Forest Practices Board

Landslide Occurrence Following Major Rain Storms on Vancouver Island

Special Investigation

FPB/SIR/27

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Executive Summary

In November 2006, two large rainfall storm events, occurring two weeks apart, caused major damage to roads, bridges, forests and streams across southern Vancouver Island. These storm events delivered extremely high rainfall and associated high winds, causing hundreds of landslides on Vancouver Island with many occurring in the Bamfield-Port Alberni area (see map on page 2).

In this investigation, the Board set out to analyze the landslide activity that occurred in the two years prior and the year following these two large rainfall storm events.

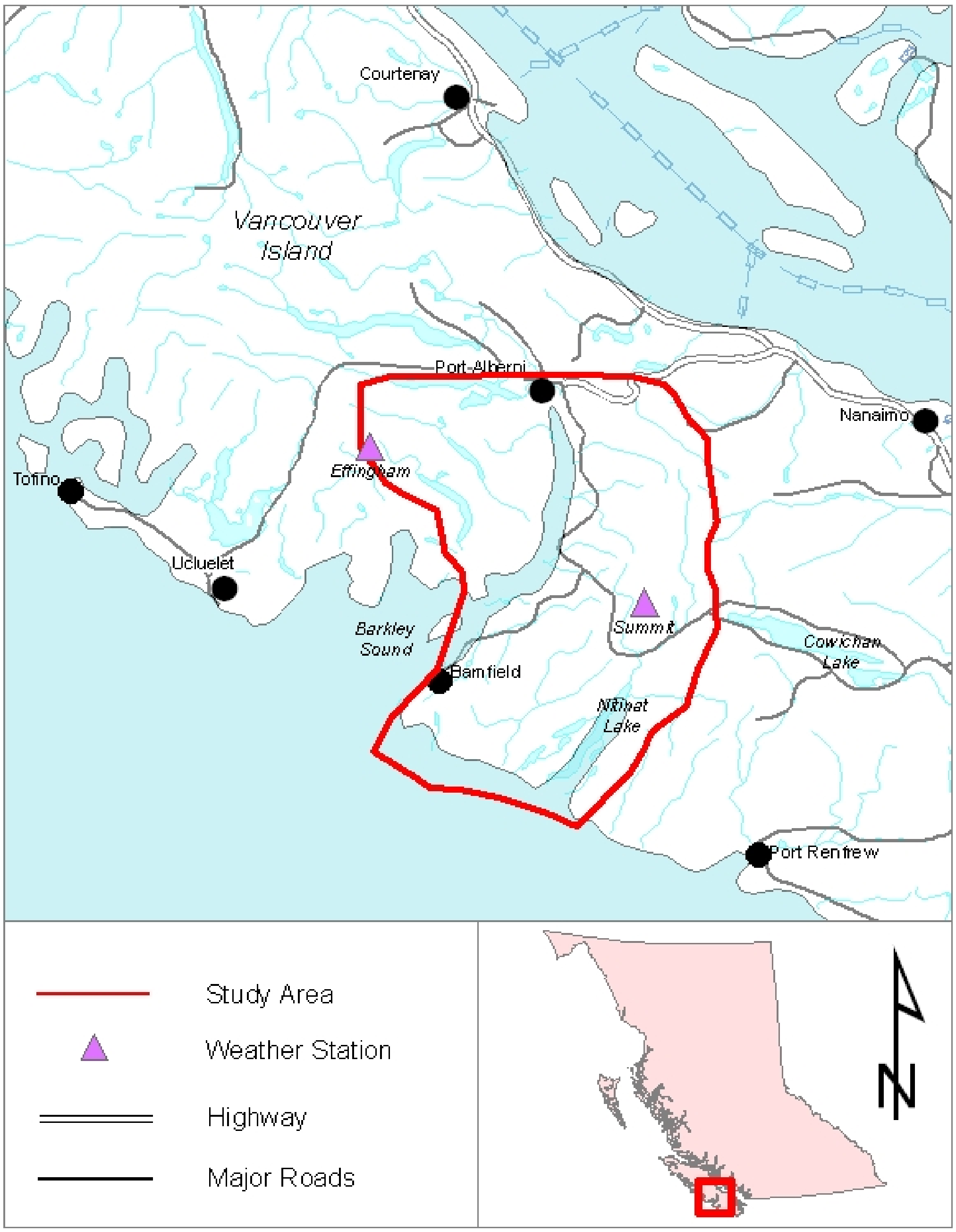
Digital analysis of satellite imagery was used to characterize landslides before and after these large rainfall storm events with respect to their age, years since harvesting of any associated cutblocks and the possible causes of the landslides. Two helicopter overviews were used to confirm the practicality and accuracy of the satellite imagery interpretation. No ground work was conducted.

The results of this investigation indicate that following these large rainfall storm events:

- The number of landslides increased from 14 slides in the two-year period prior to the storm events to 107 in the year following the storm events.
    - There were 12 landslides associated with cutblocks and roads in the two-year period prior to the storm events, and 95 in the year following the storm events.
    - The number of landslides on unharvested forest land increased from 2 slides in the two years prior to the storm events to 12 slides in the year following the storm events.
- The total area impacted by landslides increased from 8.5 hectares for the two years prior to the storm events to 94.8 hectares after the storm events.
- The landslide activity appeared to be clustered in specific areas, rather than spread uniformly across the study area.

The number of slides noted in the study area increased dramatically after the large rainfall storm events. The Board suggests that forest managers and practitioners consider the possibility that large rainfall storm events may occur more frequently in the future. Forest managers and practitioners should recognize this potential for increased slide activity when planning future roads and cutblocks in coastal areas of BC.

