Analyzing Landslide Risk Along the Sea to Sky Highway

GEOB 270: Introduction to Geographic Information Science

Final Project

The Sea to Sky Highway, British Columbia, Canada

Rock slide on the Sea to Sky Highway

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Abstract

Landslides have affected the Sea to Sky (Highway 99) historically and still affect the roadway to this day. In particular, the southern segment of the highway just north of West Vancouver is especially susceptible to landslide events. The need to analyze certain areas for construction of safety systems has been known for some time. Here we report several areas that should have safety systems implemented based on several key factors that are historically associated with landslide events. We used GIS to overlay several physical parameters that collectively may contribute to landslides: lithology, Quaternary sediment, vegetation, faults, slope and hydrology. By overlaying historical records of landslides onto these physical parameters we delineated areas characteristic of mass movement along the highway. Our analyses suggest that sedimentary and volcanic units in conjunction with coniferous vegetation, slopes ranging from ten to thirty degrees within fifty meters of a hydrologic channel are at greatest risk to structural failure resulting in a mass movement. Using these parameters, several areas on the southern section of the highway were highlighted to be equipped with safety systems to lower or nullify risk to the highway user.

Introduction

The scenic Sea to Sky Highway is one of British Columbia's most notable pieces of infrastructure as it follows along the edge of Howe Sound resting under steep glacial-valley slopes. However, this also places the highway in an environment vulnerable to frequent landslides. The Government of British Columbia is very much aware of the susceptibility to landslides here, and in the decade leading up to the 2010 Winter Olympics in Vancouver the Sea to Sky Highway underwent an improvement project with investments amounting to 600 million dollars. Yet, even since this impressive revampment, the Sea to Sky Highway has continually experienced landslide events and the Government of British Columbia must further maintain the road.

Our project analyses involved assessing the specific landscape conditions that have experienced landslide events along the sea-to-sky highway in the past in order to identify potential areas of landslide risk along the southern portion of the Sea to Sky Highway. We considered several landscape factors/attributes/conditions, including lithology, hydrology, vegetation, slope, and faults. This data was acquired from DataBC and combined into a GIS for analysis and manipulation. Past landslide events including debris flows and rock falls were pulled from a research paper (Blais-Stevens and Septer, 2008) and used as the basis for our identification of areas currently susceptible to landslides along the highway.

Figure 1: Channelized debris flow.

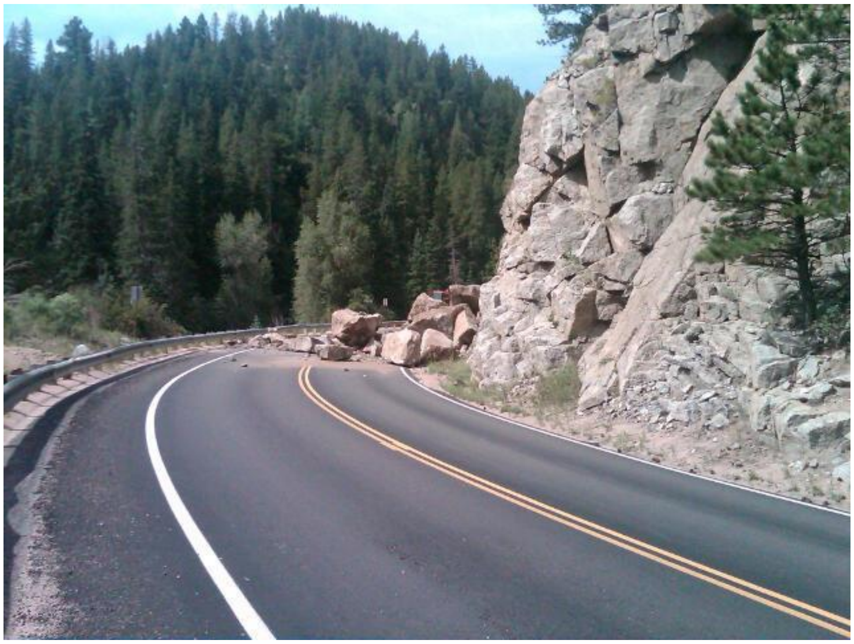

Figure 2: Rock fall from a steep roadcut.

