial fan areas within the Village of Lions Bay. Measures that may be required on mitigated debris fans include accounting for potential overland flows by establishing an FCL a minimum of 1 m above finished grade and construction using concrete reinforced foundation to the FCL (WLAP 2004). House foundations should be designed to mitigate the possibility of water ingress, requiring habitable space to be located above FCLs, or suitable tanking of habitable space below FCLs.

On Magnesia Creek, note that above Highway 99 there are several lots below Crystal Falls that border natural stream banks with relief of 2-4 m above the channel bed. These lots could be vulnerable to debris floods from water and debris that passes the decant structure during debris floods, from rare large catchment overtopping events or from ravine sidewall failures. Any debris that overtops the bank could then be directed down the surface onto the highway and down the Brunswick Beach access to Brunswick Beach Road.

On Alberta Creek, lots border the flume on both sides. The lower flume below about 150 m elevation has a reasonably constant configuration with 5 m depth and 13 m crest to crest width, as measured at the bridge on Isleview Place. It is conceivable that events exceeding the Design Event could overwhelm this channel with partial overtopping onto the fan surface. Depending on the overtopping elevation and the event magnitude, overflow debris could be directed anywhere on the modern fan. Upstream, between 150-255 m elevation (255 m elevation is the upper extent of the engineered flume), the flume is confined in ravine sidewalls 10-20 m deep, and there is little chance of debris escape in this section.

At ~260 m elevation there is a municipal water line crossing Alberta Creek. On the right bank, the buried pipe follows a bulldozed grade toward Timbertop Road. The channel cross section is 5 m deep by 10 m wide from the right bank crest to the left bank sidewall, which is higher. Any overtopping debris here could avulse onto the right bank, follow the 3% descending grade and affect houses on Timbertop Road and downslope. This is an isolated vulnerability, and its potentially affected area is not included in the NHAA. Upstream of this point Alberta Creek is deeply incised in a bedrock ravine.

On Harvey Creek, the channel is deeply confined downslope to the former fan apex where the catchment structure is located. Residual risk exists on the fan surface downslope of the catch basin. Below the catchment basin the creek is confined within an engineered flume, yet the flume does not extend to the sea. Local flood and debris flood hazard may affect coastal lots adjacent to Harvey Creek (Photo 6).

NHAA 2A may be revised by more detailed assessment of debris flow hazard and risk. This is anticipated to be a project exceeding the scope expected of individual lot owners. This is a responsibility likely needing to be undertaken by Village of Lions Bay or another level of government.

9.7.2 NHAA 2B- Upper Bayview fan (Map 5)

NHAA 2B captures the entire Upper Bayview fan including areas vulnerable to flooding and slope instability in case of misalignment of the diverted channel. This NHAA is vulnerable to debris flow and stream flooding including channel shifting. Should the diverted channel jump its banks, then the flow could further erode the gullies downslope, causing similar instability to that experienced in 1972; while minor sedimentation at the point of the 1972 diversion could redirect the creek back into its natural channel affecting housing at the fan apex. Moreover, a debris flow could directly impact several houses near the apex. In either of these scenarios, water and debris could spread throughout the NHAA in unpredictable ways.

BGC (2013) recommended mitigation of the debris flow hazard affecting this area (Appendix 1), but to date none has occurred. Until mitigation is in place, as part of the Natural Hazard Assessment Area process, Village of Lions Bay should require debris flood and debris flow assessment, with consideration for earthquake triggered landslides from slopes above, failure of excessive and irretrievable road spoil sites, open-slope slides, misaligned drainage and local instability caused by misdirected water. In addition, covenants detailing the landslide risk should be attached to title.

At a minimum, as per development on alluvial fans (WLAP 2004), house foundations should be designed to withstand debris flood impacts with concrete steel reinforced foundations, and by mitigating the possibility of water ingress by lift. This involves the establishment of a flood construction level (FCL) a minimum of 1 m above finished grade, requiring habitable space to be located above, or with suitable tanking of habitable space below.

9.7.3 NHAA 2C- Ravines (Map 6)

Ravines are landforms associated with creeks that have become incised into bedrock or thick deposits of surficial material. Typically, there is an abrupt slope break from adjacent terrain onto a steep erosional slope. At the toe of slope there may or may not be a floodplain between the toe and the creek's natural boundary. Since ravines are inherently associated with creeks, they are included within creek hazards. Ravine areas have been defined following RAR criteria and using ravine crest lines mapped on LIDAR.

To be consistent with the Riparian Assessment Regulations (RAR), RAR definitions are followed:

> A ravine is a narrow, steep-sided valley that is commonly eroded by running water and has a sidewall slope greater than 3:1 measured between the high water mark of the watercourse contained in the valley and the top of the ravine bank. The top of the ravine bank is the first significant break in a ravine slope where the slope beyond the break is flatter than 3:1 for a minimum distance of 15 meters measured perpendicularly from the break, and the break does not include a bench within the ravine that could be developed. The ravine setback area is a 30 m wide strip on both sides of the ravine measured the top of the ravine bank.

A 30 m setback from ravine crests defines the area that falls within NHAA 2C. This NHAA captures Battani and Rundle Creeks, and the ravines upstream of fan apices on Magnesia, Alberta and Harvey Creeks.

As mapped, the NHAA represents a maximum, cautious delineation. The setback from ravine crest could be reduced on the basis of a report from a qualified engineering/environmental professional, considering issues such as creek flood and debris flow hazard, factor of safety of the ravine sidewall slope and the riparian area regulation.

Within NHAA 2C, as part of the Natural Hazard Assessment Area process, for building sites beyond the ravine top of bank seismic slope stability assessments will be required to assess foundation stability; where building sites are located within ravines, a landslide assessment will be required for ravine slopes affecting the site, and to establish FCLs and other measures based on flood, debris flood and debris flow from affecting creeks.

9.8 NHAA 3 - Slope hazards (Maps 7, 8 & 9)

Three sub-categories of slope hazards are identified: open-slope failures, rockfall hazards, and stability of foundations and engineered slopes.

After District of North Vancouver (Bylaw 7900, Part 4.2A, DPA 3), the Slope Hazard Area is established to address the following objectives:

1. minimize the risk to people and property from slope hazard;
2. develop safely and minimize the impacts on or near steeply sloped lands, including the potential run out area below steep slopes;
3. reduce slope hazards and landslide risk to people and property by carefully managing development and construction practices on or near steeply sloped lands;

4. avoid alteration of steeply sloped lands that may cause increased instability of the land or adjacent areas;
5. encourage professional design of structures and mitigative works and to ensure field review during construction and post-construction certification; and
6. encourage ongoing maintenance and monitoring of steeply sloped lands.

An example list of guidelines to meet these objectives are provided in DNV Bylaw 7900, Part 4, NHAA 3C. DNV Bylaw 7900, Part 4, NHAA 3B sets out a list of exemptions. These were recently updated (amended October 13, 2017) reflecting 8-years of experience with their Risk Management system. All are directly applicable and Village of Lions Bay could decide to use in whole or in part (the Village of Lions Bay must consider legal third party reliance issues).

The list of exemptions does not include the “25% rule” which never the less is included in adopted (DNV 2009) Risk Tolerance criteria (Table 11). To be consistent with many community bylaws in BC, the 25% rule should be taken into account in the DP guidelines.

9.8.1 NHAA 3A - Open-slope slides (Map 7)

On the basis of analysis presented in Section 8.3.2, NHAA 3A extends from Highway 99 upslope to the municipal boundary.

Risk Analysis for open-slope slides requires knowledge of the frequency-magnitude model. Stratigraphic and radiometric methods must be applied to estimate historic return periods and gauge landslide intensity at the site. Such materials/methods may or may not be present or practicably attained from a single lot or group of lots. In lieu of hard data, expert judgment supported by sound geomorphic reasoning must be relied upon.

The area included within NHAA 3 has complex micro terrain, with very irregular to hummocky topography, and it is very difficult to predict individual landslide paths. Thus, while some local topographic features may shed or protect certain sites, safe sites cannot be predicted using simple rules, and caution is warranted. Landslide modeling by QPs using high resolution LIDAR topography would aid defining specific travel paths for various landslide volumes and rheologies.

If required by the outcome of risk analysis and evaluation, then siting constraints and/or design of protective measures may be required. Siting constraints, may include consideration of locations to minimize exposure to upslope hazards (local highs; sheltering behind topographic features), and/or the establishment of setbacks from the crests and/or toes of steep slopes. Protective measures may include aspects of foundation design, lift of habitable space, barrier walls and other measures. However, protection for a given lot must not transfer risk to other lots.

Development of frequency-magnitude models and protective measures might be best suited to area-wide assessment and mitigation. These tasks should be future work for consideration by the Village of Lions Bay or the Provincial Government.

9.8.2 NHAA 3B – Rockfall (Map 8)

NHAA 3B, areas affected by rockfall encompass the 27.5^0 rockfall shadow angle (Hungr and Evans 1993). The authors suggest that the shadow zone captures 99% of all rockfall events. Thus, the probability of escape beyond is low, and the NHAA boundary may be regarded as a safeline with Very Low risk beyond. Rockfall source areas requiring assessment may exist on a property or far upslope. The NHAA area is drawn by projecting the shadow angle from the base of the rock avalanche scarp between Magnesia and Alberta Creeks, and from other small scattered bluffs in and above Lions Bay.

Within NHAA 3B, the Village of Lions Bay should require rockfall risk assessments, including characterisation of 500-year to 1:2500 year return rockfall, and potential earthquake triggered events.

Rockfall modelling should be applied to aid design of protection measures. Protective measures may include scaling, bolting, shot creting application, fencing as determined by specialist P.Eng.

Rockfall must consider the hazard intensity of fall of individual blocks to the detachment of larger masses up to several thousand m^3, such as the prehistoric Kelvin Grove wedge failure and rockfall located off Kelvin Grove Way, on Lots 48, 60 & 61. Specialist bedrock structure and kinematic analysis may be required to determine potential event volumes.

