# An Aerial Photograph Inventory of the Frequency and Yield of Mass Wasting on the Queen Charlotte Islands, British Columbia

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# An Aerial Photograph Inventory of the Frequency and Yield of Mass Wasting on the Queen Charlotte Islands, British Columbia

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## ABSTRACT

This study investigated timber harvesting and mass wasting on the Queen Charlotte Islands. Logging impacts on the frequency and yield of landslides from steep slopes and on the volume of material entering streams were examined for a study area comprised of 27 basins covering 350 $km^2$ between Rennell Sound and Burnaby Island.

The influence of logging was assessed by comparing the yield and frequency of landslides calculated for clearcut and road areas to that from forested terrain. Data on the number, type, and volume of landslides were extracted from large-scale aerial photography. The yield from forested terrain was calculated from the total steepland area in the study basins, the volume associated with debris slides and debris flows, and the age range over which the landslides occurred. The typical age of the oldest landslides sampled was estimated to be 40 years. Yields from logged areas were calculated separately for roads and clearcut areas. For each basin the yield was calculated from the total volume of landsliding from roads or clearcuts, the total steepland logged area, and the age of logging in that basin. The age of logging was an areally weighted average of the number of years between logging and photography. The overall yield of landsliding from clearcut and road terrain, for comparison with the overall yield from forested terrain, was calculated as an areally weighted average from the individual basins.

The yields and frequencies from forested and logged terrain were determined from 1337 landslides. In forested steepland, 4.8 landslides per square kilometre were observed for a frequency of 0.12 per square kilometre per year. In logged areas, 29.7 landslides per square kilometre were observed, increasing the frequency to 4.1 events per square kilometre per year. Within the logged area, the frequency of events ranged from 3.6 per square kilometre per year in clearcuts to 9.2 per square kilometre per year from roads. The overall effect of logging has been to accelerate the frequency of landsliding 34 times.

In forested areas the yield was 1.6 $m^3$/ha per year. The removal of vegetation produced a yield of 50.7 $m^3$/ha per year, an acceleration of 31 times. Larger increases were associated with roads, where the yield of material was 144 $m^3$/ha per year, and the acceleration relative to forested terrain was 87 times. The yield and acceleration for debris slides in clearcut terrain on the Queen Charlotte Islands are significantly larger than those reported from similar areas in the Pacific Northwest.

Approximately 39% of the total volume of mass wasting from forested terrain and 47% from logged terrain directly enter the stream system. Yields to streams were 0.6 $m^3$/ha per year from forested areas, 24 $m^3$/ha per year from clearcut areas, and 75 $m^3$/ha per year from roads. The acceleration of yield to streams as a result of logging is slightly larger than the acceleration of the overall annual volume yield. Yields to stream are higher from road areas, but most of the total volume is from clearcuts: 78% from clearcut failures and 22% from roads. Nearly all of the yield enters the higher gradient portions of stream reaches in the upper areas of the watershed.

## ACKNOWLEDGMENTS

The assistance of the Department of Geography of the University of British Columbia is gratefully acknowledged. The department granted the use of its WILD A6 and other photogrammetric equipment, which allowed this project to be completed.

Dr. Lee Beaven, Fish/Forestry Interaction Program, and Mr. Dave Wilford, Ministry of Forests, aided in the initial organization of the study. Dr. Michael Church of the University of British Columbia provided initial guidance and assistance with interpretation of the aerial photography. Technical comments from Dr. M. Church, and Mr. Jim Schwab have been invaluable in preparing the report. The assistance of Mr. E.A. Sauder and Mr. Ray Krag of the Forest Engineering Research Institute of Canada in providing a bibliography of relevant literature and ground truthing for this study is gratefully acknowledged. Special thanks to Mr. V.A. Poulin and M. Hamilton who edited the manuscript and provided valuable perspective on the work.