Methodology of Analysis

A total of one hundred and fifty historical landslide events from 1855-2007 (Blais-Stevens and Septer, 2008) were manually entered into an excel sheet (which included easting, northing, date, event interpreted and location) and saved. This data table was then imported into ArcMap and a landslide shapefile was created. We chose to narrow our research area to the southern portion of the Sea to Sky Highway (between Squamish and Vancouver), where the majority of the landslide events took place and to omit specific landslides from our analysis that did not occur near highway (ex: western coast of Howe Sound). As a result, a total of one hundred and thirty six landslide events were included in our analysis.

Based on the locations of the majority of historical landslide events, a polygon was created through the New Feature Class function that encompassed these events and the surrounding terrain. This polygon represented our project area of interest and was used to clip imported geospatial data to keep the data at a manageable size and focused on the southern Sea to Sky highway area.

Six digital elevation model files, acquired from DataBC, spanning our area of interest were combined together into one DEM raster file using the Mosaic to Raster tool. This file was projected to NAD 1983 UTM Zone 10N and clipped to our project area polygon using the Project, and Clip tool respectively.

Bedrock, quaternary sediment, and fault layers were obtained from the Government of BC - Ministry of Energy and Mines, while streams, roads, bays and vegetation layers were downloaded from DataBC. These seven layers were all projected to NAD 1983 UTM Zone 10N, and clipped using the project area polygon.

In order to determine the areas along the highway susceptible to potential landslides, the factors driving the landslides for the last one hundred and fifty years needed to be identified. To accomplish this, the bedrock layer was spatially joined to the landslide layers. This join allowed us to determine the lithology at which the majority of landslides took place. Another spatial join was repeated with landslides and vegetation to determine which vegetation was most susceptible to landslides. The Select by Location query was used to determine how many landslides occurred on quaternary sediment, and how many landslides occurred within a certain distance of a stream, or fault. To determine the correlation between the slope of the terrain and landslide occurrence, a slope map was created from the DEM using the Slope tool. The slope raster data was edited from floating type to an integer type using the raster calculator tool and then converted to a polygon using the Raster to Polygon tool. This new layer was spatially joined to the landslide layer and we were able to determine the slope interval at which most rock falls and debris flows occur.

To create a layer of the areas susceptible to future landslides, the clipped vegetation, clipped slope polygon, and clipped bedrock layers were joined together using the Union tool. Using Select for Attributes, areas were identified that were underlain by Gambier Group Lower Cretaceous Marine Sedimentary and Volcanic Rocks, had treed coniferous vegetation classification and a terrain slope between ten to thirty degrees; a new layer was created from this selection. The stream layer was buffered to fifty meters, and used to clip the risk zone layer to produce a layer of risk zones found within fifty meters of a stream. Finally, the road layer was reclassified to show only the sea to sky highway, then buffered to one kilometer of the road. The one kilometer buffer around the highway was used to clip the risk zone layer, so that only areas susceptible to landslides that are within a one kilometer range of the highway are displayed. The final maps are created using bedrock, quaternary sediments, streams, roads, vegetation, historical landslide events, hillshade and landslide risk layers. A summary of this methodology is found in the Analysis Flow Chart in Appendix III.

Discussion and Results

Spatial analysis of the bedrock, faults and Quaternary sediment layers provided insight concerning the lithology that results in landslides along the Sea to Sky highway. Six geological bedrock units located along the highway in the area of interest have produced landslides over the past one hundred and fifty years: Mid Cretaceous granodiorite (MKgd), Mid Cretaceous quartz diorite (MKqd), Gambier Group Lower Cretaceous marine sedimentary and volcanic rock (IKGsv), Late Jurassic granodiorite (LJgd), Late Jurassic quartz diorite (LJqd), Mesozoic metamorphic rock (Mzm). Results from the queries that indicated the number of landslides per geological bedrock unit are displayed in Table 1. Of the one hundred and thirty six landslide events analyzed, the Gambier Group marine sedimentary and volcanic rocks produced just over 50% of the landslide events along the Sea to Sky highway in the past, while the Mid Cretaceous quartz diorite produced 19% of the past landslides. Furthermore, the Gambier Group bedrock experienced a mix of both rock falls and debris flows, while the Mid Cretaceous quartz diorite and the three other intrusive felsic bedrocks (MKgd, LJgd, LJqd) experienced mainly rock falls. This was expected because most all sedimentary and volcanic rocks contain internal structure which makes them inherently weaker, or can be easily weakened.