Since the Magnesia-Alberta Face unit rock avalanche headscarp (Map 2) is located high above the Village, and since the cliffs are tall (10s m) and potential rockfall volumes are reasonably large (e.g., 10s-1000s m^3), the reach of these events extends far downslope, almost reaching the highway in the vicinity of Schoolyard Creek. Elsewhere, the smaller and lower elevation bluffs with benched terrain below, result in less extensive reach of potential rockfall.

9.8.3 NHAA 3C - Slopes >30% (Map 9)

Various guidelines and precedents set by other jurisdictions requires a NHAA category based on simple slope class. This slope-based NHAA is concerned with stability of foundations, excavations, fillslopes, the existence of very local rockfall and/or slide hazards, and with water control.

Worksafe regulation Section 20.78 of the OHS Regulation ("Regulation") states:

> (1) excavation work must be done in accordance with the written instructions of a qualified registered professional if
> (a) the excavation is more than 6 m (20 ft) deep,
> (b) an improvement or structure is adjacent to the excavation,
> (c) the excavation is subject to vibration or hydrostatic pressure likely to result in ground movement hazardous to workers, or
> (d) the ground slopes away from the edge of the excavation at an angle steeper than a ratio of 3 horizontal to 1 vertical.

Note regulation 20.78(1)d refers to slopes of 3HD:1VD, or 33%; this criteria is rounded down and adopted in the NHAA framework. Following the Worksafe regulation, NHAA 3C applies to areas where natural average ground slope was >30%. Most areas in Village of Lions Bay have average slopes >30% and require hillslope excavation and fillslope construction to develop building sites. Village of Lions Bay should require written reports from qualified professional for excavations, roads, drainage, fillslopes and foundations proposed at these sites. Local rockfall assessment and mitigation may also be required. Evaluation of onsite and nearby municipal drainage structures, and design of buildings to prevent water ingress is also required.

Areas like the tennis courts and local parking are expansive flat areas, but they are built in part on fill, and included in NHAA 3C. Small areas of gentle terrain exist along Bayview Road toward Mountain Drive, but most lots encompass some areas of steeper slope. Thus, these areas are included in the NHAA.

Current guidelines for assessment of slope hazards provided by the National and Provincial Building Code and the Engineers and Geoscientists of BC (2010), indicate seismic-initiated slope instability needs to be considered. Seismic slope analysis requires comparatively detailed knowledge of subsurface bedrock, soil and groundwater conditions. The required factor of safety calculation references many data sources, including but not limited to:

i. seismic hazard maps and reports;
ii. ground motion data;
iii. seismic Site Class; and
iv. modal magnitude values of the design earthquake.
v. assessment of shallow groundwater conditions and the anticipated effects of infiltration pits, septic fields, footing drains, etc., on local slope stability.

With respect to water control off small non-identified drainages, the conveyance capacity of drainage structures should be designed for 200-year floods to be consistent with legislated flood assessments (EGBC 2012) for residential areas. It could be required that as part of the development permit application, developers conduct a review of adjacent/nearby storm drainage structures to identify which may be undersized and presenting risk of blockage and overland flow affecting the development site.

The only areas within Village of Lions Bay exempt from NHAA 3C are below Highway 99, along Brunswick Beach, Harvey Creek fan excluding sites adjacent to the engineered flume, and Sweetwater Place inside the road center line of Tidewater Way and Periwinkle Place.

9.9 Additional possible exemptions

In addition to the Exemptions considered for each NHAA in the previous sections, The Village of Lions Bay may choose to grant general exemptions in the following circumstances:

For “Low Importance” structures, as defined in the BC Building Code: Buildings that represent a low direct or indirect hazard to human life in the event of failure, including: low human-occupancy buildings, where it can be shown that collapse is not likely to cause injury or other serious consequences, or minor storage buildings.

Where the proposed construction involves a structural change, addition or renovation to existing conforming or lawfully non-conforming buildings or structures, provided that the footprint of the building or structure is not expanded, and provided that it does not involve any alteration of land.

A subdivision where an existing registered covenant or proposed covenant with reference plan based on a qualified professional’s review, relating to the protection of the environment or hazardous conditions outlined in the subject Natural Hazard Assessment Area, is registered on title or its registration secured by a solicitor’s undertaking.

Immediate threats to life and property provided they are undertaken in accordance with the provincial Water Act and Wildlife Act and the Federal Fisheries Act, and are reported to the Village of Lions Bay.

Emergency procedures to prevent, control or reduce erosion, or other immediate threats to life and property provided they are undertaken in accordance with the provincial Water Act and Wildlife Act and the Federal Fisheries Act, and are reported to the Village of Lions Bay.

10. Discussion

In this report for the first time geohazards affecting Lions Bay have been reviewed and analysed in a comprehensive assessment. Since the community was developed before georisk was commonly considered a fundamental part of the subdivision process, and since Lions Bay was developed in and below steep terrain, it is not unexpected that much of the community is apparently vulnerable to multiple geohazards, including ocean, creek and hillslope hazards.

The Natural Hazard Assessment Areas (NHAAs) proposed in this report are necessarily conservative. This is because it is judged that, given the preliminary level of assessment applied in a complex topographic setting, it would be unwise and improper to attempt to refine and reduce the extent of NHAA zones beyond the level predicted by the simple empirical tools available. This would amount to provision of a false “positive” assessment for properties thereby excluded, and would expose the consultant and the Village of Lions Bay to excess liability. The designation of conservative NHAA boundaries does not preclude development. Rather the boundaries outline where and in what context more detailed assessments are required.

Further, while it may be appropriate with some NHAAs, to allow the developer to carry the burden of a more detailed assessment, for the assessment of others, the burden may more logically be the responsibility of the Village of Lions Bay or a higher level of government. For example, the ocean hazards, ravines, rockfall and slopes >30% Slope Hazard Assessment Areas are sufficiently refined and reasonable such that they may be applied on a site by site basis. On the other hand, the NHAAs for Magnesia, Alberta and Harvey creek fans and the area potentially affected by open-slope slides are quite extensive, and refinement producing consistent results may be most efficiently and fairly pursued as a single area wide analysis, rather than repeated assessments conducted by multiple and various consultants. This refined analysis should apply more sophisticated tools such as some or all of the following methods: subsurface exploration, stratigraphy, radiometric dating, regional analysis, computer modelling and risk assessment.

11. Recommendations for Future Work

For NHAA 1, Ocean hazards, adaptive management is recommended, applying periodic, ongoing monitoring of future sea-level rise by literature review and attention to government guideline updates.

For all landslide hazards, it is recommended that Village of Lions Bay adopt a landslide safety policy consistent with the District of North Vancouver (DNV 2009). As part of the risk assessment, a minimum landslide magnitude to consider is the 1:500-year event, but larger events up to the 1:2500-year earthquake triggered landslide should be considered. It is unreasonable to expect estimation of a 1:10,000-year event as required by District of Squamish, Fraser Valley Regional District or MoTI.

It is recommended that Village of Lions Bay assess residual risk affecting NHAA 2A. A qualified professional should estimate a frequency-magnitude (F-M) model for debris flows on Magnesia, Alberta and Harvey Creeks. The F-M model will include consideration of channel yield and point source volumes, and the event scenarios may include event process chains, such as point source failures mobilizing channel debris, with peak discharge augmented by temporary jams and outburst. Once developed, the runout of various landslide scenarios should be modelled to assess residual risk on the debris fans. Modeling should be conducted using high resolution (0.5-1.0 m contour) topography with various landslide volumes and rheologies.

It is recommended that the isolated vulnerability at the pipe crossing on Alberta Creek at 260 m elevation be assessed and mitigated to provide continuous confinement for the revised design event.

Even with partial or full mitigation of creek hazards, consistent with flood hazard management on dike protected floodplains, development on debris fans of Magnesia, Alberta and Harvey Creeks should employ failsafe mitigation. At the very least this will entail measures for low hazard areas on alluvial fans as recommended by WLAP (2004).

Similarly, NHAA 2B for Upper Bayview should be revisited, but must consider rockfall, debris flow, open-slope slide and potential avulsion of the diverted channel; stability of the irretrievable road-related fillslopes below the old logging road should be considered.

It is recommended that Village of Lions Bay refine NHAA 3A, open-slope hazards, and hire a qualified professional to estimate the frequency-magnitude (F-M) of open-slope landslides affecting Lions Bay and to suggest, using computer modeling, more refined runout limits for the design event. Depending on the results of a more detailed study, Village of Lions Bay may require proposed developments within the revised NHAA to implement site-specific measures, or it may be more practicable that Village of Lions Bay implement area wide protection. Alternatively, a higher level of government might be lobbied to effect these recommendations.

Similarly, it might be reasonable for Village of Lions Bay or the Province to conduct a Village or neighbourhood wide rockfall analysis and implement extensive protection strategy, as done a-priori at Sunset Highlands as a condition of development.

Potentially large but uncertain sackung hazards loom above parts of Lions Bay and Highway 99. These features require more detailed assessment to determine if they are stable or represent potential catastrophic hazards. Remote sensing using high resolution radar and optical satellites and LIDAR imagery is being applied to screen for unstable terrain, by differencing images and digital elevation models produced from sequential acquisitions. Interferometric Synthetic Aperture Radar (InSAR) satellite technique can detect cm/mm-scale displacements of slow deforming slopes over large areas. This technique has been applied to obtain multi-year national scale ground deformation map and it has been proven applicable for landslide early warning systems. If screening with LIDAR, optical satellite and InSAR were to identify movement, these same techniques can be applied to monitor the slopes. Analytical methods are then available to predict catastrophic failure providing an effective early warning system framework.

Court cases have arisen in the past regarding landslide damages experienced at Lions Bay (Lister 1985). Where existing homes exist in areas potentially affected by hazards, there may be a duty to warn. The Village of Lions Bay is advised to carry out public education and make hazard information available to all landowners and to prospective purchasers by means of various methods like public meetings, information mail out, and having material available on the Village website. The permit approval process should also be used as a trigger to attach save harmless covenant on title. The Village of Lions Bay is advised to consult with a lawyer for advice on these matters.