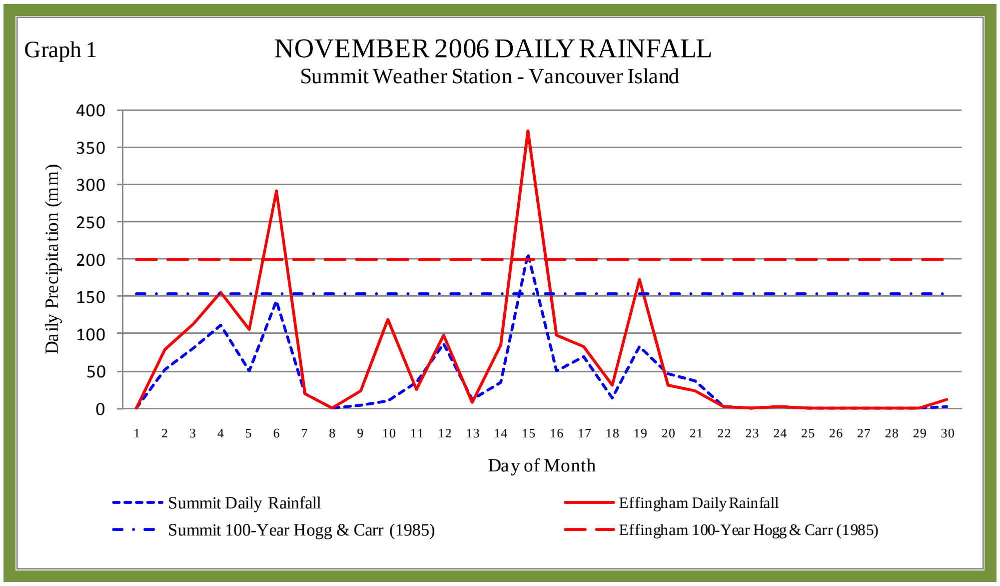
Vancouver Island Landslides
Study Area



Introduction

Objectives

In November 2006, a series of intense rainfall storm events occurred across southern Vancouver Island. These storm events, which were accompanied by high winds, saw record-breaking rainfall recorded at the Effingham and Summit weather stations. On November 6, 290.8 millimetres of rain was recorded at the Effingham weather station. On November 15, 372.2 millimetres and 206.8 millimetres of rain were recorded at the Effingham and Summit weather stations[1] respectively (see Graph 1). Based on the Rainfall Frequency Atlas of Canada (Hogg and Carr, 1985), each of these rainfall storm events exceeded the 100-year return period[2] daily rainfall records for these weather stations (or the 20-year return period based on Miles[3]).



The landslides that occurred after the storms in the Bamfield-Port Alberni area caused debris flows and debris slides that blocked roads, buried campgrounds, wiped out bridges, scoured and filled streams. In addition, high wind speeds blew down sections of forest, stripped trees of branches and severely disturbed transmission corridors. (Guthrie et al. (in press)).

The objective of this investigation was to assess landslide activity by comparing several characteristics of the landslides that followed the 2006 large rainfall storm events with characteristics of landslides that occurred in the preceding two years. These characteristics include the area; number and distribution;

[1] Weather station data supplied by the British Columbia Ministry of Forests Protection Branch.

[2] A return period is an estimate of how long it will be between rainfall events of a given magnitude.

[3] The rainfall events exceeded the 100-year return period daily rainfall event reported in the Rainfall Frequency Atlas for Canada (Hogg and Carr, 1985) for the study area. However, this report is now 24 years old and was based on limited data and no data within the study area. Miles (2008) research is based on three years of current data from local weather stations. Miles suggests that the Hogg and Carr analysis underestimate the true return periods for severe precipitation events.

years' post harvesting; as well as whether windthrow (trees blown down by wind) was related to the initiation of the landslides.

Through the course of the investigation, it was determined that the impacts of landslides on other resource values (fish habitat, productive land loss, plantations, etc.) could not efficiently be assessed, so those effects were not evaluated during this investigation. In addition, it was also not possible to investigate interplay between management activities and landslides, due to the limited sample period and the lack of on-the-ground investigation for this work.

The study area is located south of Port Alberni and primarily east of Barkley Sound on the southwest coast of Vancouver Island, and is approximately 235,000 hectares in size. (See map on page 2.)

Background

Landslides are a common natural process and an important forest disturbance agent in the mountainous areas of British Columbia. They create gaps in the forest, mix soil, and contribute significant amounts of gravel and large woody debris to streams, providing important attributes to fish habitat (Horel and Higman, 2006; Forest Practices Board, 2005). However, landslides often have detrimental consequences because they can damage fish streams and water intakes, destroy forest plantations and damage private land.

Landslide occurrence, both natural and human-influenced, is strongly affected by many factors including:

- topography (slope gradient, aspect, elevation)
- geology (soil type, depth to bedrock, bedrock lithology and structure, rooting zone, surface and subsurface drainage)
- disturbance (earthquakes, wildfires, forest harvesting, roads and road construction technique and water diversion)
- biology (vegetative cover, age, type, rooting strength, rainfall interception)
- climate and weather (rain and wind)

In 1995, the *Forest Practices Code of British Columbia Act* (the Code) legislated requirements for assessing and managing landslide-prone terrain when conducting forestry activities in BC. In a report published in 2005, the Board found that the number of landslides related to forestry activity (primarily harvesting, skid trail and road construction and deactivation) was significantly reduced after the Code came into effect.[1] Under current legislation, the *Forest and Range Practices Act* (FRPA) allows for greater flexibility in managing landslide prone terrain and the 2005 Board report identified that the challenge for landslide management under FRPA is to maintain and improve on the gains made during the Code.

Climate change models predict that weather patterns will change, and precipitation intensity and variability are projected to increase, over most of the 21st century (Bates et al, 2008). If this holds true,

[1] Managing Landslide Risk from Forest Practices in British Columbia, page 23. This Board report is found on the Board's website under 2005 - Special Investigation reports. Or currently at: http://www.fpb.gov.bc.ca/assets/0/114/178/186/358/010669b7-28b7-48ac-8ebe-d45ed427f9d8.pdf

more frequent and larger storm events, particularly along the west coast of Vancouver Island, are expected.