On the contrary, the massive crystalline intrusive rocks that make up a large part of the Coast Mountains are very strong, and rarely give way unless they have been exposed at the surface and subject to weathering for long periods of time. Given the abundance of historical landslides that correlate with the Gambier Group marine sedimentary and volcanic rocks, we concluded that it is the geological bedrock unit most at risk for landslides.

Interestingly, only seven landslides occurred on Quaternary sediment. This was surprising due to the loose, weak nature of the sediments, but could be simply due to their low presence in relation to other geological units, or a result of fluids maintaining cohesiveness. Furthermore, this sediment is in large part only present at very low slopes, in large river or stream basins. Therefore, we did not consider Quaternary sediment as a major factor driving landslides in the region.

Fifteen landslides occurred within one kilometer of a geological fault, twenty within two kilometers and twenty-nine within three kilometers. This relationship is expected as should there be any large movement along these faults, a landslide would be inevitable. However, going into the field and finding dates for previous fault movement would be necessary to evaluate the risk of future movement of the faults, and whether they are currently active. Based on the poor correlation of fault proximity to historical landslide (and to some degree, lack of data on the faults themselves), they were not taken into account during our hazard analysis.

Following the analysis of lithology, surficial sediment and faulting along the Sea to Sky, we analyzed the correlation between vegetation classification and landslide occurrence. Landslides along the highway have occurred on a wide variety of landcover and vegetation types, as seen in Table 2. The 58% of historical landslide events occurred on areas that were covered with predominantly coniferous trees (Tc). Treed land seems to be the most susceptible land cover for landslides along the Sea to Sky highway, although we suspect that this strong correlation between treed land and past landslide events exists primarily because most land around the highway is represented by this type of vegetation. Only a small proportion of land around the highway is covered with a different vegetation type or cleared for development. Taking this into account, only the terrain covered in coniferous trees was used for hazard analysis along the highway.

The relationship between landslides and terrain slope was also analyzed. Using our historical data, and the slope data discussed above, it was found that in the past most landslides have occurred on slopes ranging from ten to thirty degrees.

Of these landslides, rock falls dominated the higher range of slope angles, while debris flows populated the lower slope angles. This was an expected relationship between the two since rock falls require an exposed surface and high gravitational energy, while debris flows are nucleated by moisture and flow down stream channels. As a result of this relationship, a wide range of angles - ten to thirty degrees - was used in our hazard analysis.

In terms of hydrology, twenty six landslides occurred within thirty meters of a stream, whereas forty-eight landslides occurred within fifty meters of a stream. For this reason, relative proximity to streams was not seen as a critical factor contributing to a terrains susceptibility to landslides. However, these streams can and are used as speed channels for landslides (specifically debris flows), and had to be taken into account if they intersected or approached the highway. Since streams alter their paths over time, and as we used historical data to correlate current streams to landslide frequency in the area, this is a potential source for error that we discuss later in the paper. Using this data, the streams were buffered to fifty meters as a potential source for landslide nucleation and were taken into account in our final hazard analysis.

The final maps produced delineate the areas along the sea to sky highway that, under our criteria, are at significant risk to future landslides. The only section of the highway that was found to be at risk through our analysis was a portion only slightly north of West Vancouver. These areas, depending on whether they are at the intersection of the highway and a roadcut, or the highway and a stream, should have protective measures emplaced. Areas deemed hazardous along roadcuts should have netting to catch falling rock and debris. Streams, which are most susceptible to debris flow events, should have catchment areas or underpasses which stop debris, or allow it move underneath the highway into the sound, respectively. Photos of these structures are highlighted in the photos below (Figures 3 and 4).

Figure 3: Rock fall netting used to capture large chunks of rock, and allowing them to pass safely to the base of the net.

Figure 4: Debris flow catchment structure which stops large solids from passing, but allows water and fine sediment to travel downstream.