An archive of area-wide and site-specific hazard/risk reports should be created and made available to professionals conducting georisk assessment reports. This will allow professionals to become informed about previously identified hazards, and will promote efficiency and consistency of results and recommendations.

To aid qualified professionals and for public interest, derivative mapping products from VoLB LIDAR data and our orthophoto models should be compiled and provided on the Village of Lions Bay website. This should include 1 m & 5 m contour topography, the hillshade model, slope theme and orthophotos from years 1939, 1946, 1957, 1968, 1979, 1982, 1992, 1996 and 2004.

12. References

Engineers and Geoscientists of British Columbia (EGBC), 2010. Guidelines for Legislated Landslide Assessments for Proposed Residential Developments in BC. Dated May 2010.

Engineers and Geoscientists of British Columbia (EGBC), 2012. Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC. Dated June 2012.

Ausenco Sandwell, 2011. Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Use– Guidelines for Management of Coastal Flood Hazard Land Use. Report prepared for Ministry of the Environment. 23 pp + appendices.

Berger, T.B. 1973. Reasons for Judgment for the Honourable Mr. Justice Berger on the Matter of the Land Registry Act – And on Application for Approval of a Proposed Subdivision by Cleveland Holdings Ltd. Supreme Court of British Columbia, Victoria, BC, 26 pp.

BC Ministry of Environment. 1999. “Mapping and Assessing Terrain Stability Guidebook, Second Edition. 36 p.

BGC Engineering Inc., 2009. Metro Vancouver, regional IDF curves, Metro Vancouver climate stations: Phase 1 final. Report to Metro Vancouver, Burnaby, BC.

BGC Engineering Inc., 2012 & 2013. Upper Bayview Road debris flow hazard and risk assessment. Reports for BC Ministry of Forests, Lands and Natural Resource Operations and Emergency Management BC.

Blaise-Stevens, A., and Septer, D., 2008. Historical accounts of landslides and flooding events along the Sea to Sky Corridor, British Columbia, from 1855-2007. Geological Survey of Canada, Open File 5741, 117 pp.

Bovis, M.J., and Dagg, B.R., 1987. Mechanisms of debris supply to steep channels along Howe Sound, southwest British Columbia. Erosion and Sedimentation in the Pacific Rim (Proceedings of the Corvallls Symposium, August, 1987). IAHS Publ. no. 165.

Bunce, C.M. Cruden, D.M. and Morgenstern, N.R., 1997. Assessment of the hazard from rock fall on a highway. Canadian Geotechnical Journal, 34: 344–356.

Canadian Standards Association, 1997. Risk Management: Guideline for Decision Makers.

Catani, F., Tofani, V., Lagomarsino, D., 2016. Spatial patterns of landslide dimension: A tool for magnitude mapping. Geomorphology, 273: 361–373.

Cave, P. (1992, revised 1993). Hazard Acceptability Thresholds for Development Approvals by Local Government, British Columbia. BC Geological Survey Branch, Open File 1992-15.

Church, M., and Ryder, J.M. 1972. Paraglacial sedimentation: consideration of fluvial processes conditioned by glaciation. Geological Society of America Bulletin, 83(1): 3059-3072.

Clague, J.J., Harper, J.R., Hebda, R.J., Howes, D.E., 1982. Late Quaternary sea levels and crustal movements, coastal British Columbia. Can. J. Earth Sci. 19, 597-618.

Clague, J.J., Munro, A., and Murty, T.S., 2003. Tsunami hazard and risk in Canada. Natural Hazards 28 (2-3), 407-434.

Clague, J.J., and Orwin, J., 2005. Tsunami Hazard to North and West Vancouver, British Columbia. Centre for Natural Hazard Research Simon Fraser University. Prepared for North Shore Emergency Planning Office.

Clague, J.J., Hungr, O., and Vandine, D., 2014. Report of the Cheekye River and fan expert review panel. Report to Province of BC, District of Squamish and the Squamish Nation.

Clague, J.J., Hungr, O., Morgenstern, N.R., and Vandine, D., 2015. Cheekye River (Ch'kay Stakw) and Fan Landslide Risk Tolerance Criteria: Report of the Cheekye Expert Review Panel #2. Report to Province of British Columbia Squamish Nation and its Partnership, and District of Squamish.

Cordilleran Geoscience, 2001. Prehistoric debris flow, Sunset Highlands housing development, Sunset Beach. Report to United Properties, Vancouver, BC.

Cordilleran Geoscience 2011.Terrain Stability Assessment along the access road beyond Oceanview Road. Report to Village of Lions Bay, Lions Bay.

Cordilleran Geoscience 2012a. Rundle Creek windfall and creek hazard assessment, Lions Bay. Report to Sea to Sky District, Ministry of Forests, Lands and Natural Resource Operations, Squamish, BC.

Cordilleran Geoscience, 2012b. Alberta/Harvey Creek face, Lions Bay landslide hazard assessment. Report prepared for Ministry of Forests, Lands and Natural Resource Operations. 13pp.

Cordilleran Geoscience 2013. Lions Trail fillslope pullback-Alberta/Harvey Creek face, Lions Bay. Report to Sea to Sky District, Ministry of Forests, Lands and Natural Resource Operations, Squamish, BC.

Cordilleran Geoscience 2014a. Rock Chamber Slide, Harvey Creek, Lions Bay. Report to Village of Lions Bay, Lions Bay.

Cordilleran Geoscience 2014b. Channel assessments: Magnesia, Upper Bayview and Harvey Creeks, Lions Bay. Report to Village of Lions Bay, Lions Bay.

Corominas, J., 1996. The angle of reach as a mobility index for small and large landslides. Canadian Geotechnical Journal, 33: 260-271.

Couture, R., and VanDine, D., 2004. Field Trip – Guidebook, Some Geological Hazards in North Vancouver and along the Sea-to-Sky Highway, British Columbia Geological Survey of Canada, Open File 4642. 84 p.

District of North Vancouver (DNV), November 10, 2009. Report to Council: Natural Hazards Risk Tolerance Criteria; District of North Vancouver, British Columbia. Report prepared for DNV Council.

District of Squamish. 2009. Official Community Plan, Bylaw 2100, Section 25 Hazard Lands, District of Squamish, BC.

District of Squamish. 2017. To Qualified Professionals, Land Owners and Developers: Terms of reference for Natural Hazard and/or Risk Assessments. Memo from Development Services, November 29, 2017.

Earle, S., 2003. Course PDF presentation on Debris Flow Defensive Structures at Howe Sound, British Columbia. Earth Science Department, Vancouver Island University, https://web.viu.ca/earle/howe-sound/

Eisbacher, D.H., 1983. Slope stability and mountain torrents, Fraser Lowlands and southern Coast Mountains, British Columbia; Geological Association of Canada/ Mineralogical Association of Canada/ Canadian Geophysical Union Annual Meeting, Field Trip Guide Book No. 15, 46 p.

Englander, J., 2014. High Tide on Main Street: Rising Sea Level and the Coming Coastal Crisis (revised second edition). The Science Bookshelf, Bocan Raton, Florida. 227 pgs.

Environment Canada, 2017. Accessed online at http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnProx&txtRadius=50&optProxType=city&selCity=49%7C17%7C123%7C8%7CVancouver&selPark=&txtCentralLatDeg=&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongDeg=&txtCentralLongMin=0&txtCentralLongSec=0&stnID=341&dispBack=0

Evans, S. and Savigny, K., 1994, Landslides in the Vancouver-Fraser Valley-Whistler region, in J. Monger (ed) Geology and Geological Hazards of the Vancouver Region, Geological Survey of Canada, Bull. 481, p. 251-286.

Fairbanks, R.G., Mortlock, R.A., Chiu, T.C., Cao, L. Kaplan, A., Guilderson, T.P., Fairbanks T.W. and Bloom, A.L., 2005. Marine Radiocarbon Calibration Curve Spanning 10,000 to 50,000 Years B.P. based on Paired 230Th/234U/238U and 14C Dates on Pristine Corals. Quaternary Science Reviews v. 24, 1781-1796.

Fannin, R.J., and Rollerson, T.P. 1993. Debris flows: some physical characteristics and behavior. Canadian Geotechnical Journal, 1993, 30(1): 71-81.

Fieber Rock Engineering Services, 2011. Rock Slope Stability - 300 Block Mountain Drive, Lions Bay, BC. Report to Village of Lions Bay, Lions Bay.

Friele, P.A., Ekes, C. and Hickin, E.J. 1999: Evolution of Cheekye fan, Squamish, British Columbia: Holocene sedimentation and implications for hazard assessment. Canadian Journal of Earth Sciences 36, 2023–31.

Friele, P.A., and Clague, J.J. 2002. Younger Dryas readvance in Squamish river valley, southern Coast Mountains British Columbia. Quaternary Science Reviews, 21(18-19) 1925- 1933.

Friele, P.A. and Clague, J.J. 2009. Paraglacial geomorphology of Quaternary volcanic landscapes in the southern Coast Mountains, British Columbia. In Knight, J. and Harrison, S. (eds), Periglacial and Paraglacial Processes and Environments. Geological Society, London, Special Publications, 320: 219-233.

Geopacific 2016. Rock Fall Review, Harvey Creek Intake Access Road, Lions Bay, BC. Report to Village of Lions Bay, Lions Bay.

Golder Associates Ltd., 1989. Kelvin Grove Developments, Rock Slope Stability on Lot 48. Report to Village of Lions Bay, Lions Bay.

Golder Associates Ltd., 2006. Slope condition assessment phase 4 & 5 access road, Lions Bay. Report to Village of Lions Bay, Lions Bay.

Guthrie, R.H., Evans, S.G., 2004. Magnitude and frequency of landslides triggered by a storm event, Loughborough Inlet, British Columbia. Natural Hazards and Earth Systems Science 4, 475–483.

Guthrie, R.H., Hockin, A., Colquhoun, L., Nagy, T., Evans, S and Ayles, C., 2010. An examination of controls on debris flow mobility: Evidence from coastal British Columbia. Geomorphology. 114. 601-613.

Horel, G., 2007. Overview-level Landslide Runout Study: Western Forest Products Inc., Tree Farm Licence 6. Streamline Watershed Management Bulletin, 10(2):15-24.