The prediction that more frequent and larger storms will occur is supported by Madsen and Figdor (2007) whose research has demonstrated an increase in frequency and severity of storms in the Pacific Northwest over the past 60 years.

An increase in the amount of precipitation in a given time period is important, since water plays a major role in initiating landslides. Water reduces the coefficient of friction between the soil (sometimes weathered rock) and the bedrock, increasing the possibility of a landslide. In addition, saturated soils involved in landslides tend to travel greater distances.

If rainfall frequency and magnitude increase, a corresponding increase in the frequency of landslides in managed and unmanaged forest lands can be expected. Guthrie et al. (in press) identified 268 landslides on southern Vancouver Island following the November 2006 storms and found that 88 percent were associated with greater than 80 millimetres of precipitation in 24 hours and 70 percent were associated with precipitation greater than 100 millimetres.

Methodology

Digital analysis of satellite imagery was used as the initial tool to identify landslide locations, estimate the date of the landslide, landslide area, initiation and possible cause for two time periods:

- 2004-2006 period (covering the two years prior to the two large rainfall storm events from November 2004 to October 2006); and
- 2007 period (covering the period during or shortly after the large rainfall storm events from November 2006 to October 2007).

It was assumed that the satellite imagery taken between 2004 and 2006 represented a proxy for a two-year period with normal rainfall storm events[4], while the satellite imagery taken in 2007 represented a proxy for a one-year period with large rainfall storm events.

In the summer of 2007, investigators carried out a helicopter reconnaissance of those landslides identified as having occurred during, or shortly after, the large rainfall storm events, and having an area greater than one hectare, to determine if change detection mapping and satellite imagery interpretation was a practical tool for such an investigation. The investigators determined that it was practical. In January 2008, a terrain specialist used the imagery to interpret all landslides with respect to the initiation location, the number of years since harvesting of the associated cutblocks, and whether the landslides were related to windthrow. Change detection mapping was used to determine the age of the landslide.

[4] In considering the findings, it is important to recognize that data collected between 2004 and 2006 forms the basis for measuring the landslide activity for the period prior to the two large rainfall storm events. A more accurate comparison would require evaluating landslide activity over a longer period.

Further, in June 2008, the terrain specialist and investigators carried out a second helicopter reconnaissance to confirm and calibrate the satellite imagery interpretation. The field confirmation focused on landslides greater than one hectare, for ease of detection, and examined area, age of the landslide and possible cause. No ground work was conducted. After the helicopter reconnaissance, the terrain specialist reviewed his January 2008 interpretative work and rejected some of the landslides that appeared on the satellite imagery because some landslides likely occurred prior to 2004, and some disturbed areas were windthrow or non-productive areas rather than landslides.

Analysis and Discussion

For this investigation, the landslide activity for the 2004-2006 period was compared to the landslide activity after major storm events (the 2007 period). A more accurate assessment of whether the landslide activity following the major storm events should be considered abnormal would require an evaluation of landslide activity over a much longer period.

Area

Table 1. Summary of Landslide Area

	Slide Area	Total Avg Area	Average Area of Non-Windthrow Related Slides (ha)				Average Area of Windthrow Related Slides (ha)			
Period	**(ha)**	**(ha)**	**All**	**OB**	**IB**	**Road**	**All**	**OB**	**IB**	**Road**
2004 – 2006	**All Slides**	**0.61**	**0.60**	**0.40**	**0.54**	**0.70**	**0.66**	**-**	**0.66**	**-**
	Range	**0.14-2.53**	**0.14-2.53**	**0.35-0.45**	**0.27-1.00**	**0.16-2.53**	**0.66**	**---**	**0.66**	**---**
2007	**All Slides**	**0.89**	**0.84**	**1.18**	**0.86**	**0.71**	**1.00**	**1.01**	**1.01**	**0.95**
	Range	**0.06-5.88**	**0.16-5.88**	**0.16-5.88**	**0.06-4.07**	**0.16-5.32**	**0.30-3.42**	**0.51-1.80**	**0.14-3.42**	**0.30-1.43**

Note: OB = out-of-block, IB = in-block, Road = road-related

When comparing the 2004-2006 period with the 2007 period, the overall area of landslides in the study area increased from 8.5 hectares for the 2004-2006 period to 94.8 hectares for the 2007 period.

Number and Distribution of Landslides

For the 2004-2006 period, 14 landslides occurred in the study area. This increased to 107 landslides in the 2007 period (Table 2). The number of landslides less than 1 hectare increased from 12 to 83, and landslides greater than 1 hectare increased from 2 to 24 during the same time periods.

Visual evaluation of the landslide activity in the 2004-2006 period showed that they tended to be more dispersed throughout the study area, whereas landslides in the 2007 period exhibited localized areas of higher numbers of landslides with some dispersed single events. This is consistent with previous studies (for example Guthrie and Evans, 2004; Pinto et al, 2008), which suggest that, within regionally significant storm events, there are intense storm cells[5] that cause the majority of the landslides.

[5] An air mass formed by powerful updrafts and downdrafts moving in convective loops, the smallest unit of a storm system.

Several studies have indicated that the number of landslides increases following major storm events (i.e., Guthrie and Evans, 2004). This investigation confirms that landslide frequency in both harvested and un-harvested areas, as well as road-related landslides, increased following the large rainfall storm events (Table 2).