Error and Uncertainty

There are various sources of uncertainty and error in the project. Primarily, the landslide data obtained from the Blais-Stevens and Septer (2008) paper documented past landslides as coordinates and thus have been represented as points rather than polygons in our analysis. This is an inherently inaccurate representation of landslide events and depending on where the coordinates correspond to in the area of extent of the landslide, the slope analysis may be incorrect.

As well, the historic landslides, plotted and utilized to determine areas at potential future risk of landslides, were all pulled from a single source. The authors of this paper may have omitted some landslides on purpose if they were not relevant to their study, or unintentionally if the landslide was not recorded by anyone. Either way, it is possible that there have been landslide events that were not documented from this source. Additionally, the data only ranges from the years 1855 to 2007 and is lacking any landslide events along the Sea to Sky highway that have occurred in the past ten years. These issues of inaccurate representation of data present sources of possible error to our data visualization and analysis efforts.

DEM data, from which the slope data was taken from, was highly pixelated. In conjunction with our point data for landslides, the slope analyses could have been highly flawed depending on where the landslide data point was captured. This returns to the discussion of landslide data being captured as polygons to represent their full extent instead of single points. Using very high resolution data such as LiDAR, which is very expensive, would nonetheless solve the accuracy problem. A company which has the resources to use such data would be urged to include it in their final risk assessment of the roadway.

We've also assumed that the environmental conditions have remained unchanged through time. This assumption provides us with a simplification of reality as we are assuming that the environmental conditions at the time our data was captured is exactly the same as the environmental conditions present when the landslides happened in the past. This assumption is certainly a source of error and uncertainty because we know that conditions change through time and after natural occurrences such as landslide events.

Further Research and Recommendations

For future research regarding landslide events along the Sea to Sky highway of British Columbia, we recommend examining landslide events that occurred in the past decade to compliment our study and determine whether the safety nets and catchments put in place by the government were effective. We also recommend including factors that affect ground stability and may induce landslides, such as intense precipitation events, vegetation density, and soil type. Furthermore, analyzing whether there is a correlation between the season, weather, and the frequency of landslides may be of use in maintaining the highway and response time in clearing the highway after a landslide. The use of LIDAR data may also be of benefit for a more accurate representation of the current slope and vegetation classification of the area.

In addition, it would also be interesting to analyze how future climate change may affect the frequency of landslide events as stream flow regimes are subject to change and potential temperature fluctuations would affect freeze-thaw stress on bedrock that is a factor in rock falls.

Furthermore, it may be of interest to developmental agencies, insurance companies, and the Government of British Columbia to add damage cost estimates to the landslides that affect infrastructure and areas of human development. This information may especially be useful for The Walt Disney Company as they evaluate how to insure areas of their future seven billion dollar investment in the Disney Ski Resort at Garibaldi.

Appendices

I. Bibliography

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Cover photo 1: https://www.hellobc.com/getmedia/2aedcfff-41d5-4155-957c-e67e2d72e574/2-6805-Sea-to-Sky.jpg.aspx
Cover photo 2: https://i.cbc.ca/1.3451153.1455673638!/fileImage/httpImage/image.jpg_gen/derivatives/16x9_620/hwy-99-rockslide.jpg

Figure 1: http://www.landslidetechnology.com/images/landslides-beartooth.jpg
Figure 2: http://i.huffpost.com/gen/718380/original.jpg
Figure 3: http://nebula.wsimg.com/3c55a3961b067858a841fdadee7cf9b0?AccessKeyId=9F0CA1F6337BC9EA5CA7&disposition=0&alloworigin=1
Figure 4: https://pubs.usgs.gov/of/2001/ofr-01-0144/Venezuela/image045.jpg