Hungr Geotechnical Research Inc, 2007. Aerial inspection of the check dam on Alberta Creek. Report to BC Ministry of Transportation, Burnaby, BC.

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

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.

Hungr, O., Evans, S.G., and Hazzard, J., 1999. Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia. Canadian Geotechnical Journal, 36: 224–238.

Jackson, L.E., Jr., Blais-Stevens, A. Hermanns, R.L., van Zeyl, D.P., Stead, D., Jermyn, C.E., Barrie, J.V., Conway, W.K. and Hetherington, R., 2014. Geological Survey of Canada, Open File 7616 Late

Glacial and Holocene sedimentation and investigation of fiord tsunami potential in lower Howe Sound, British Columbia

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

Jakob M., 2012. The fallacy of frequency: statistical techniques for debris-flow frequency-magnitude analysis. In: 11th International Symposium on Landslides. Banff ISL.

Jakob, M., and Friele, P.A., 2010. Frequency and magnitude of debris flows on Cheekye River, British Columbia. Geomorphology, 114: 382–395.

Jakob, M. and Holm, K., 2012. Risk assessment for debris flows. *In* Landslides: Types, Mechanisms and Modelling, *edited by* J.J. Clague and D. Stead. Cambridge University Press, Cambridge, UK.

Jakob, M. and Lambert, S., 2009. Climate change effects on landslides along the southwest coast of British Columbia. Geomorphology, 107: 275-284.

Jakob, M. and Weatherly, H., 2003. A hydroclimatic threshold for landslide initiation on the North Shore Mountains of Vancouver, British Columbia. Geomorphology 54: 137-156.

Jordan, P. and Slaymaker, O. 1991: Holocene sediment production in Lillooet River Basin, British Columbia: a sediment budget approach. Géographie Physique et Quaternaire 45, 45–57.

Klohn Leonoff 1992. Sea to Sky Highway Caulfield Interchange to Furry Creek, functional design, geological, geotechnical and hydraulic engineering. Report to Ministry of Transportation of Highways, Surrey, BC.

Kerr Wood Leidal, 2014. Geotechnical Hazards Report: Egmont/Pender Harbour OCP Area. Report for Sunshine Coast Regional District, Sechelt, BC.

Kerr Wood Leidal 2016. District of Squamish Integrated Flood Hazard Management Plan, River Flood Risk Mitigation Options, Final Draft, May 2016.

Lian, O.B. and Hickin, E.J. 1996: Early postglacial sedimentation of lower Seymour Valley, southwestern British Columbia. Géographie Physique et Quaternaire 50, 95–102.

Lister, D., Kerr, J., Morgan, G. and VanDine, D., 1984, Debris torrents along Howe Sound, British Columbia; Proceedings of the 4th International Symposium on Landslides, V.1, p. 649-654.

Lister, D.R., 1985?. Litigation resulting from debris torrent activity along Howe Sound. Ministry of Transportation and Highways, Victoria.

Millard, T., Rollerson, T.P. and Thomson, B., 2002. Post-logging landslide rates in the Cascade Mountains, south-western British Columbia. Res. Sec., Van. For. Reg., B.C. Min. For., Nanaimo, B.C. Tec. Rep. TR-023/2002.

Morgan, G.C., Rawlings, G.E., and Sobkowicz, J.C., 1992. Evaluating total risk to communities from large debris flows. In Geotechnique and natural hazards, *edited by* GeoHazards '92 Organizing Committee, GeoHazards '92; Vancouver, British Columbia, pgs 225-236.

MOTI (Ministry of Transportation and Infrastructure). 1993. Subdivision Policy and Procedures Manual, Systems Planning Research Officer, Victoria, BC.

MOTI (Ministry of Transportation and Infrastructure). 2009, revised 2013 and 2015. Subdivision Preliminary Layout Review – Natural Hazard Risk, internal document, March 13, 2009.

NBCC (National Building Code of Canada). 2005. Published by the National Research Council of Canada, Ottawa, ON.

Nhc, 2014. City of Vancouver coastal flood risk assessment final report. Report to City of Vancouver, Vancouver, BC.

Piteau Gadsby Macleod Limited (PGM), 1976. Proposed Development on the Northeast Shore of Lillooet Lake above the Forestry Road. Letter report prepared for Heather Jean Properties Ltd. dated April 2, 1976.

Piteau and Associates, 1981. Evaluation of proposed subdivision for rockfall hazard, Log “G”, District Lot 2361, Plan 14536, Sunset Point, West Vancouver, BC. Report to David O’Brian and Associates, North Vancouver, BC.

Roberti, G., Friele, P., van Wyk De Vries, B., Ward, B., Perotti, L., Clague, J.J., and Giardino, M., 2017. Prelandslide edifice kinematics due to glacial debuttressing of a volcano: the evolution of the 2010 Mount Meager Landslide from deep seated gravitational deformation to debris avalanche. Landslides,

Rollerson, T., Millard, T., Jones, C., Trainor, K. and Thomson, B., 2001. Predicting post-logging landslide activity using terrain attributes: Coast Mountains, BC, MoF technical report TR-011

Rollerson, T., Maynard, D., Higman, S., and Ortmayr, E., 2005. Phillips River landslide hazard mapping project. In Landslide Risk Management, Hungr, Fell Couture (eds), Taylor Francis Group, London.

Septer, D., 2006. Flooding and landslide events southern British Columbia 1808-2006. BC Ministry of Environment, Victoria BC.

Transport Canada, 2011- http://www.tc.gc.ca/eng/roadsafety/tp-tp3322-2007-1039.htm#t12

VanDine, D.F., 1985. Debris flows and debris torrents in the Southern Canadian cordillera. Canadian Geotechnical Journal, 22, 44-68.

Water, Land and Air Protection, 2004. Flood hazard area land use management guidelines. Province of British Columbia, Victoria, BC.

Westmar, 2005. Tsunami probability and magnitude study, summary report. Report to Village of Lions Bay, Lions Bay.

Appendix 1. Summaries of site specific reports at Lions Bay

Golder Associates Ltd., 1989. Kelvin Grove Developments, Rock Slope Stability on Lot 48. Report to Village of Lions Bay, Lions Bay.

Four natural bluff areas were identified as potential rock fall hazards on Lot 48 and adjacent areas, including Lots 58-70 inclusive. Rockfall was described as fragmental blocks in the range of 0.5 m to 10 m diameter. Potential triggering mechanisms were listed as water or ice pressures developing during periods of wet or cold weather, tree roots growing in a crack and causing it to open, or an earthquake. Stabilization work was recommended before development work proceeded.

Westmar, 2005. Tsunami probability and magnitude study, summary report. Report to Village of Lions Bay, Lions Bay.

This was a literature review to determine tsunami hazard at Lions Bay. It was concluded that while mechanisms can be postulated (Hamilton and Wigen 1987), there is no geological or historical evidence of tsunami within Georgia Basin (Clague et al. 1994), megathrust earthquake induced tsunami generated at the continental margin would attenuate to ~1 m before reaching Lions Bay (Clague et al. 2003), local sources for landslide induced tsunami are not evident, and events such as submarine slope failure at Squamish delta would not amplify in the deep water offshore at Lions Bay. The maximum credible tsunami was cited as 2 m with a return period of 100-1000 years. Given a 4-5 m tidal range, such an event would have to be coincident with HHW to cause damage, resulting in a very low probability of severe consequence occurring.

Golder Associates Ltd., 2006. Slope condition assessment phase 4 & 5 access road, Lions Bay.Report to Village of Lions Bay, Lions Bay.

This report provides fillslope pullback recommendations to remediate roadfill instability that had developed on Oceanview Road. Apparently, the work was completed immediately.

Hungr Geotechnical Research Inc, 2007.Aerial inspection of the check dam on Alberta Creek. Report to BC Ministry of Transportation, Burnaby, BC.

In 2007, the administrator of the Village of Lions Bay expressed concerns about the check dam on Alberta Creek at about 700 m elevation. Hungr stated the check dam was built for a temporary purpose before the completion of the concrete lined debris chute channel in 1985. Its foundation and abutments are anchored into strong rock and it was well built with a design life of more than 100-years. They are left to naturally fill with debris to full capacity, and thereby protect the structure from dynamic impact by debris. The incipient shallow slide upstream of the check dam, that was the original reason for its construction, seems to be still perched on the steep hillside. Thus, the check dam reduces the hazard and will continue to do so, as long as it is structurally sound. No works were recommended, in fact attempting cleanout was discouraged.

Fieber Rock Engineering Services, 2011. Rock Slope Stability - 300 Block Mountain Drive, Lions Bay, BC. Report to Village of Lions Bay, Lions Bay.

An area of recent rockfall extending an approximate 100 m length of slope, from roughly the driveway at 340 Mountain Drive to the driveway at 390 Mountain Drive. Ditch improvements were recommended to act as a catch for small rockfall sourced a limited distance up the slope. It was noted that the recommended ditch improvements will not provide protection from rockfall originating from the higher areas of the mountain slope.

Cordilleran Geoscience 2011.Terrain Stability Assessment along access road beyond Oceanview Road. Report to Village of Lions Bay, Lions Bay.

Residents expressed concern about terrain stability and downslope risk as a result of recent hauling, handling and storage of construction aggregate on the access road extending beyond Oceanview Road and the construction of a skid trail from a private property up to the access road. The area of concern consisted of interspersed moderate (30-50%) and moderately steep (50-70%) slopes mantled by weathered till veneer on bedrock, with local seepage on impermeable bedrock. Under natural conditions there was judged to be a very low to negligible potential for landslide initiation. However, with human modification, fill materials perched on locally steep slopes could result in small failures, likely less than $1000m^3$ in total volume, but of a size could cause property damage and death should they directly impact a house or persons. Following this assessment some unstable fillslope areas were remediated and the lock block storage bin was removed from the fillslope shoulder. It was recommended that the Village of Lions Bay review their development policies to ensure that they require developers to involve qualified professionals when development (including roads) is proposed in “steep” terrain.

