In the proceedings of the first international conference, "Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment"; American Society of Civil Engineers, August 7-9, 1997, San Francisco, California.

Identification of Coastal British Columbia Terrain Susceptible to Debris Flows

T. P. Rollerson[1], B. Thomson[2], and T. H. Millard[3]

ABSTRACT

Debris flows are common in many areas of the coast of British Columbia (BC), where glacially oversteepened slopes are subjected to high rates of rainfall and snowmelt. Identifying terrain susceptible to debris flows following logging is a critical component of forest land management in BC. This information is used at the planning and operational levels to ensure that environmentally sensitive areas are not damaged. An empirical approach, applied to a representative sample of logged hillslopes within a specific geographical area, is used to quantify the likelihood and frequency of post-logging landslide occurrence. For each map polygon within a sample area, terrain attribute data including slope, slope morphology, surficial material, bedrock type, and the presence or absence of natural and post-logging landslides are recorded. Analysis of the data typically uses non-parametric, univariate or multi-variate statistical tests to identify relationships between landslide frequency or likelihood and terrain attributes. In this paper data collected from the west coast of Vancouver Island is analyzed and relationships between terrain attributes and post-logging landslide occurrence are presented.

---

[1] Research Manager, Ministry of Forests, Vancouver Forest Region, Research Section, 2100 Labieux Road, Nanaimo, B.C., V9T 6E9. Canada. (Phone: 250-751-7121; Fax: 250-751-7198; E-mail trollers@mof01.for.gov.bc.ca)

[2] Regional Geomorphologist, Ministry of Environment, Lands and Parks, Lower Mainland Region, 10334 152A Street, Surrey, B.C., V3R 7P8. Canada.

[3] Research Geomorphologist, Ministry of Forests, Vancouver Forest Region, Research Section, 2100 Labieux Road, Nanaimo, B.C., V9T 6E9, Canada.

INTRODUCTION

In this paper we focus on identifying landscapes vulnerable to debris flows following logging on the British Columbia (BC) coast. Unlike areas subject to natural debris flow activity where there is often evidence of past landslide activity, we do not always have clear evidence of past instability as an indicator of possible future debris flow activity. As a consequence, data on terrain attributes other than natural instability must be utilized to develop predictive criteria for terrain which may be subject to debris flow initiation following logging.

The method outlined in this paper requires collecting data on the frequency of debris flows and other types of landslides following logging and the characteristics of terrain susceptible to and not susceptible to post-logging slope failure, followed by the development of empirical criteria for terrain stability interpretations based on this data.

Early work with limited data from the southwest coast of Vancouver Island (Rollerson and Sondheim 1985), the southern Coast Mountains (Howes 1987), and a larger data set from the Queen Charlotte Islands (QCI) (Rollerson 1992) indicates that the approach has promise.

OBJECTIVES

The objectives of this study are to:

- characterize steepland terrain types that are susceptible to landslides following forest harvesting (clearcutting) and those which are not.
- develop, for specific geographic areas, terrain-based stability classifications that estimate the likelihood or frequency of landslide activity following forest harvesting.

STUDY AREAS

This paper presents the analysis of a data set collected in four large contiguous land units within the Vancouver Island Mountains along the central and northern west coast of Vancouver Island. These areas are representative of the range of climate and terrain present on the central and northern west coast of Vancouver Island. They are generally significantly wetter than the southern, central and eastern portions of the Vancouver Island Mountains.

Physical Setting

The four study areas (Quatsino, Kyuquot, Nootka, and South Clayoquot/ Barkley) are located on the west coast of Vancouver Island and encompass terrain ranging from Quatsino Sound in the north to Barkley Sound in the south (Figure 1).

The study areas lie within the northern portion of the Vancouver Island Mountains, a major northwest to southeast-trending physiographic unit that forms the core of Vancouver Island (Holland 1964). Elevations range from sea level to 2200 m. Within the study areas, the Vancouver Island Mountains can be subdivided into two sub-units consisting of the North Vancouver Island Ranges and the Vancouver Island Fiordland (Hoadley 1953, Yorath and Nasmith 1995).