Table 2. Summary of Landslide Initiation

Period	Slide Area	Total All Slides	# of Non Windthrow Related Slides						# of Windthrow Related Slides					
			Total	OB	In-block Years Post Harvest			Road	Total	OB	In-block Years Post Harvest			Road
	(ha)	#			<5	5-15	>15				<5	5-15	>15	
2004 – 2006	<1.0	12	11	2	1	0	2	6	1	0	1	0	0	0
	>1.0	2	2	0	0	1	0	1	0	0	0	0	0	0
	Total	**14**	**13**	**2**	**1**	**1**	**2**	**7**	**1**	**0**	**1**	**0**	**0**	**0**
2007	<1.0	83	63	7	7	14	8	27	20	2	7	7	2	2
	>1.0	24	12	2	1	0	7	2	12	1	5	3	1	2
	Total	**107**	**75**	**9**	**8**	**14**	**15**	**29**	**32**	**3**	**12**	**10**	**3**	**4**

Note: OB = out-of-block, IB = in-block, Road = road-related

Years Post Harvest (time since harvesting) for In-Block Landslides

It should be noted that road-related landslides were not categorized as in-block landslides, even if they occurred within the cutblock. The time since harvesting was estimated from the helicopter review and satellite imagery and was based on vegetative cover. Three post-harvest categories were used: less than 5 years, 5 to 15 years and greater than 15 years.

With respect to slides within the 2007 period, on average, 4 slides occurred per year during the first 5 years after harvesting, 2.4 slides occurred per year during the period from 5 to 15 years after harvesting, and 0.4 slides occurred per year in blocks greater than 15 years post harvest.[6] This indicates the number of slides per year in a given cutblock diminishes over time.

These findings can be attributed to a number of factors, such as:

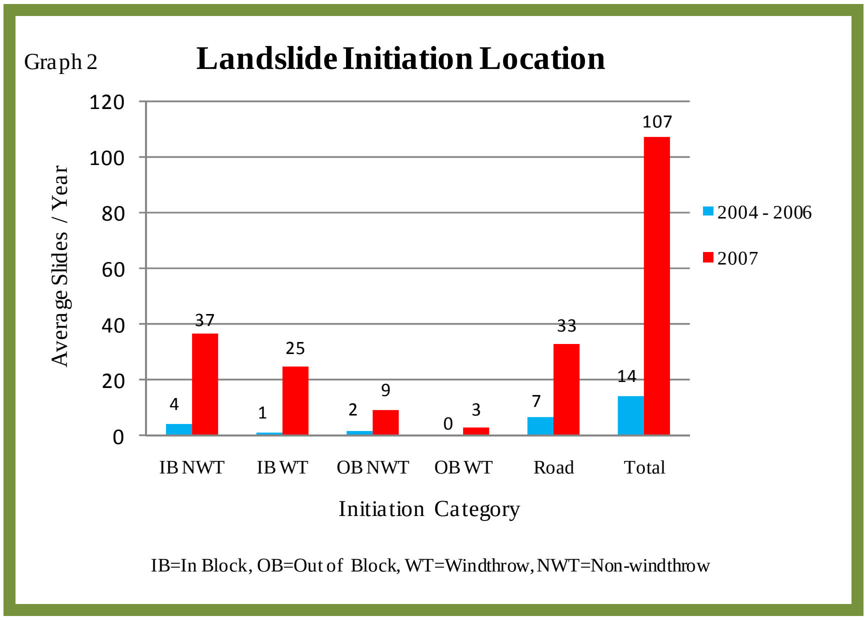
- Recently harvested blocks may be located on steeper slopes, which are more susceptible to landslides.
- The ground may have been disturbed during harvesting and vegetation may not have re-established, which would allow more precipitation to infiltrate the soil, increasing susceptibility to landslide initiation.
- As cutblocks age, the shear strength associated with new vegetative cover increases along with the amount of rainfall being intercepted and taken up through evapotranspiration.[7]

[6] In this analysis it was assumed that the area harvested for each of the last 60 years was approximately the same and that harvesting had been ongoing for the last 60 years.

[7] The combination of water transpired from the plant and evaporated from the soil and plant surfaces.

Initiation

Five initiation locations were used for analysis; in-block non-windthrow related (IB NWT), in-block windthrow related (IB WT), out-of-block non-windthrow related (OB NWT), out-of-block windthrow related (OB WT), and road-related (Road) (Graph 2).



In-block Landslides

In the 2004-2006 period, there were 5 in-block landslides, of which 4 were non-windthrow related. The number of in-block landslides increased to a total of 62 in the 2007 period, of which 37 were non-windthrow related. The average size of windthrow-related landslides in the 2007 period was 1.01 hectares. Road-related landslides were not considered as in-block landslides.

Out-of-block Landslides

In the two-year period prior to the two large rainfall storm events of 2006, there were 2 out-of-block landslides and both were less than 1 hectare in size. Following the large rainfall storm events, there were 12 out-of-block landslides (Photo 1); 9 were less than 1 hectare and 2 of these were windthrow related, while the other 3 landslides were greater than 1 hectare and only 1 was windthrow related (Table 2). Landslides under mature tree canopy are often difficult to see from satellite imagery or from a helicopter, therefore, the total number of landslides under closed canopy may be underestimated.