Cordilleran Geoscience 2012a.Rundle Creek windfall and creek hazard assessment, Lions Bay. Report to Sea to Sky District, Ministry of Forests, Lands and Natural Resource Operations, Squamish, BC.

Concern was expressed regarding recent windfall and its effect on Rundle Creek, specifically with regard to aggravating creek hazards and risk to lots downslope. Based on field inspection, it was noted Rundle Creek is a very small channel with low water power, and there is low debris flow initiation potential at the windfall site and immediate vicinity. For such small streams, typically no cleaning would be required, even after logging had introduced substantial woody debris. No action was recommended.

Cordilleran Geoscience 2012b.Alberta/Harvey Creek face, Lions Bay landslide hazard assessment. Report to Sea to Sky District, Ministry of Forests, Lands and Natural Resource Operations, Squamish, BC.

This report was commissioned following a SAR member reporting a cutslope failure on the old logging road above Lions Bay. While the cutslope failure was deemed to be of little concern, two major findings were discovered. Firstly, it was noted that the logging road construction spoiled excessive sidecast onto the slopes below, and that there were several sites where the fillslope was presenting tension cracking and settlement and thereby deemed unstable; and secondly, in traversing the slopes below it was noted there was an error in both the 1:50,000 and 1:20,000 scale topographic mapping which showed a small basin on the Harvey/Alberta face draining into Alberta Creek; while in fact it was identified that this drainage was directed downslope to a fan apex on 545 Upper Bayview Drive. In the Septer (2006) report this drainage is identified as Lions Brook. This newly identified slope condition implied that there was a previously unappreciated hazard affecting 545 Upper Bayview and environs. Two key recommendations followed from the report: 1) pullback the unstable fillslopes as much as practicable, and 2) have a second QP conduct a QRA to assess the landslide risk affecting Upper Bayview Road.

BGC Engineering Inc., 2012 & 2013. Upper Bayview Road debris flow hazard and risk assessment. Reports for BC Ministry of Forests, Lands and Natural Resource Operations and Emergency Management BC.

Following from Cordilleran (2012b), BGC (2012) conducted a preliminary QRA that concluded that unacceptable risk existed at several properties on Upper Bayview Road, and that measures would be required to reduce the risk. They recommended several items that would permit a refined analysis, including acquiring a high resolution topographic map base, radiocarbon dating of stratigraphic exposures, and debris flow modelling. The results of BGC (2013) suggest that individual risks at 540 and 545 Upper Bayview Road were unacceptable when compared with individual risk tolerance criteria adopted by the District of North Vancouver (DNV). Four potential mitigation options were identified, including 1) construction of a deflection berm and excavation of a channel that would direct debris flows from the mid-slope area of Bayview Creek towards Alberta Creek before they could enter the lower gully; 2) installation of flexible debris flow nets in the lower gully and near the fan apex; 3) construction of an earthworks barrier in the lower gully; and 4) acquisition of the property at 545 Upper Bayview Road and construction of an earthworks barrier near the location of the existing home.

Cordilleran Geoscience 2013. Lions Trail fillslope pullback-Alberta/Harvey Creek face, Lions Bay. Report to Sea to Sky District, Ministry of Forests, Lands and Natural Resource Operations, Squamish, BC.

This report signs off on deactivation work conducted to reduce logging road related landslide risks affecting Lions Bay identified by Cordilleran (2012b). Sites where road-fillslope material presented a potential landslide hazard were pulled back as much as is practicable given access constraints. There is residual risk remaining that affects residential areas downslope; it arises from road-related fills that are too far below the existing bench and cannot be retrieved or from natural hazard areas above the road. The risk from these areas is best mitigated through constructed protection measures.

Cordilleran Geoscience 2014a. Rock Chamber Slide, Harvey Creek, Lions Bay. Report to Village of Lions Bay, Lions Bay.

On October 22, 2014 rainfall at low elevation stations was 30-50 mm/24 hr, with maximum gusts of 50-70 kmh in Howe Sound. The storm triggered a small slide on the north facing sidewall of Harvey Creek, directly upslope of the domestic water intake and rock chamber building. The slide debris impacted the intake access road downstream of rock chamber building, partly inundating the building with sediment. High sediment transport on Harvey Creek on the same day filled the rock chamber plugging the water intake. Debris, from the slide and from a debris flood on Harvey Creek partly filled the debris catchment basin above Highway 99.

Cordilleran Geoscience 2014b. Channel assessments: Magnesia, Upper Bayview and Harvey Creeks, Lions Bay. Report to Village of Lions Bay, Lions Bay.

On December 9-10, 2014, a storm delivering precipitation >70 mm/24hr for 2 consecutive days, totalling 146 mm/48 hr with 40-60 kmh winds affected Lions Bay with debris flows and creek erosion causing damage to both Magnesia and Harvey community water intakes. As well there was anomalous flow on the 545 Upper Bayview (Upper Bayview) debris fan. On Magnesia Creek, the intake access road was undermined by high flows and sections of rock stack fillslope had collapsed. The Magnesia Creek washout was triggered by a debris flow on a south facing slope at 1300 m snowline. The debris stopped 200 m downslope on a bench, and damage farther downstream consisted mostly of bank scour. The Harvey debris catchment was partially filled with deltaic gravel and woody debris. The Harvey Creek flood event was not related to landslide activity. High peak discharges entrained rubble from colluvial veneer and talus slopes and this resulted in high bedload, but not debris flow.

Geopacific 2016. Rock Fall Review, Harvey Creek Intake Access Road, Lions Bay, BC. Report to Village of Lions Bay, Lions Bay.

Geopacific conducted a review of a rock fall onto the Harvey Creek intake road that occurred between January 18-20, 2015. They noted that rockfall at this site has been known since 2004, and that some debris remained from a small rock fall occurred at this location after a small earthquake occurred in the area on December 30th, 2015 (Fig. 2). Rockfall hazard along the intake road was stated to be a chronic and ongoing hazard.

Appendix 2. List of geohazards affecting East side of Howe Sound near Lions Bay, up to 2006. Source: Septer 2006.

Year	Date	Hazard	Description
Ca 1935	?	Debris flow	Identified on airphotos, debris flows on Newman and unnamed #1 creeks.
Ca 1935	?	Debris flow	Identified on airphotos, a debris flow on Alberta Creek reaches the sea.
Ca 1935	?	Debris flow	Identified on airphotos, a debris flow on small creek (Upper Bayview) between Alberta and Harvey Creek stopping at 550 m elevation.
Ca 1935	?	Debris flow	Identified on airphotos, a debris flow on Harvey Creek stopping at 500 m elevation.
1969	Feb 9	Rockfall	1-tonne boulder falls onto highway at Porteau, kills 3 people
1969	Feb 13	Rockslide	6000 m3 rockslide at Brunswick Point. Highway blocked for several days.
1969	Sept 17	Debris flow	Water supply intake destroyed on Harvey Creek and flooding and erosion threatened 5 houses on alluvial cone
1969	Sept 18	Debris flow	Torrent on Charles Creek destroys 4 bridges between Highway 99 and sea.
1969	Sept 18	Debris flow	Newman Creek bridge buried.
1972	Dec 15	Debris flow	Highway blocked and house damaged.
1972	Dec 25-26	Debris slide	Small landslide affecting 6 homes. Caused by creek diversion of tributary to Harvey Creek into Alberta Creek. Referred to as Lions Brook, this creek is now known as Upper Bayview. This is the creek affecting 545 Upper Bayview.
1973	May 23-25	Flooding and erosion	Harvey Creek flooding and erosion, Lot 33 Cloudview affected by overflow; Lot 17 Seaview affected by bank undermining.
1976	Aug 25	Rockfall	1500 m3 rockfall at Brunswick Point closes highway and causes railway derailment.
1976	Sept 1	Rockfall	Rockfall north of Lions Bay causes train derailment.
1978	Sept 9-10	Flooding and erosion	Erosion of riprap on Harvey Creek
1981	Oct 27	Debris flow	M-Creek debris flow destroyed highway bridge claiming 9 lives, covered the rail line and a destroyed a house at creek mouth
1981	Oct 28	Debris flow	Rail bridge blocked diverting water onto private property affecting a truck and garage.
1981	Dec 4	Flooding and erosion	Channel constriction almost forces avulsion of Harvey Creek into subdivision below highway.
1981	Dec 4	Debris flow	Small debris flow on Newman Creek, overflow of debris affecting marina
1981	Dec 4	Debris flow	Small debris flow on Alberta Creek.
1981	Dec 4	Debris flow	Small debris flow on Charles Creek.
1981	Dec 20	Rockfall/debris slide	Small landslide blocks Highway

1982	Jan 16	Rockfall	Vehicles stopped on highway due to snow. At Brunswick Point single rock, dislodged by tree-topple, falls onto car kills one occupant injures another.
1982	Oct 6	Flooding, erosion & sedimentation	Floods on Harvey, Newman and Magnesia Creeks. Erosion on Newman Creek triggered overflow and sedimentation at marina.
1982	Dec 2-3	Landslide	Landslide blocks highway north of M-Creek
1982	Dec 3	Debris flow	Small event on Alberta Creek
1983	Feb 11	Debris flow	A large debris flow destroyed all bridges except railway, damaged 6 houses and claimed 2 lives, another person rescued from damaged residence.
1983	Feb 11	Debris flow	Debris flow on Charles Creek blocks highway bridge and floods road.
1983	Feb 11	Debris flows	Smaller debris flows also occurred on Newman and Turpin Creeks blocking crossings and causing overflows.
1983	Nov 15	Debris flow	Debris flows on Charles, Newman and Montizambert Creeks. Bridges destroyed on Charles Creek.
1984	Oct 8	Debris flow	Small debris flow on Sclufield Creek.
1984	Oct 8	Flooding	Harvey Creek flooding washed away 6 weeks of work on protection structure under construction.
1987	Apr 29	Rockfall	Small earthquake triggers rockfall onto highway between Lions Bay and Britannia, affecting 2 vehicles.
1990	Oct 21	Rockfall/debris slide	Slide 6 km north of Lions Bay at Tunnel Point blocks highway and railway
1990	Oct 25	Rockfall/debris slide	Repeat event at Tunnel Point injures workers clearing highway.
1990	Nov 16	Rockfall/debris slide	Another Tunnel Point slide closes highway
2005	Jan 23	Rockfall	Large rock fell on highway north of Lions Bay.
2006	Nov 17	Tension cracking	A 5 m long by 10 cm wide fissure observed at Lions Bay.