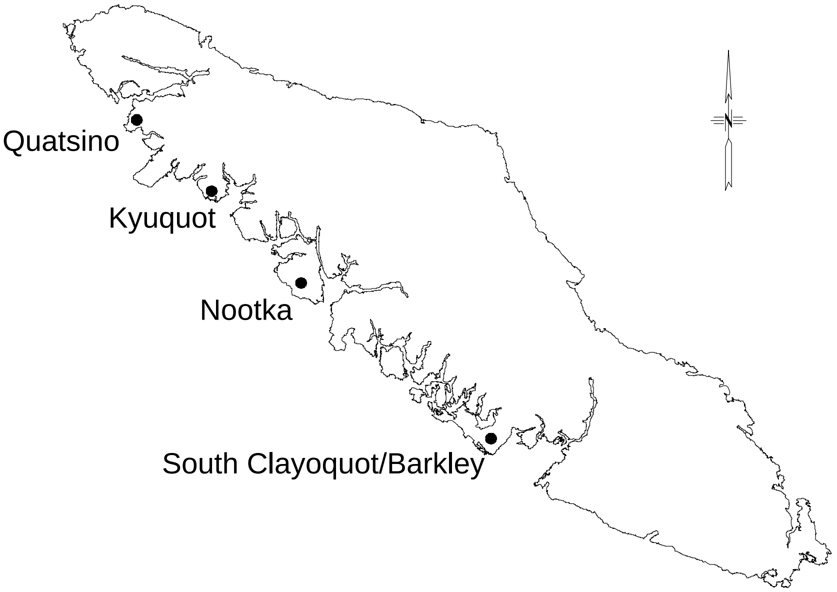

Figure 1. Vancouver Island Study Areas

The North Vancouver Island Ranges are 270 km long and 60 km wide, extending from Quatsino Sound in the north to Barkley Sound in the south. Topography tends to be rugged, surfaces being modified by Pleistocene glacial erosion resulting in a rounding of lower peaks and creation of steep U-shaped valley profiles (Howes 1981). Mid to upper valley side slopes tend to be mantled with shallow deposits of colluvium and till. Exposures of bedrock are common. In narrow valleys, these materials may extend to the valley floor. In wider valleys, lower slopes and valley floors tend to be mantled with thicker deposits of till, fluvioglacial, fluvial and debris flow materials.

Fiordland is 260 km long and 60 km wide, extending along the western portion of Vancouver Island from the Brooks Peninsula south to Barkley Sound. It includes both islands and peninsulas bounded by a network of fiords that penetrate

The study areas lie within the northern portion of the Vancouver Island Mountains, a major northwest to southeast-trending physiographic unit that forms the core of Vancouver Island (Holland 1964). Elevations range from sea level to 2200 meters. Within the study areas the Vancouver Island Mountains can be subdivided into two sub-units consisting of the North Vancouver Island Ranges and the Vancouver Island Fiordland (Hoadley 1953; Yorath and Nasmith 1995).

The North Vancouver Island Ranges are 270 km long and 60 km wide, extending from Quatsino Sound in the north to Barkley Sound in the south. Topography tends to be rugged, surfaces being modified by Pleistocene glacial erosion resulting in a rounding of lower peaks and creation of steep U-shaped valley profiles (Howes 1981). Mid to upper valley side slopes tend to be mantled with shallow deposits of colluvium and till. Exposures of bedrock are common. In narrow valleys, these materials may extend to the valley floor. In wider valleys, lower slopes and valley floors tend to be mantled with thicker deposits of till, fluvioglacial, fluvial and debris flow materials.

Fiordland is 260 km long and 60 km wide, extending along the western portion of Vancouver Island from the Brooks Peninsula south to Barkley Sound. It includes both islands and peninsulas bounded by a network of fiords that penetrate inland from the exposed western coast. Within this sub-unit the land rises abruptly from the shoreline to elevations of 900 meters beyond which a more gradual slope leads to inland summits. Glaciation has rounded summit peaks, and these are usually completely forested (Howes 1981). Colluvial materials, bedrock outcrops and thin veneers of till tend to dominate on steep hillsides, ridges and summits. Till, fluvioglacial, fluvial and debris flow deposits predominate along gentle, lower hillsides and on valley floors in broader valleys.