II. Maps and Figures

Table 1: Lithology Type and Landslide Events

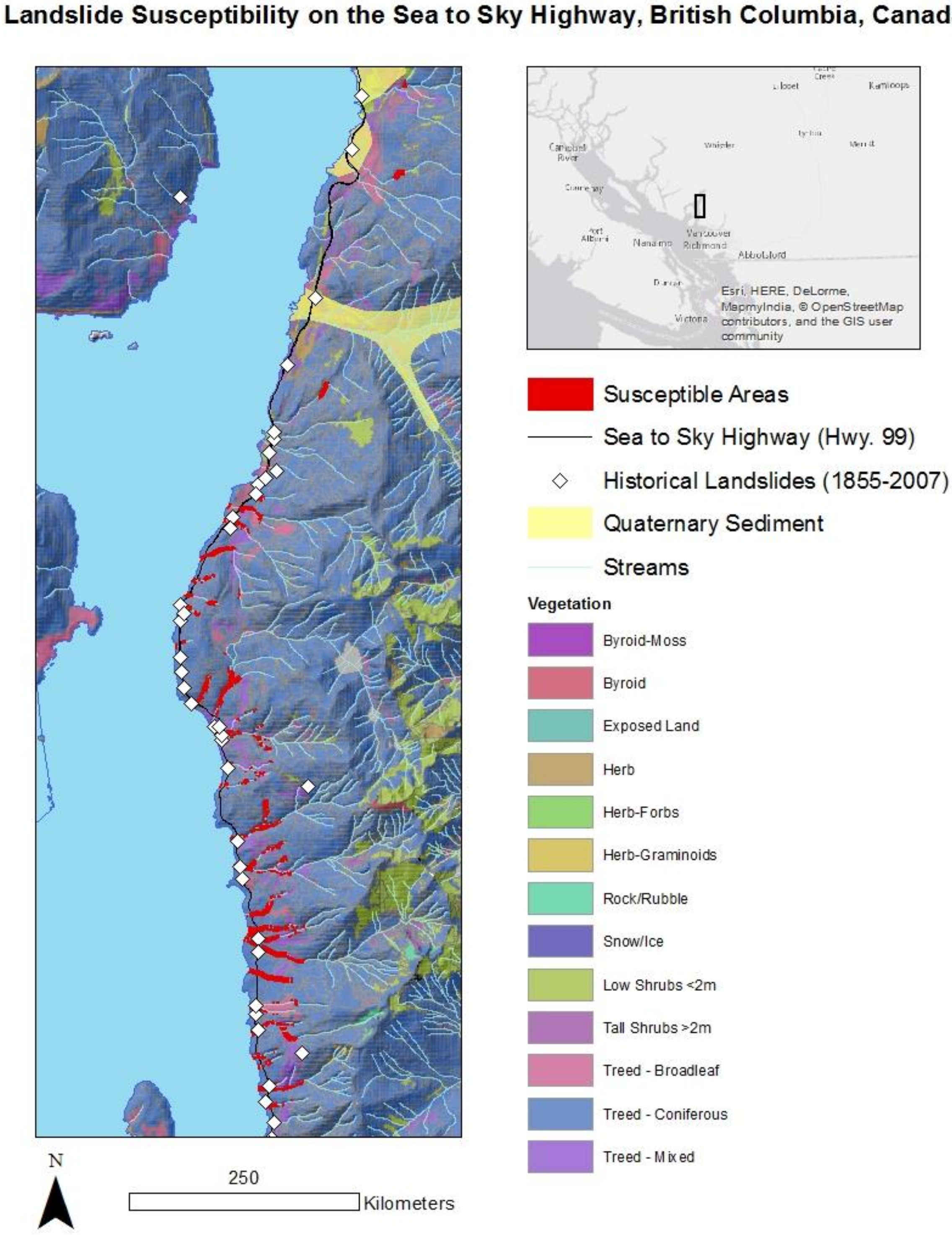
Stratigraphic Unit	Lithology Type	Number of Landslide Events
LJgd	Late Jurassic granodiorite	11
LJqd	Late Jurassic quartz diorite	14
IKGsv	Gambier Group Lower Cretaceous marine sedimentary and volcanic rocks	69
MKgd	Mid Cretaceous granodiorite	5
MKqd	Mid Cretaceous quartz diorite	26
Mzm	Mesozoic metamorphic rock	11