Appendix 3. Annotated photos.

Photo 1. Till in house excavation, Lot 60 Oceanview Road.

Photo 2. Glaciofluvial fan-delta sediments, 160 m elevation, Lot 22 Highview Place.

Photo 3. Blocky talus slope on Lots 60-61, Kelvin Grove Way.

Photo 4. View of the tombolo spit, Brunswick Beach. Low lying land is subject to flooding and erosion given sea level rise.

Photo 5. Magnesia Creek catch basin.

Photo 6. Lots 21 & A Lions Bay Avenue have natural banks not significantly raised above Harvey Creek, and could be vulnerable to flood hazard.

Photo 7. Lot 66 Kelvin Grove Way. Small Creek captured by drainage system undersized for full range of flows requires sand bagging to prevent overflow onto local road.

Photo 8. Open-slope landslide, North Vancouver mountains, triggered by rain on snow, November 22, 2017.

Photo 9. Unfavourable jointing in road cut, Lot 85 Kelvin Grove Way.

Photo 10. Waypoint 46. Antislope ridge indicating steep joint cutting crest of cliff. Several 10s m^3 to 1000s m^3 could be released from this site.

Photo 11. Bluff above Mountain Drive with unfavourable joint, parallel to steep slope.

Photo 12. Rockfall debris, Lots A & B Timbertop Road. Note the person for scale.

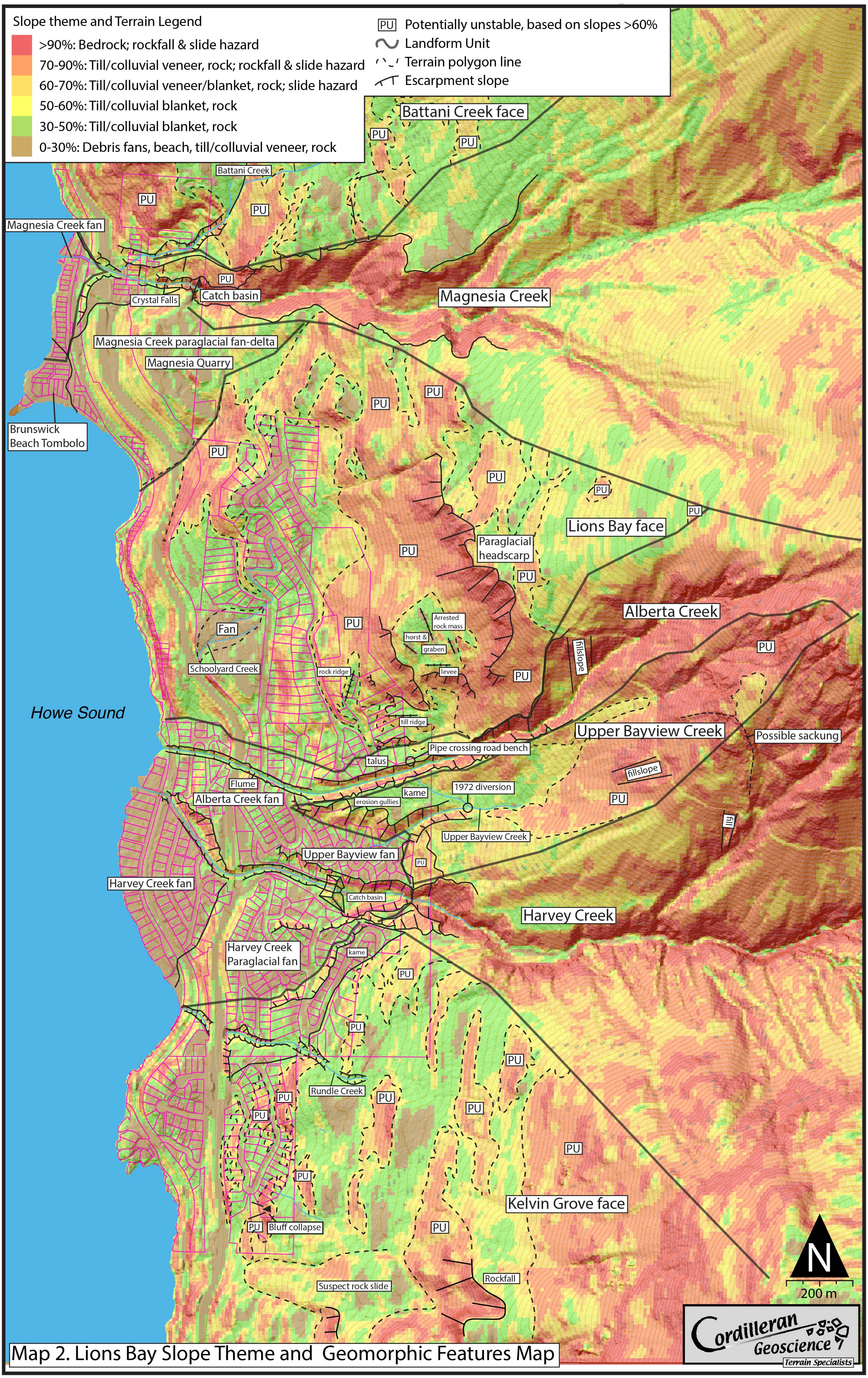
Photo 13. Rockfall block, Lot 36 Timbertop Road.

Photo 14. Lot 8 Isleview Place. Retaining walls in steep terrain require engineered design.

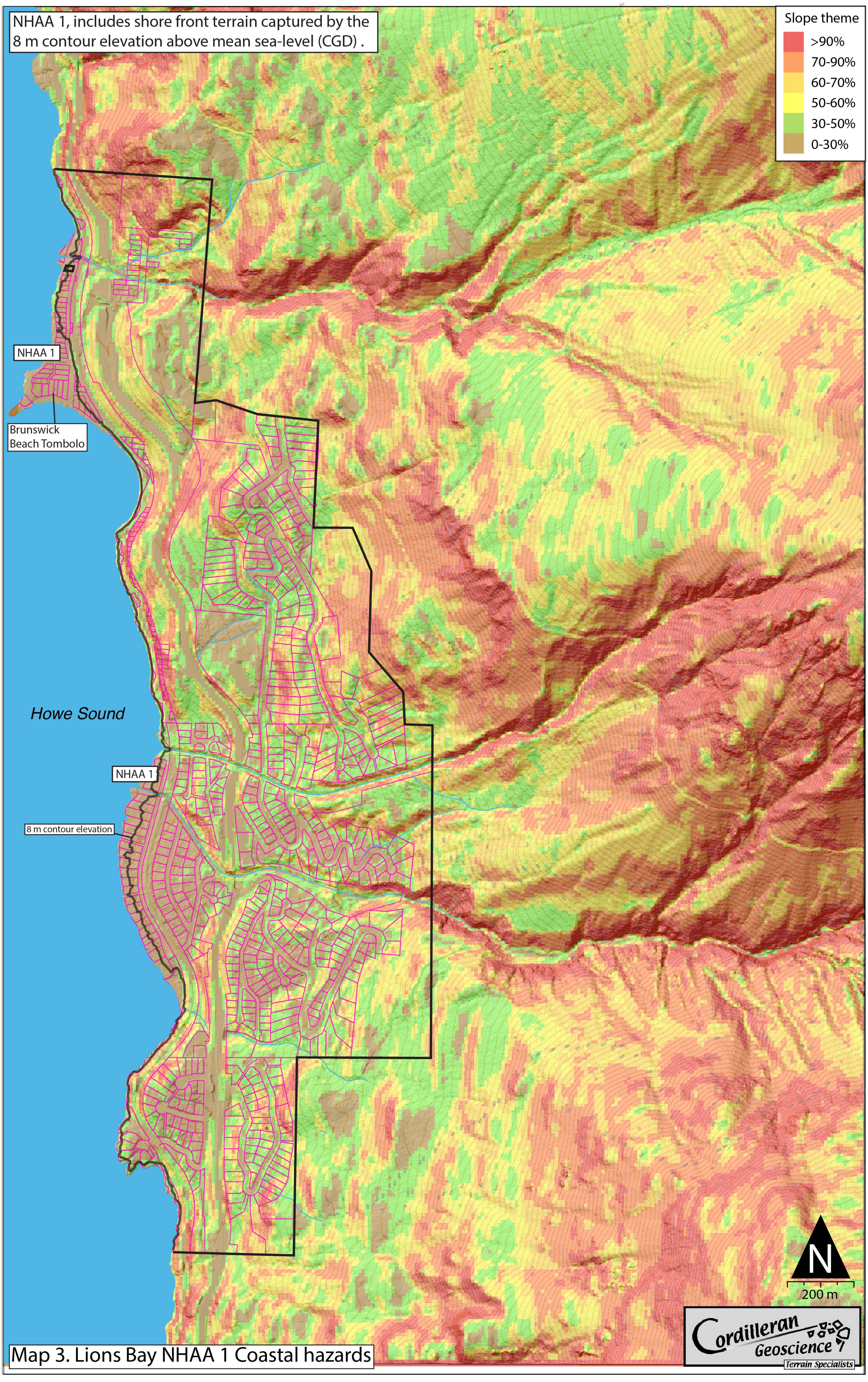
Photo 15. Stacked rock wall in steep terrain using geotextile to tie back into slope.

Photo 16. Substandard retaining walls represent a slope hazard.