Bedrock

The area north of Esperanza Inlet is dominated by Bonanza Group volcanics, including andesites, dacites and rhyolites. Also present are Karmutsen Formation basalts, Quatsino and Parson Bay Formation limestones and argillites, and granodiorites of the Vancouver Island Intrusions (VII).

South of Esperanza Inlet the dominant bedrock formations are the Karmutsen, the VII composed of quartz monzonite and granodiorite, and the Coast Plutonic Complex (CPC) diorites and amphibolites. Sicker Group meta-andesites and dacites are occasionally present (Roddick, Muller and Okulitch 1979).

Climate

The central and northern west coast of Vancouver Island is characterized by cool, wet winters and warm, moist summers. Mean annual precipitation increases from about 2900 mm at sea level on the outer west coast to greater than 4600 mm inland at sea level at the heads of inlets. Seventy to eighty percent of the precipitation occurs between October and March (Howes 1981). Snow is usually confined to higher elevations and is ephemeral at lower and mid elevations; the area is subject to occasional rain-on-snow events. The coastline is exposed to Pacific frontal storms of high intensity and long duration. Long-term precipitation records for coastal stations show three-day extreme totals with ten-year return periods ranging from 257 to 330 mm (Howes 1981). Limited short-term records from some unofficial inland stations show periods of significantly higher extreme rainfall. Wind data for the west coast of the Island is scarce, however, lighthouse station records (Cape Scott, Spring Island and Estevan) indicate maximum hourly speeds ranging from 60 to 120 km/hr. Greatest precipitation intensity/duration rain storms and highest wind velocities usually occur during the winter months (October to March). Rainstorms of sufficient magnitude to initiate debris flows usually occur several times every year and may not be confined to the winter period.

METHODOLOGY

Sampling Design

Within each main study area, all logged areas ranging in age from 6 to 15 years following harvesting were selected for study. The lower age limit was imposed to ensure that the study areas have experienced a number of large storms and to give time for loss in root strength to occur. The upper age limit was imposed because crown closure and increasing tree height in the regenerating plantations tends to mask local terrain features including small landslides, making collection of accurate data difficult.

Each selected area was mapped at a scale of 1:20,000 using the BC Terrain Classification System (Howes and Kenk 1988), and 1:15,000 to 1:20,000 scale aerial photography. Each terrain polygon was verified in the field. For the sake of efficiency, most terrain polygons with slopes less than 20 degrees were excluded from the study, because they rarely show evidence of post-logging failure. Each terrain polygon constitutes a single sample.

The data set currently consists of a total of 1647 terrain polygons, representing an aggregate area of approximately 6442 hectares. The mean polygon area is 3.96 hectares, with a standard deviation of 3.25 hectares and a range of 0.2 to 38.8 hectares. Over time this data set will be augmented by additional sampling within the main study areas. Updating landslide incidence will occur periodically, usually after major storm events or when new aerial photography is flown. At any point in time, the data set will slightly underrepresent the total number of post-logging landslides which have occurred in the study areas.

With terrain mapping it is common knowledge that no two mappers will produce identical map polygons for a given landscape or describe an area in exactly the same manner. Because this study involved several mappers, the terrain mapping approach will have introduced some unknown amount of bias or variability. This was limited by providing clear definitions and descriptions of the terrain attribute data to be collected and by having the mappers work together with a mapping coordinator to ensure a consistent approach. The analysis of categorical terrain data involves the grouping of a large number of distinct terrain types into a smaller set of more generalized terrain categories. This consolidation reduces the effect of differences in terrain polygon delineation and classification.

Data Collection

For each map polygon, terrain attribute data such as landscape position, slope, aspect, slope morphology, slope curvature, soil drainage class, surficial material, bedrock type, and the presence or absence of natural and post-logging landslides was recorded. For estimating post-logging landslide frequency, landslides smaller than 0.05 hectares were excluded because they could not be reliably identified at the air photo scales used. Landslides identified in the field or on aerial photography that were 0.05 hectares or larger were included in the data set.