Photo 1: An example of an out-of-block landslide

Windthrow Related Landslides

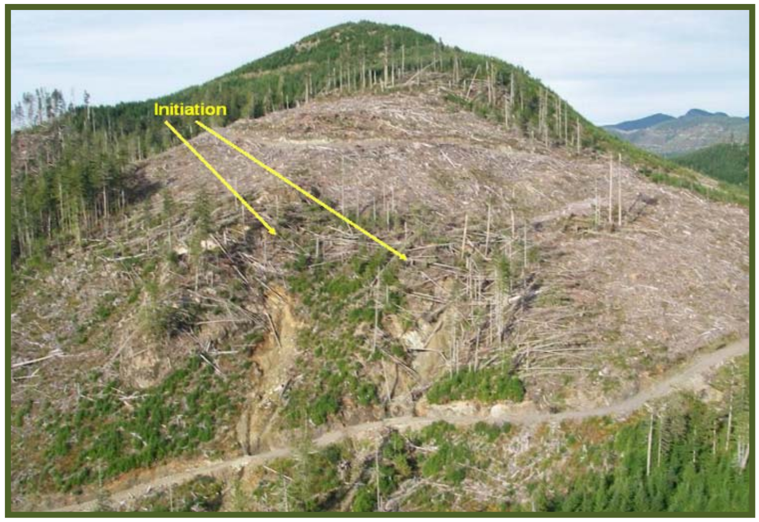
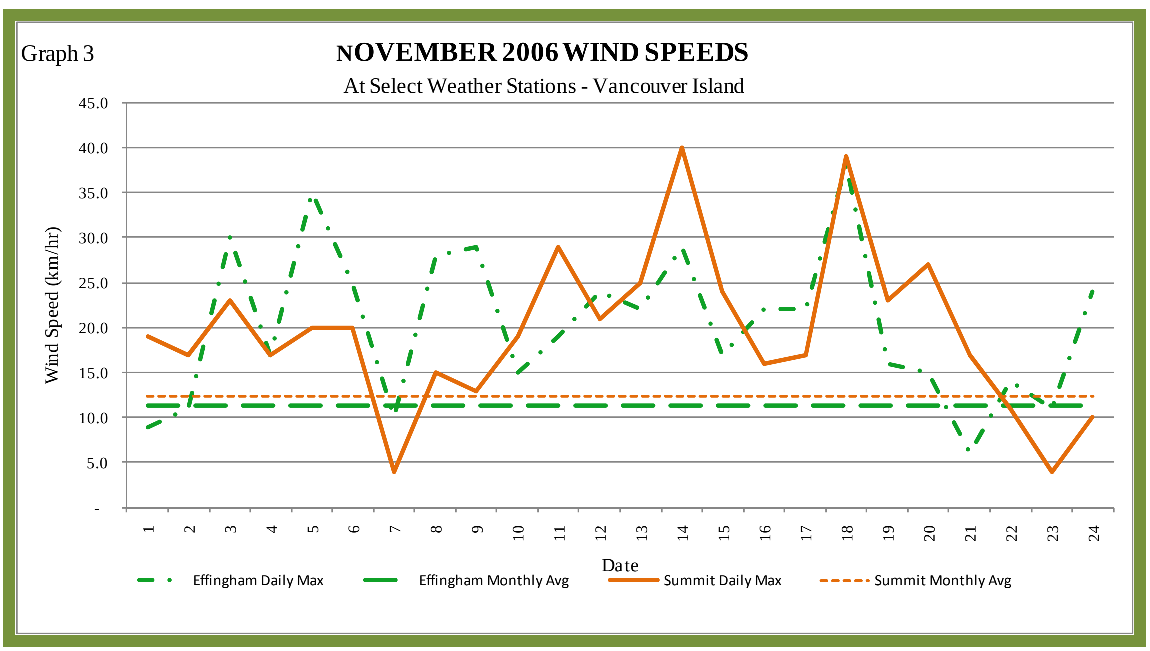


Photo 2: Example of a windthrow related landslide.

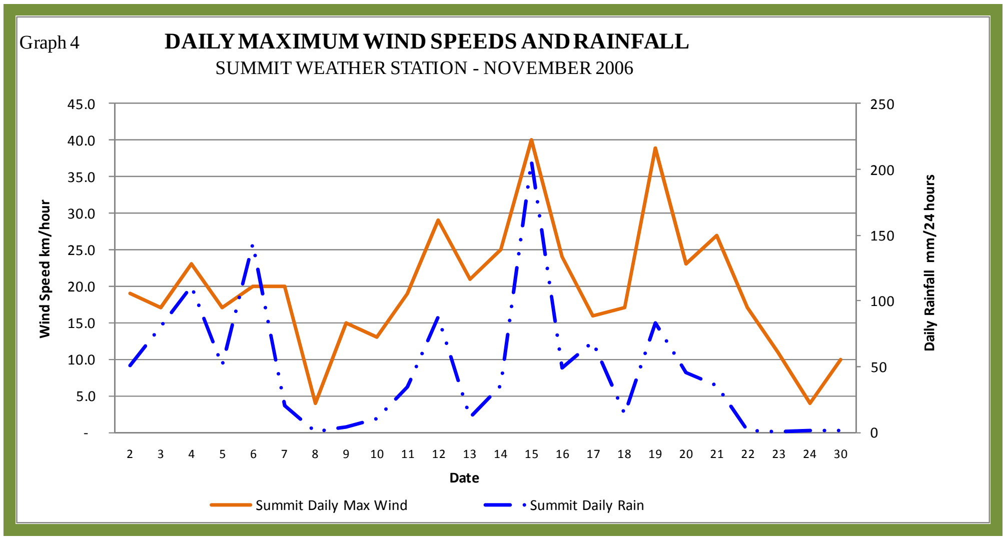
It was anticipated that windthrow might be a primary cause of landslides, as windthrow often occurs adjacent to previous harvesting or within wildlife tree patches (Photo 2), and is often found in areas of steep slopes and rocky ground with incised gullies. Windthrow affects an area's susceptibility to landslides in a number of ways: it can initiate a landslide, provide momentum to the landslide or remove trees, which, when intact, create a resisting force to landslides by the anchoring and reinforcing effect of their roots (provided the failure surface is within the rooting depth of vegetation). Windthrow also exposes more soil to rain saturation and, as the interception of rain and the evapotranspiration effect of trees are reduced, more rain directly infiltrates the soil, making the area more prone to landslides.