Map 1. Lions Bay Waypoints



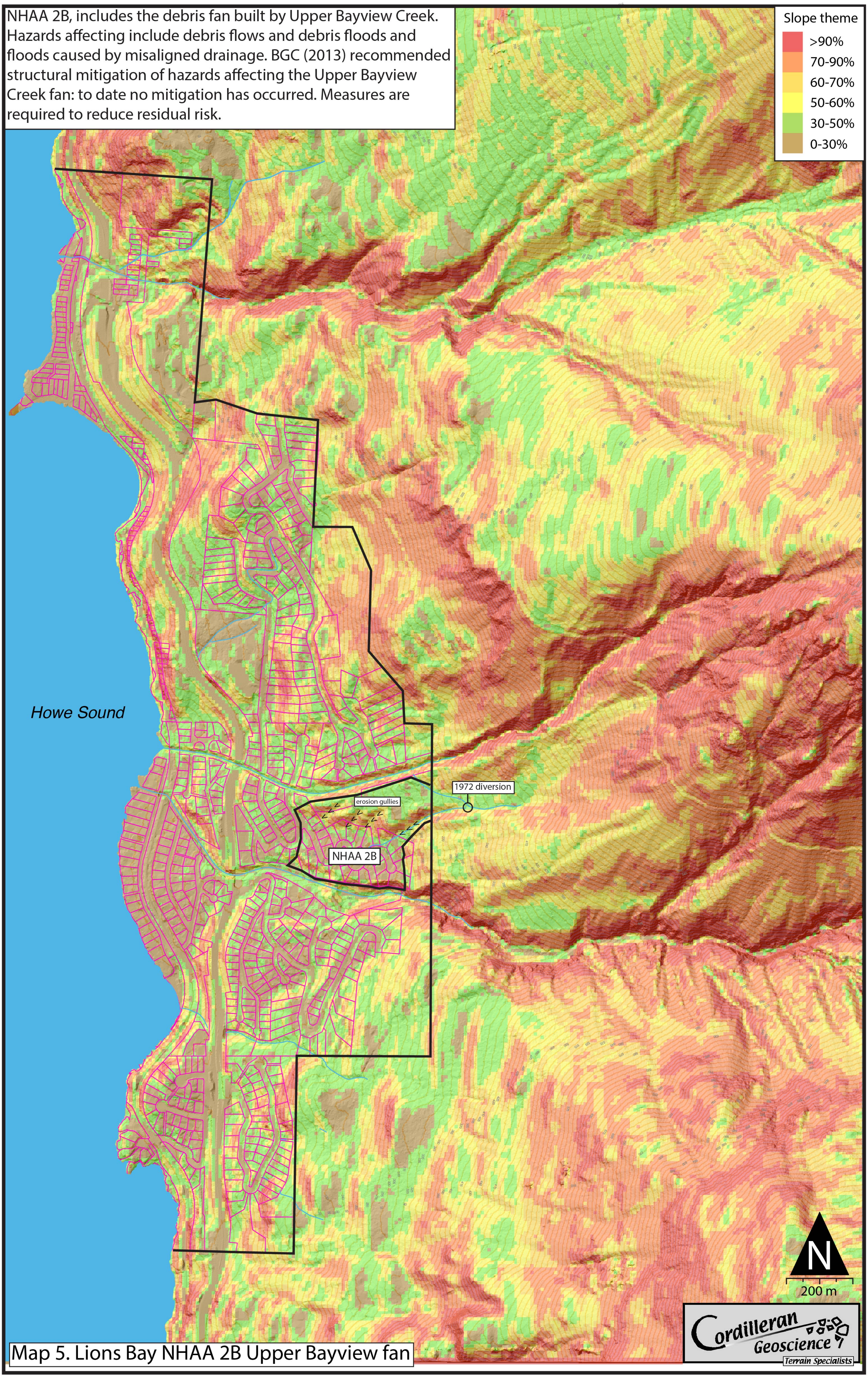
Map 2. Lions Bay Slope Theme and Geomorphic Features Map



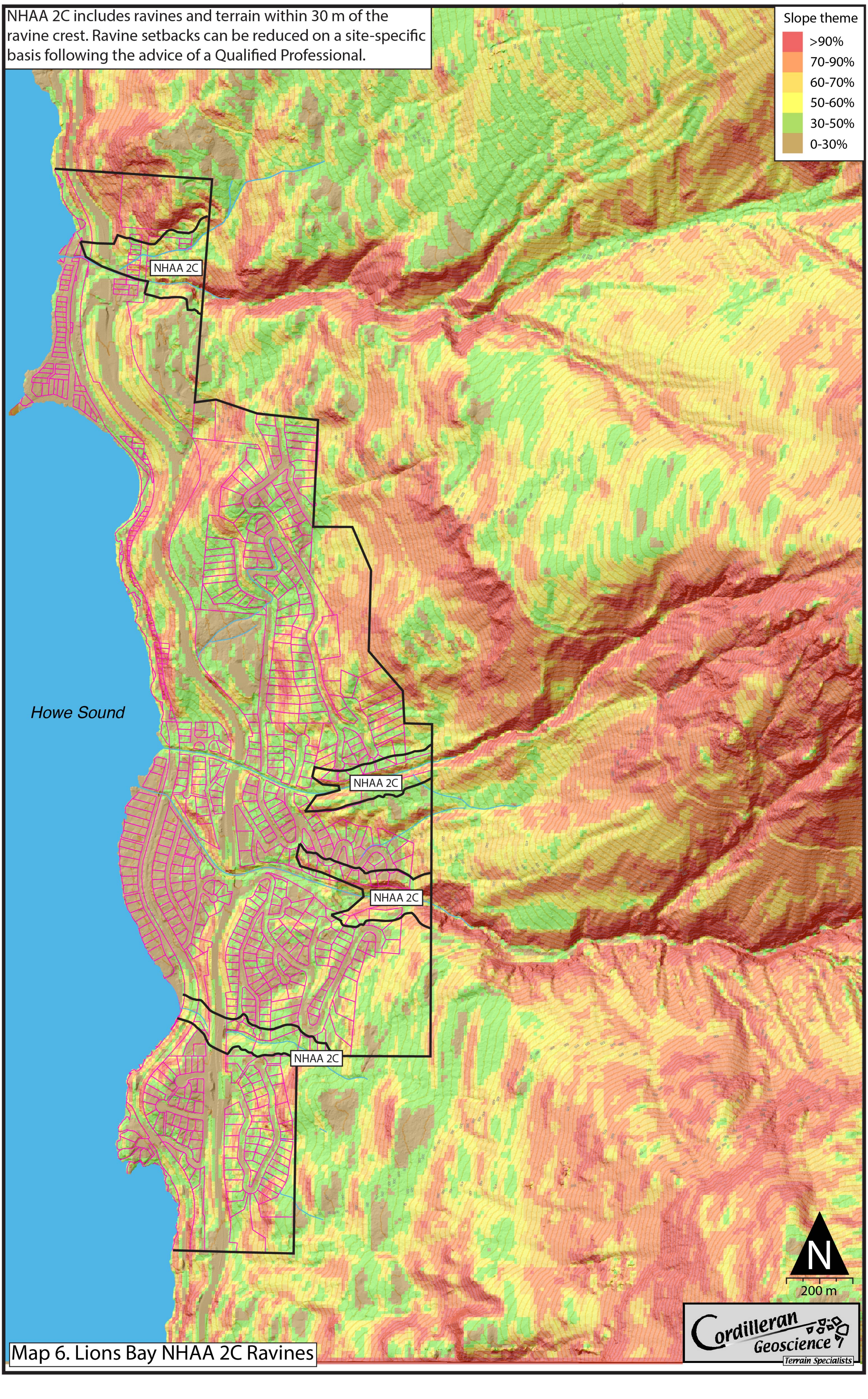
Map 3. Lions Bay NHAA 1 Coastal hazards

NHAA 2A, includes debris fans formed by Magnesia, Alberta and Harvey Creeks. The area potentially affected reflects the fact that existing mitigation on these channels was not designed to a known return period standard, and engineered structures could be overwhelmed by rare events. Measures are required to mitigate residual risk. Conditional area may be removed once pipe crossing grade on left bank is assessed and mitigated.

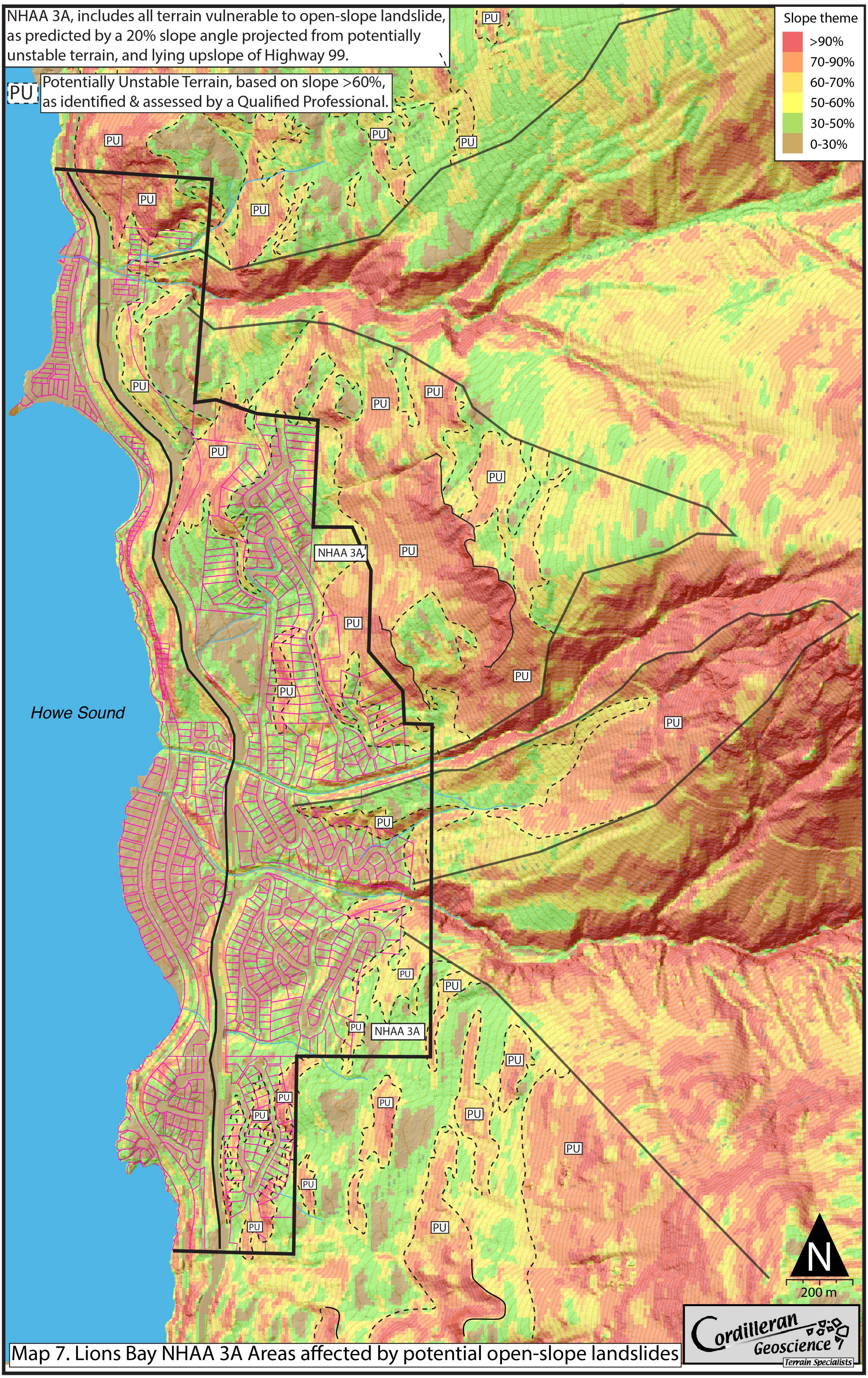
Map 4. Lions Bay NHAA 2A Debris fans of mitigated channels