Data Analysis

Non-parametric statistical tests (Table 1) were applied to identify relationships between landslide frequency and individual terrain attributes. Individual terrain polygons were then grouped into a limited number of multi-factor terrain categories having a similar likelihood of post-logging failure using CHAID (Chi-squared Automatic Interaction Detector). CHAID is a relatively new, non-parametric, multi-variate procedure known as segmentation modeling (Magidson J./SPSS 1993). The procedure divides a sample population into two or more distinct groups based on the best predictors of a dependent variable. Segments defined by

Table 1. Comparison of terrain attributes with post-harvesting landslide frequency

	Significance Level	
Variable	**Kruskal-Wallis(1)**	**Chi-square(2)**
Slope class	.0000	.00000
Natural landslides	.0003	.00073
Minor natural landslides	.0006	.00063
Landscape position	.0000	.00003
Slope morphology	.0000	.00000
Horizontal curvature	.0000	.00014
Soil drainage	.0010	.00199
Slope aspect	.1723	.15491
Seaward/Inland exposure	.0032	.00256
Elevation	.0191	.01641
Terrain category	.0207	.00979
Bedrock formation	.5440	.33603
Bedrock lithology	.0051	.00505
Bedrock structure	.0064	.01462
Bedrock competence	.0009	.00431

(1) based on post-logging clearcut landslide frequency (number/ha).
(2) based on presence or absence of post-logging clearcut landslides.

the analysis do not overlap. Both dependent and predictor variables are treated as categorical variables. The procedure merges categories of a predictor variable that are not significantly different at each segmentation level. The analysis produces an easy-to-read tree diagram (Figure 2) that identifies the defining variables and presents statistics for each separate group or segment of the dependent variable. These categories can then form the basis of a terrain stability classification which estimates the likelihood of landslides occurring after forest harvesting. CHAID was first used in BC for this purpose by Pack (1995) in a study of landslides related to logging roads in the interior of the province.

RESULTS AND DISCUSSION

Eighty-three percent of the 1647 sample terrain polygons in the data set remained stable after logging. By comparison, 78 percent of the 760 samples in a data set from the QCI (Rollerson 1992) remained stable for the same 6 to 15-year period after logging. The overall mean post-logging landslide frequency for the study area was 0.08 landslides per hectare, contrasting sharply with a overall mean landslide frequency of 0.17 landslides per hectare for areas of similar terrain in the QCI.

Post-logging landslide frequencies show a statistically significant relationship at the 0.00 level for 11 out of the 15 terrain variables analyzed (Table 1). As we have seen elsewhere (Rollerson 1992, Rollerson and Sondheim 1985), increases in landslide frequency on a per hectare basis tend to correspond with an increase in the percentage of polygons (cases) within a group or class that experience failure (Table 2). In a general sense, the percentage of cases experiencing failure can be interpreted as a measure of the likelihood or probability of landslide activity following logging on similar terrain in the same climatic region. Because the actual sample polygons vary in number, size and character somewhat, we are uncertain how precise this statistic is as a measure of probability.

Groupings of average polygon slope angle show a trend of increasing landslide frequency with increasing slope angle up to approximately 46 degrees, when landslide frequency drops off. This lower frequency is likely explained by the dominance of bedrock and relatively limited and discontinuous character of surficial materials on these very steep slopes. The presence of natural landslides shows a positive association with post-logging landslide activity; some of the highest post-logging landslide frequencies are associated with these features. Steep stream escarpments and headwater drainage basins are associated with fairly high landslide frequencies, as are areas of highly dissected (gullied) terrain. Differences in landslide frequencies associated with varying surficial materials (terrain categories) are not great; however, cross-tabulation shows a fair degree of correspondence between different terrain categories and slope class. For example, till, which one would expect to be less stable than angular, bedrock-derived colluvium, tends to be associated with a gentler range slope angles than colluvium. Slope curvature shows higher failure frequencies associated with concave and complex slopes than with convex and straight slopes. Soil drainage shows reasonable correspondence with failure frequency. There is no strong association with either aspect or elevation. However, when aspect is expressed as exposure to seaward (ESE to NNW) versus inland areas (NNE to ENE), the relationship is significant. This suggests that small, hillside-specific rain shadows may affect landslide frequency on inland-facing slopes. Bedrock formation does not show a statistically significant association with failure frequency; however, lithology, structure and competence do. Unlike bedrock formation which was observed or inferred at every polygon, lithology, structure and competence were only recorded where bedrock was exposed at the ground surface or in road cuts, typically areas of shallow overburden. These are the very situations where we might expect to see stronger bedrock control over soil physical properties or local stability conditions.