As discussed previously, in the 2004-2006 period, 1 windthrow-related landslide was identified in the study area. In the 2007 period, there were 32 windthrow-related landslides with an average area of 1 hectare. Of these landslides, 20 were less than 1 hectare in area and 12 were greater than 1 hectare (Table 2). The increase in windthrow-related landslides indicates that strong winds accompanied the large rainfall storm events. Wind speeds 3 to 4 times higher than the average for the month were recorded at the Effingham and Summit stations[8] during November. (Graph 3).



[8] Weather station data supplied by the British Columbia Ministry of Forests Protection Branch.

High winds also occurred throughout the rest of the month, which may have caused windthrow before or after the large rainfall storm events. However, there was a correlation between wind speeds and daily rainfall (Graph 4); as daily rainfall increased, so did the daily maximum wind speed. It is difficult to ascertain whether such landslides are a result of windthrow only, windthrow and rainfall together, or intense rainfall occurring after a windthrow event.



Non-windthrow Related Landslides

The number of non-windthrow related landslides increased from 13 in the 2004-2006 period, to 75 in the 2007 period (Table 2). The average area of the non-windthrow related landslides increased from 0.60 hectares to 0.84 hectares over the same period (Table 1). In the 2004-2006 period, there were two landslides greater than 1 hectare; which increased to 12 landslides greater than 1 hectare in the 2007 period.

Road-related Landslides

In the 2004-2006 period, there were 7 road-related landslides (Photo 3 & Table 2). Of these, 6 were less than 1 hectare. In the 2007 period, the number of road-related landslides increased to 33, of which 4 were windthrow related and 29 were less than 1 hectare. No assessment of drainage systems, such as culvert placement, cross drains or blocked culverts, was conducted.

Photo 3. Example of a road-related landslide.

Current Landslide Management Practices

There are many factors, both human and natural, that affect landslide occurrence. This study did not address how management practices interact with weather events to cause landslides, due to the difficulties in separating out these different factors. The increase in out-of-block landslides indicates that an increase in landslide activity must be anticipated on the unmanaged land base following large rainfall storm events. Similarly, the large increase in in-block and road-related landslides suggests that an increase in landslides activity in the managed landbase must also be anticipated if more severe rainfall storm events occur with increasing frequency in the future. However, proactive management strategies may mitigate the number and size of the landslides on the managed landbase.

Road maintenance and proper deactivation are critical in mitigating road-related landslides since these activities are required to ensure that the integrity of a planned drainage system is maintained. Without them, minor volumes of water discharged onto an unstable slope can have unintended consequences.

Current engineering standards for culvert size and cross drain locations are based on historic rainfall data. Miles (2008) has shown this data to be outdated and it underestimates current rainfall intensities and return periods. As a result, culverts may be undersized and may not handle the runoff from large rainfall storm events. Consequently, some of the water may continue down the ditch line and eventually spill over the road, or be picked up by a cross drain culvert and discharged onto the fill slope. This can saturate the fill slope and initiate a landslide.

Conclusions

The Board investigated the change in landslide activity following two large rainfall storm events on southern Vancouver Island that occurred in November 2006. Daily rainfall in both storm events exceeded the Rainfall Frequency Atlas of Canada 100-year return period daily rainfall records (or the 20-year return period daily rainfall records as calculated by Miles 2008) in these areas. The Board examined the area of the landslides; their number and distribution; years' post harvesting; windthrow and initiation location, but did not assess the impacts of the landslides on forest resources.

Using data from the preceding two years for comparison purposes, the Board found that there was an increase in the area and number of landslide activity following the large rainfall storm events, and that windthrow associated with strong winds accompanying the storms also added to the number of landslides.

The Board found that following the large rainfall storm events:

- The number of landslides increased from 14 in the 2004-2006 period to 107 in the 2007 period.
    - The number of in-block landslides increased from 5 in the 2004-2006 period to 62 in the 2007 period.
    - The number of road-related landslides increased from 7 in the 2004-2006 period to 33 in the 2007 period.

    - The number of out-of-block landslides increased from 2 in the 2004-2006 period to 12 in the 2007 period.
- The number of non-windthrow related landslides increased from 13 in the 2004-2006 period to 75 in the 2007 period. There was one windthrow-related landslide in the 2004-2006 period and 32 in the 2007 period.
- The total area impacted by landslides increased from 8.5 hectares for the two years prior to the storm events to 94.8 hectares after the storm events.
- The landslide activity appeared to be clustered in specific areas, rather than spread uniformly across the study area.
- It cannot be determined whether the increase in landslide activity is attributed entirely to the two large rainfall storm events, or to the fact that these storms occurred only nine days apart.

Both natural and forestry-related landslides tend to occur in response to large rainfall storm events. This was confirmed in this investigation by the increase in both out-of-block and in-block landslides across all post-harvest time periods: less than 5 years, 5 to 15 years and greater than 15 years. In addition, large rainfall storm events are typically accompanied by strong winds that can cause windthrow, which in turn can increase the number of landslides.

The Board suggests that a risk-based approach should be developed to address the anticipated increased frequency of large rainfall storm events. Forest land managers and practitioners should begin to assess the effectiveness of current planning (such as cutblock boundaries and wildlife tree patches); operational activities related to roads (such as culvert sizing, maintenance, deactivation and cross drain spacing); and harvesting, given the anticipated increase in frequency of large rainfall storm events, not only along the coast of Vancouver Island, but in other parts of British Columbia. Specific emphasis should be placed on planning, road construction and harvesting occurring on slopes greater than 60 percent that have a high consequence if landslides occur.

Research is currently being conducted by the BC Ministry of Forests and Range, Ministry of Environment and Simon Fraser University on landslide cause, and work is ongoing to improve current landslide and windthrow probability models. As new information becomes available, it should be communicated to forest land managers and practitioners so that planning and operational practices can incorporate the new knowledge. The Board believes this information can improve current practices concerning the spatial deployment of block boundary location, wildlife tree patches, and silviculture systems as they relate to windthrow management. Factors such as biodiversity, potential liability for licensees, effects on timber supply, economics and appraisals will need to be addressed as well.