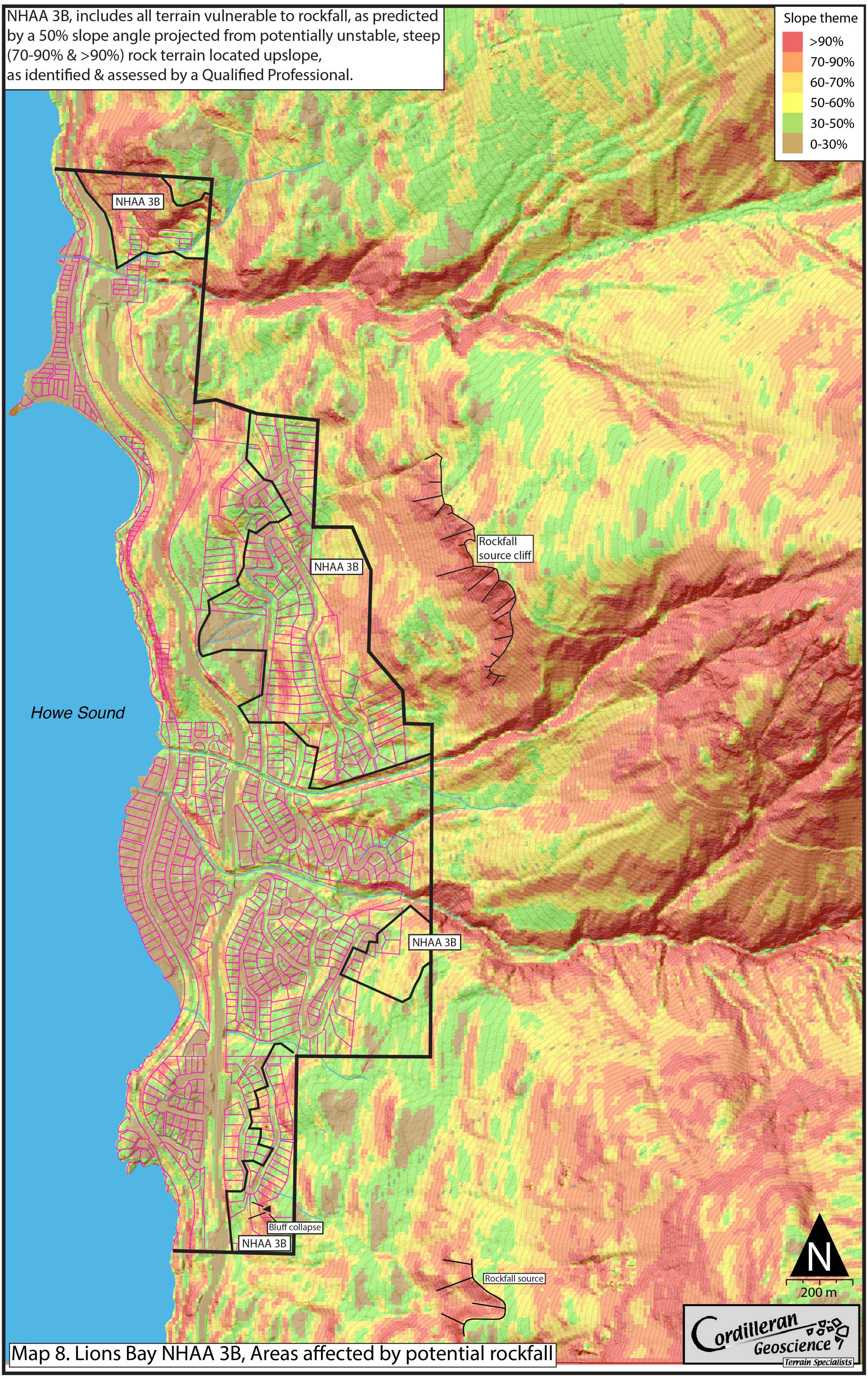
Map 5. Lions Bay NHAA 2B Upper Bayview fan



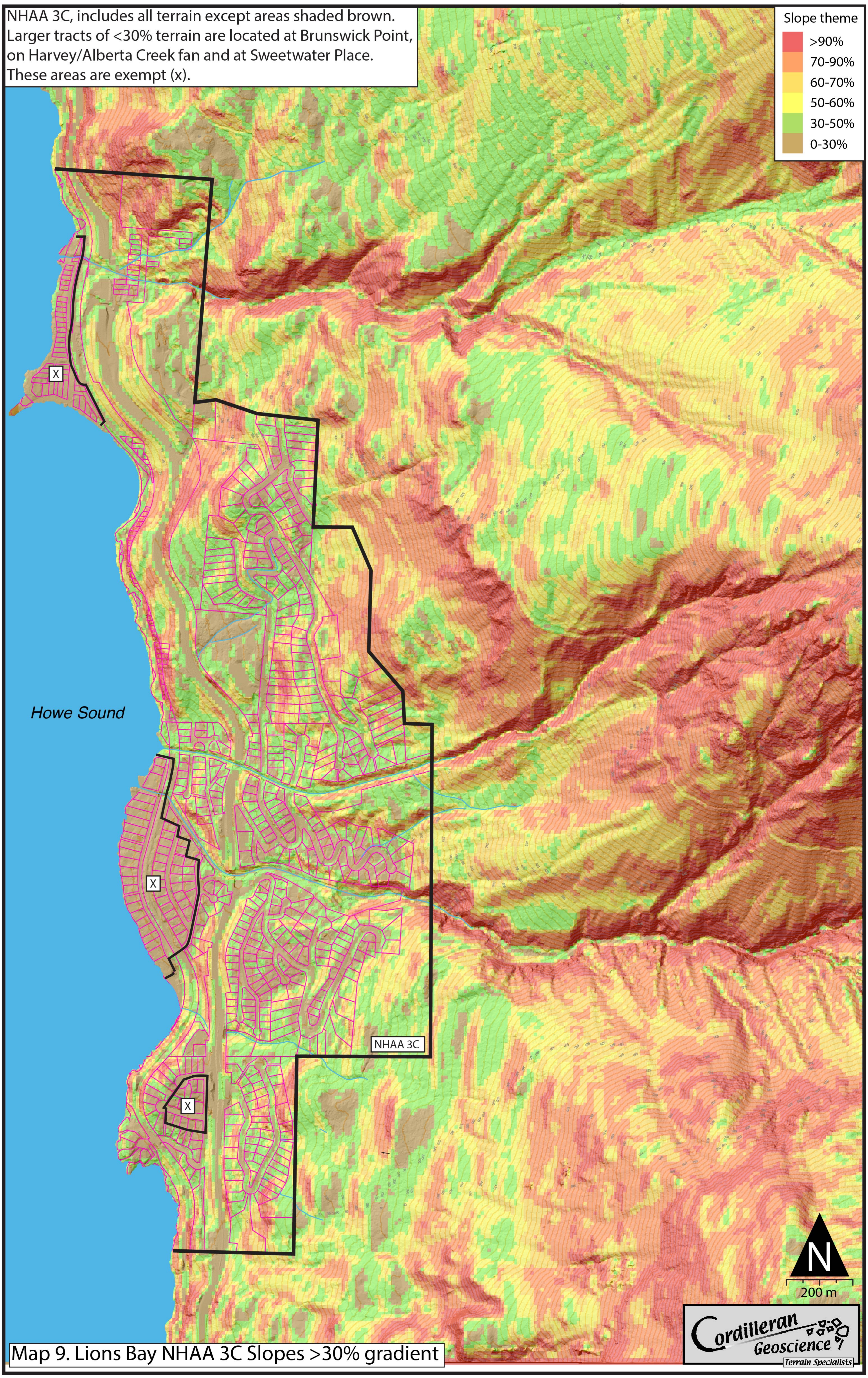
Map 6. Lions Bay NHAA 2C Ravines



Map 7. Lions Bay NHAA 3A Areas affected by potential open-slope landslides



Map 8. Lions Bay NHAA 3B, Areas affected by potential rockfall


NHAA 3C, includes all terrain except areas shaded brown.
Larger tracts of <30% terrain are located at Brunswick Point,
on Harvey/Alberta Creek fan and at Sweetwater Place.
These areas are exempt (x).
Slope theme
>90%
70-90%
60-70%
50-60%
30-50%
0-30%
X
Howe Sound
X
NHAA 3C
X
N
200 m
Cordilleran
Geoscience
Terrain Specialists
Map 9. Lions Bay NHAA 3C Slopes >30% gradient