CHAID (Figure 2) shows similar trends. Slope angle is the most significant predictor variable, followed closely by hillslope configuration, soil drainage and hillslope curvature, the order of significance varying between branches of the CHAID tree. Bedrock formation is a significant predictor for one branch, but the degree of differentiation provided may not be of practical significance. The presence or absence of natural landslides, possibly because of the small population of natural landslides and an association with steeper slopes, was overlooked as a predictor even though univariate analysis shows it highly correlated with post-logging landslide activity. The same analysis run on the QCI data set resulted in a similar grouping of predictors, the only difference being that the presence or absence of natural landslides was a significant predictor and soil drainage was not. Perhaps because of higher overall landslide frequencies and somewhat less variable terrain, CHAID was more successful at segregating more stable from less stable groups using the QCI data set. In neither instance was surficial material used as a predictor variable, most likely because of the correspondence between slope angle and the type of surficial material present.

CHAID shows promise as a tool for developing stability classifications. Like many multi-variate techniques, it needs to be used with caution, preferably by an experienced terrain scientist who can ensure that critical attributes, especially those that occur infrequently, are not overlooked.

Table 2. Terrain Attributes - Summary Statistics

Variable	Code	n	Mean landslide frequency (#/ha)	Percent units failing
Slope class (°)				
15-19	1	19	.00	0.0
20-25	2	329	.02	3.6
26-30	3	323	.06	15.2
31-35	4	521	.10	23.4
36-40	5	318	.13	22.6
41-46	6	85	.07	16.5
>46	7	38	.04	7.9
Natural landslides				
absent	A	1605	.08	16.1
present	P	42	.25	35.7
Minor natural landslides				
absent	A	1628	.08	16.2
present	P	17	.19	47.1
Landscape position				
apex	A	16	.00	0.0
upper slope	U	480	.06	16.8
mid slope	M	923	.08	16.5
lower slope	L	177	.08	11.9
stream escarpment	E	15	.67	56.3
headwater basin	H	33	.13	30.3
Slope morphology				
uniform	U	1024	.08	17.7
benchy	B	36	.02	5.6
dissected	D	98	.17	31.6
faceted	F	16	.03	12.5
irregular	I	321	.03	8.1
single gullies	S	149	.16	20.1
Terrain category				
Morainal (till)	1	752	.11	18.6
Colluvial	2	201	.08	16.4
Fluvioglacial	3	1	---	---
Marine	4	9	.26	22.2
Rock	5	5	---	---
Morainal+colluvial	6	216	.06	17.9
Morainal+fluvioglacial	7	3	.04	---
Morainal/rock	8	190	.05	14.2
Colluvial/rock	9	153	.05	15.7
Rock/colluvial (1)	a	115	.01	4.3
Horizontal curvature				
concave	1	395	.12	20.8
convex	2	338	.06	12.1
straight	3	796	.05	14.9
complex	4	114	.17	27.0

(1) proportion symbols: / = dominant/subdominant;
+ = either component may be dominant or they may be equivalent.

continued

Table 2 (continued)