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Appendix 1

Slide Information Data

VANCOUVER ISLAND LANDSLIDES DATA

				Years Since Harvesting			Initiation Zone					
Id	**Year**	**Area (ha)**	**SlideType**	<3-5	3-5:10-15	>10-15	Out of Block	Road	Mid Block	Upper Block	Lower Block	**Windthrow Related**
1	2004 - 2006	0.52	debris slide					X				No
2	2004 - 2006	0.27	debris slide			X			X			No
3	2004 - 2006	0.16	debris slide					X				No
4	2007	0.31	debris slide					X				No
5	2004 - 2006	0.57	debris slide			X			X			No
6	2007	0.25	debris slide					X				No
7	2007	0.39	debris flow					X				No
8	2007	0.65	debris slide-debris flow					X				No
9	2007	0.23	debris slide					X				No
10	2007	4.04	debris slide			X			X			No
11	2007	1.97	debris slide			X				X		Yes
12	2007	0.38	debris flow					X				No
13	2007	0.41	debris slide					X				No
14	2007	0.17	debris slide					X				No
15	2007	1.06	debris slide-debris flow			X				X		No
19	2007	0.57	debris flow		X				X			No
20	2007	5.88	debris flow				X					No
21	2004 - 2006	0.31	debris slide	X							X	No
22	2007	3.28	debris slide	X					X			No
23	2007	0.34	debris slide		X					X		Yes
24	2007	0.16	debris slump				X					No
25	2007	1.10	debris slide-debris flow			X			X			No
26	2007	4.07	debris flow			X			X			No
27	2007	0.43	debris slide			X			X			No
28	2007	0.18	debris slide					X				No
30	2007	0.38	debris slide					X				No
31	2007	0.24	debris slide					X				No
32	2007	0.69	debris slide		X						X	Yes
33	2007	0.37	debris slide			X				X		No
34	2007	0.93	debris flow			X			X			No
35	2007	0.36	debris slide					X				No
36	2007	0.51	debris slide/debris flow					X				No
39	2007	0.94	debris slide					X				No
40	2007	0.20	debris slide			X			X			No
41	2007	0.36	debris slide		X				X			No
43	2007	0.27	debris slide			X			X			No

				Years Since Harvesting			Initiation Zone					
Id	**Year**	**Area (ha)**	**SlideType**	<3-5	3-5:10-15	>10-15	Out of Block	Road	Mid Block	Upper Block	Lower Block	**Windthrow Related**
44	2007	0.38	debris slide-debris flow		X				X			No
46	2007	1.50	debris slide-debris flow			X			X			No
47	2007	4.46	debris slide-debris flow					X				No
48	2007	0.34	debris slide			X			X			No
49	2007	0.23	debris flow		X					X		Yes
50	2007	1.28	debris flow					X				Yes
51	2007	0.66	debris slide		X				X			No
52	2007	0.28	debris slide					X				No
53	2007	0.75	debris slide					X				No
55	2007	0.56	debris slide		X				X			No
56	2007	0.29	debris slide		X				X			No
57	2004 - 2006	0.56	debris slide					X				No
58	2004 - 2006	0.66	debris slide	X						X		Yes
59	2007	0.09	debris slide		X				X			No
62	2007	3.42	debris slide-debris flow	X							X	Yes
63	2007	0.63	debris slide			X			X			No
64	2007	0.27	debris slide		X				X			No
65	2007	0.69	debris slide	X					X			No
66	2007	0.68	debris slide-debris flow				X					No
67	2007	1.96	debris slide		X				X			Yes
68	2007	0.31	debris slide	X					X			No
69	2007	0.29	debris flow	X					X			No
70	2007	0.07	debris slide	X						X		No
71	2007	0.82	debris slide-debris flow	X						X		No
72	2007	0.76	debris slide	X						X		No
73	2007	0.23	debris slide		X				X			Yes
74	2007	0.53	debris slide	X							X	Yes
75	2007	0.16	debris slide	X					X			Yes
77	2007	0.73	debris slide				X					Yes
78	2004 - 2006	2.53	debris flow-debris slide					X				No
79	2007	0.34	debris slide-debris flow					X				No
83	2004 - 2006	0.28	debris slide					X				No
84	2007	1.80	debris slide				X					Yes
85	2007	0.16	debris slide					X				No
87	2007	1.43	debris flow					X				Yes
88	2007	0.72	debris slide			X			X			Yes
89	2007	0.30	debris slide					X				Yes
90	2007	1.68	debris slide		X					X		Yes
91	2007	0.68	debris slide-debris flow		X						X	Yes
92	2007	1.18	debris flow				X					No
93	2007	5.32	debris slide-debris flow					X				No