Table 2: Vegetation Classification and Landslide Events

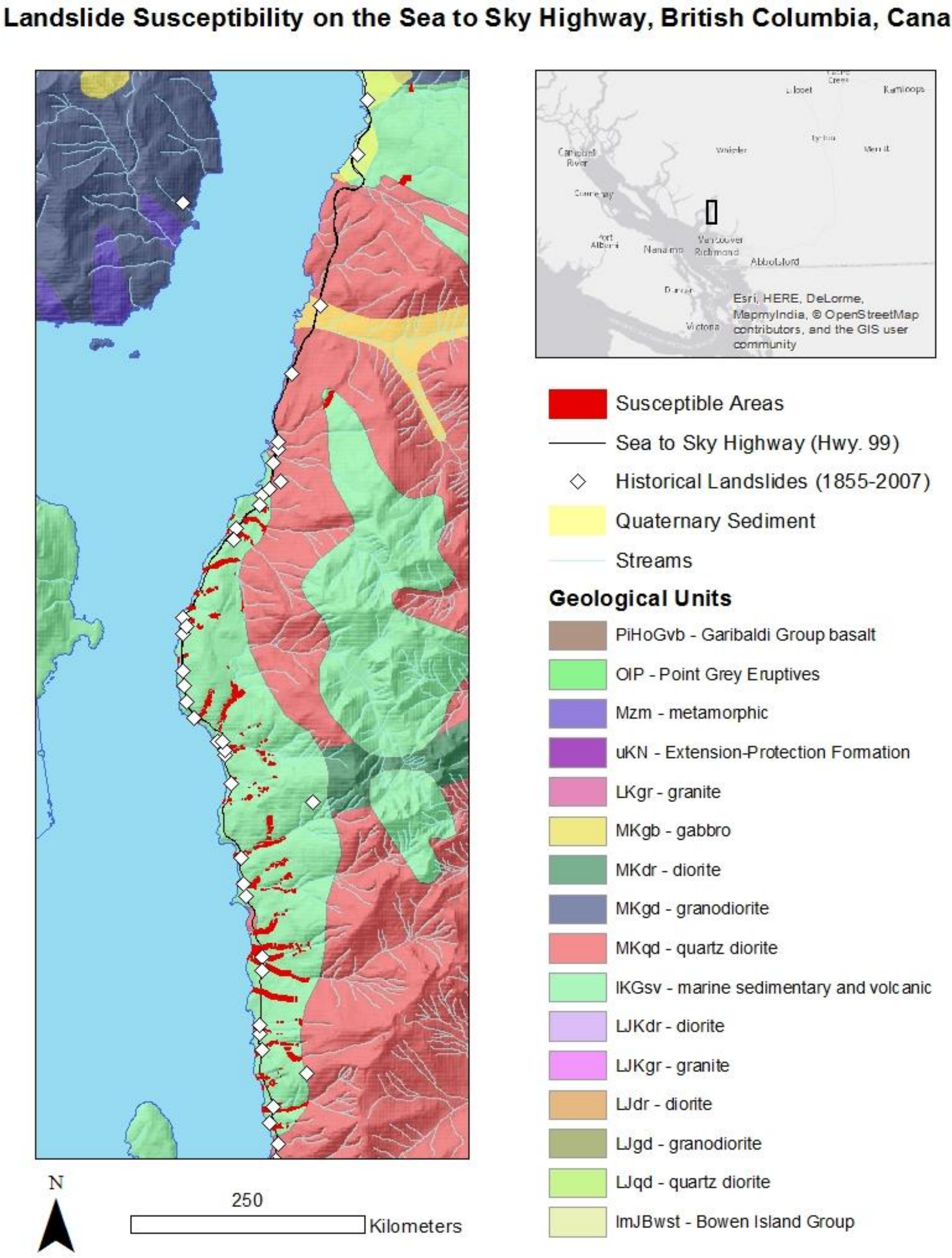
Vegetation Classification	Number of Landslide Events
Exposed Land	5
Herbs	2
Shrubs	6
Treed Coniferous	79
Treed Broadleaf	10
Treed Mixed	12
Unknown	26

Table 3: Landscape Slope and Landslide Events

Slope (°)	**Number of Landslide Events**
0 - 10	11
10.01 - 20	47
20.01 - 30	46
30.01 - 40	17
40.01 - 53	18



Map 1. Relationship between landslide susceptibility and vegetation.



Map 2. Relationship between landslide susceptibility and geology.

III: Analysis Flow Chart