Variable	**Code**	**n**	**Mean (#/ha)**	**% Failing**
Soil drainage				
rapidly	r	348	.06	10.9
well	w	1127	.08	18.5
moderately well	m	162	.09	15.3
imperfectly	I	3	---	---
poorly	p	1	---	---
Slope aspect				
NNE	1	137	.05	10.9
ENE	2	187	.06	11.2
ESE	3	243	.08	17.3
SSE	4	216	.09	19.9
SSW	5	150	.13	18.0
WSW	6	248	.10	19.4
WNW	7	254	.06	17.7
NNW	8	176	.07	15.9
Elevation (m)				
100	1	56	.09	10.7
101-200	2	160	.10	16.3
201-300	3	217	.08	16.1
301-400	4	322	.08	13.0
401-500	5	340	.09	20.6
501-600	6	295	.10	21.0
601-700	7	165	.04	13.3
700	8	79	.02	8.9
Bedrock formation				
VII / CPC	1	925	.08	16.8
Bonanza	2	439	.09	16.1
Karmutsen	3	252	.06	17.8
Quatsino	4	28	.02	7.0
Bedrock lithology				
quartz monzonite	2	291	.09	21.0
granodiorite	4	83	.04	15.7
diorite	6	151	.02	6.6
andesite	15	15	.02	13.3
basalt	17	354	.08	13.8
volcanic breccia	19	22	.09	31.8
gneiss	30	1	---	---
greywacke	53	11	.05	18.2
limestone	58	21	.03	9.5
Bedrock structure				
massive	1	199	.03	8.5
fractured	2	372	.07	17.4
sheared	3	30	.12	23.3
bedded	4	3	---	---
Bedrock competence				
high	1	366	.06	11.5
moderate	2	143	.07	18.2
low	3	35	.13	31.4