				Years Since Harvesting			Initiation Zone					
Id	Year	Area (ha)	SlideType	<3-5	3-5:10-15	>10-15	Out of Block	Road	Mid Block	Upper Block	Lower Block	Windthrow Related
94	2007	0.12	debris slide			X				X		No
95	2007	0.52	debris slide				X					No
96	2004 - 2006	1.00	debris slide		X					X		No
97	2007	1.84	debris flow	X					X			Yes
98	2007	1.82	debris flow	X						X		Yes
99	2007	0.79	debris slide					X				Yes
100	2007	0.51	debris slide				X					Yes
102	2007	0.19	debris slide	X							X	Yes
103	2007	0.63	debris flow				X					No
105	2007	0.34	debris slide	X							X	No
106	2007	0.21	debris slide					X				No
107	2007	0.10	debris slide		X				X			No
108	2007	0.43	debris flow					X				No
112	2007	0.68	debris flow				X					No
114	2007	0.62	debris slide-debris flow				X					No
121	2004 - 2006	0.58	debris slide-debris flow					X				No
122	2007	0.25	debris flow		X						X	No
125	2007	0.66	debris flow					X				No
126	2007	1.65	debris flow			X			X			No
127	2007	0.11	debris slump		X				X			No
128	2007	0.66	debris slide-debris flow	X							X	Yes
129	2007	0.32	debris slide	X							X	Yes
130	2007	1.08	debris slide-debris flow		X						X	Yes
131	2007	0.69	debris slide-debris flow	X							X	Yes
133	2007	0.18	debris slump					X				No
134	2007	0.38	debris slide-debris flow					X				No
135	2004 - 2006	0.25	debris slide					X				No
136	2007	2.30	debris slide-debris flow	X							X	Yes
137	2007	3.57	debris slide-debris flow			X				X		No
138	2007	0.66	debris slide					X				No
139	2007	0.22	debris flow				X					No
140	2007	0.94	debris flow		X					X		No
141	2007	0.29	debris slide					X				No
143	2007	0.79	debris slide-debris flow	X					X			Yes
145	2007	0.37	debris slide-debris flow		X						X	No
146	2007	1.62	debris slide-debris flow	X					X			Yes
147	2007	0.64	debris slide		X						X	Yes
148	2007	0.14	debris slide			X			X			Yes
150	2007	0.52	debris slide					X				No
151	2007	0.45	debris slide					X				No
152	2004 - 2006	0.45	debris slide-debris flow				X					No
153	2004 - 2006	0.35	debris slide				X					No
154	2007	0.06	debris slide		X						X	No
155	2007	0.34	debris slide		X				X			Yes

Please note that those landslides that appeared on the satellite imagery but were later rejected because they likely occurred prior to 2004, or were windthrow or non-productive areas rather than landslides, have been deleted from the above slide information data.

Appendix 2

Computer-generated Change Detection Mapping (CDM)

Digital satellite imagery was used as the initial tool to estimate the extent of the landslides resulting from the two large rainfall storm events that occurred in the study area in November 2006[9].

The imagery used for the investigation was collected for three points in time: 2004 and 2006 (before the two large rainfall storm events), and 2007 (after the two large rainfall storm events).

The imagery for all three years was enhanced for computer and visual interpretation. Using change detection software, the enhanced satellite imagery was combined to develop two change stack images; the 2004-2006 period (a proxy for the normal conditions previous to the large rainfall storm events) and the 2007 period (a proxy for conditions during or shortly after the large rainfall storm events). The change stacks facilitated the comparison of changes between the two time periods, the differences between the two time periods were then identified by the computer and polygons were generated around each of the changes.

The original intent of the investigation was to use the computer to extract the features from the images; however, initial quality control tests proved that this approach would not generate accurate results. For example, tree canopy would obscure narrow landslides and portions of roads.

Consequently, manual analysis by an operator was incorporated into the process. Polygons for each time period were digitized manually using the change stack images as a guide. The images were then overlain with topography, location of harvested cutblocks and forestry roads. The operator then identified four feature types using the imagery and overlays: roads, harvested cutblocks, windthrow and landslides.

An internal quality control review of the resulting data was conducted to assess the spatial accuracy (the line work) and the attribute accuracy of the data. This involved a review of the data by an independent operator. Any issues or discrepancies that were identified were resolved.

Based on the process employed, CDM is a good method for initial review of land-based events over a period of time. However, there are limitations:

- Cloud cover and shadow are virtually always present in portions of the remotely sensed imagery.
- The source SPOT images are mosaics of the best data available for each of time period, however the individual scenes used to build the mosaic are likely to have been taken at different times and, as a result, temporal variations are present in the source data. For example, trees can be at varying stages of leaf growth. These variations can result in false triggers in the change stack images which can potentially affect the numbers of both omissions and commissions in the derivative datasets.

[9] Change Detection Mapping was conducted by the Ministry of Environment, with funding from the Forest Practices Board and other government and industry partners.

- There are small positional shifts, both within and between, the various source images. These shifts can result in false triggers in the change stack images which can potentially affect the numbers of both omissions and commissions in the derivative datasets.
- The exact boundaries of windthrow events are difficult to ascertain in some areas due to the imprecise nature of the windthrow areas. Windthrow areas have a higher likelihood of being omitted as they are indistinct features and can be confused with other subtle changes in the landscape.
- Small landslide and windthrow events are not necessarily discernable under closed canopy, especially within confined gullies/draws.

There are also advantages for the continued use of satellite imagery:

- There is a potential to save time and money to focus field work on activities and potential problem areas.
- There is potential to sample a larger area for an overview and then focus additional review on specific areas of concern or areas of best practice.

For this project, the CDM was used to identify the population of landslide events, and the focused helicopter overview flight was used to assess the 26 landslides greater than 1 hectare in area. Through the use of the CDM, along with GPS points for each landslide, the helicopter could be flown directly to each landslide, so the overview flight is more efficient and cost effective.

Note: A recent article in *Island Geoscience* entitled: Change detection on Vancouver Island, discusses CDM in greater detail. This article can be found in the 2008 Fall issue, volume 5. Also, a more recent article entitled: Land-cover Change Mapper (LCM): How objects-based change detection mapping can improve landscape management, covers off almost the same geographical area as this study. This article can be found in the 2009 Fall issue, volume 6. Both volumes can be referenced at: http://www.for.gov.bc.ca/hfd/LIBRARY/Island_Geoscience.htm

Forest Practices Board

PO Box 9905, Stn Prov Govt
Victoria, BC, Canada V8X 9R1
Tel. 250.213.4700 | Fax 250.213.4725 | Toll Free 1.800.994.5899
For more information on the Board, please visit our website at: www.fpb.gov.bc.ca