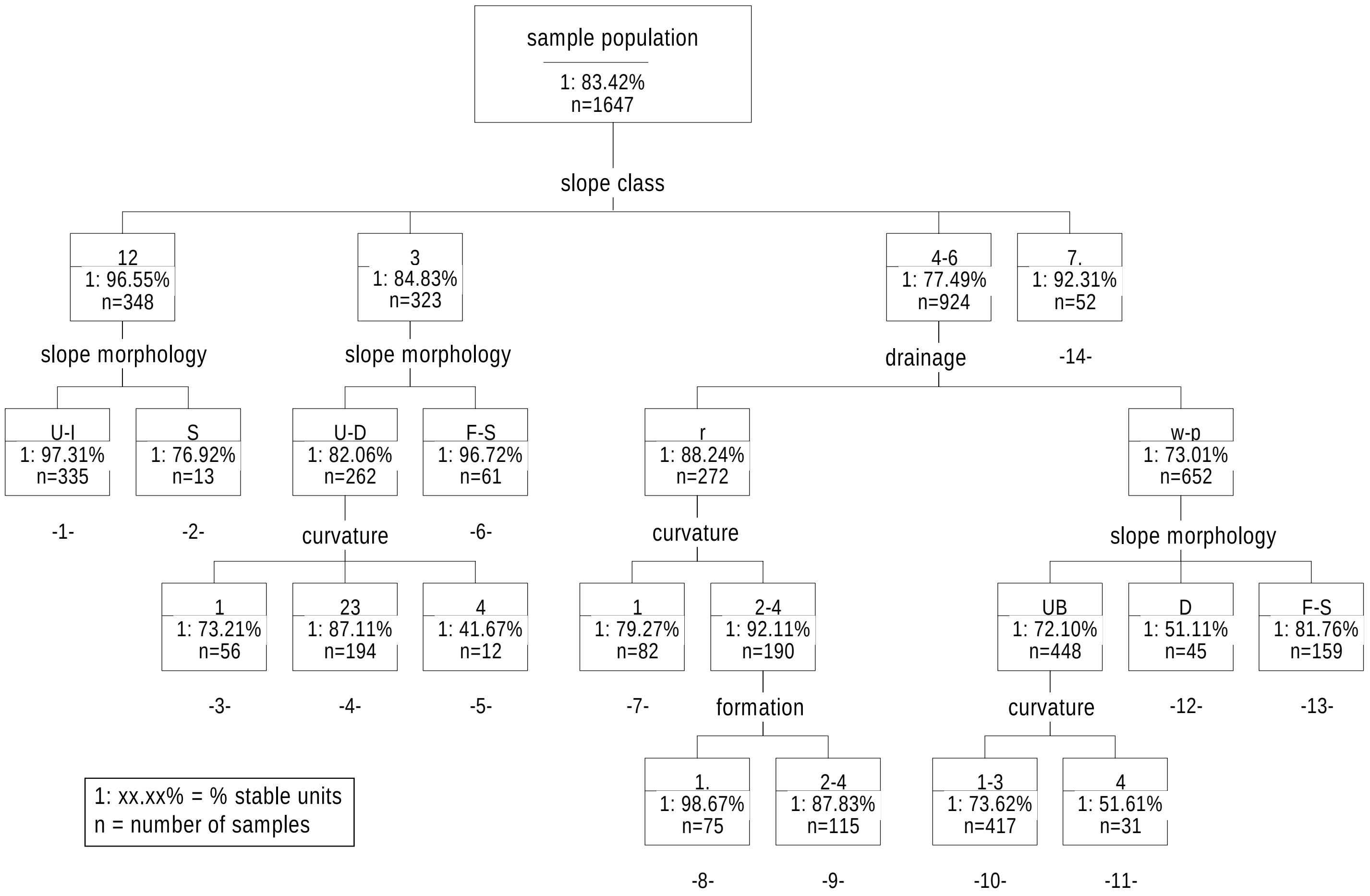

Figure 2. CHAID Tree for the Central and Northern West Coast of Vancouver Island

ACKNOWLEDGEMENTS

We would like to thank Frank Bauman, Gordon Butt, Anthony Callette, Pierre Friele, Denny Maynard, Gray Switzer, Sid Tsang and Mel Zwiernk for their assistance with what was at times onerous and difficult field work We also thank Liz Steele who assisted with the preparation and editing of the manuscript.

APPENDIX 1. REFERENCES

Hoadley, J.W. (1953). “Geology and Mineral Deposits of the Zeballos-Nimpkish Area, Vancouver Island, British Columbia,” Memoir 272, Geological Survey of Canada.

Holland, S.S. (1964). “Landforms of British Columbia A Physiographic Outline.” Bulletin 48, British Columbia Mines and Petroleum Resources, Victoria, B.C., Canada.

Howes, D.E. and Kenk, E. (1988). “Terrain Classification System for British Columbia (Revised Edition).” Ministry of Environment, Ministry of Crown Lands, Victoria, B.C., Canada.

Howes, D. (1987). “A method for predicting terrain susceptible to landslides following forest harvesting: a case study from the southern coast mountains, British Columbia.” *Proc., International Association of Hydrological Sciences, Symposium. XIX General Assembly of the International Union of Geodesy and Geophysics*, August 19-22, 1987, University of British Columbia, Vancouver, B.C., Canada.

Howes, D.E. (1981). “Terrain Inventory and Geological Hazards: Northern Vancouver Island.” APD Bulletin 5, British Columbia Ministry of Environment, Victoria, B.C., Canada.

Magidson, J. / SPSS Inc. (1993). “SPSS for Windows CHAID Release 6.0.” SPSS Inc., 444 North Michigan Avenue, Chicago, Illinois, USA 60611.

Pack, R.T. (1995). “Statistically based terrain stability mapping methodology for the Kamloops Forest Region, B.C.” *Proc., 48th Canadian Geotechnical Conference*, September 25-27, 1995, Vancouver, B.C., Canada.

Roddick, J.A., Muller, J.E., and Okulitch, A.V. (1979). “Fraser River (Sheet 92). 1:1,000,000 Geological Atlas,” R.J.W Douglas coordinator, Geological Survey of Canada.

Rollerson, T., and Sondheim, M. (1985). “Predicting post-logging terrain stability - a statistical-geographical approach.” *Proc., Joint Symposium of the I.U.F.R.O. Mountain Logging Section and the Sixth Pacific Northwest Skyline Symposium*, Vancouver, B.C., Canada.

Rollerson, T. (1992). “Relationships between landscape attributes and landslide frequencies after logging - Skidegate Plateau, Queen Charlotte Islands.” Land Management Report No. 76. Ministry of Forests, Victoria, B.C., Canada.

Yorath, C.J. and Nasmith, H.W. (1995). “The Geology of Southern Vancouver Island: A Field Guide.” Orca Book Publishers, Victoria, B.C., Canada.