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# 1 INTRODUCTION

This study is part of the Physical Processes component of the Fish/Forestry Interaction Program (Poulin 1983), and its objective is to document the impact of forest harvesting on mass wasting and the impact of mass wasting on streams on the Queen Charlotte Islands. These tasks involve a comprehensive assessment of the frequency and yield of mass wasting from forested and logged terrain, and of the proportion of landslides that directly enter streams.

The Queen Charlotte Islands are particularly prone to mass wasting, and sediment transfer is dominated by episodic processes (Alley and Thomson 1978; Wilford and Schwab 1982; Church 1983). The Islands are perhumid; annual precipitation ranges from 1400 mm on the east coast of the Islands (Port Clements or Sandspit) to in excess of 3000 - 5000 mm on the west side of the Queen Charlotte Ranges. The 10-year, 24-hour storm, delivers in excess of 150 mm rainfall over most of the islands (Wilford and Schwab 1982; Church 1983). Other factors contributing to slope instability include rapidly weathered volcanic and sedimentary rocks (Lewis 1982), glacially oversteepened slopes, high winds, and frequent seismic activity.

Mass wasting is further aggravated by logging on steep slopes. There is little dispute that the rate of sediment transfer by mass wasting is accelerated following logging. Increased mass wastage from clearcut areas is apparently due to yarding disturbance of soils and the root decay and loss of support from the root mat following vegetation removal (Nakano 1971; Swanston 1974; Megahan et al. 1979). Increased landsliding also occurs following road construction because of overloaded or oversteepened slopes and inadequate or poorly maintained drainage (v. Sidle et al. 1985, for a recent review).

An inventory of landslides in forested and logged steepland areas is used in this study to examine the impact of clearcutting and road construction on natural rates of slope failure on the Queen Charlotte Islands and on the proportion of landslides entering streams. The specific objectives of the study are:

1. to estimate the frequency (the number of events per square kilometre per year) and the yield (volume per hectare per year) of landsliding from logged and forested terrain;
2. to assess the relative contribution of different failure types to the frequency of landslides and yield of sediment from logged and forested terrain;
3. to estimate the relative contribution of roads and clearcuts to the frequency of landslides and yield of sediment from logged terrain;
4. to estimate the yield of sediment from logged and forested terrain to different stream gradient classes; and
5. to compare mass wasting conditions observed in this study to those in other Pacific Northwest regions.

A future report will examine the characteristics of failure sites in both forested and logged terrain.

## 2 STUDY DESIGN AND METHODOLOGY

The approach of this study was to enumerate and measure all episodic failures within certain age and size limits, visible on aerial photography of each study watershed. This approach provides a complete inventory of landslides for each basin.

### 2.1 The Study Area

The study area covered 350 $km^2$ and included 27 basins distributed between Rennell Sound and Burnaby Island (Figure 1). Nineteen of the 27 basins included some logged areas; 17 included some steepland logged area (Table 1). These basins are a subset of a larger sample used for an integrated study of harvesting activities on fish resources. This larger sample was intended to include the range of physical conditions and harvesting situations occurring on the Queen Charlotte Islands.

The study basins lie within the Queen Charlotte Ranges and Skidegate Plateau physiographic regions (Holland 1976; Table 1). Ten of the basins are located in the Skidegate Plateau and include 40% of the forested steepland area and 65% of the logged steepland area. The watersheds are also evenly distributed between the west coasts of Graham and Moresby islands and the area lying to the east of the axis of the Queen Charlotte Ranges.

The study basins are primarily underlain by the Masset, Yakoun (soft volcanics), Karmutsen (hard volcanics) and Haida and Honna (clastic sedimentaries) geologic formations (Sutherland Brown 1968). The sedimentary and soft volcanic formations are generally considered to weather very rapidly (Lewis 1982); the more massive hard volcanics weather at a slower rate. Minor occurrences of other geologic formations -- principally intrusive granitic rocks -- are found in Government Creek, Mountain Creek, and on Burnaby Island.

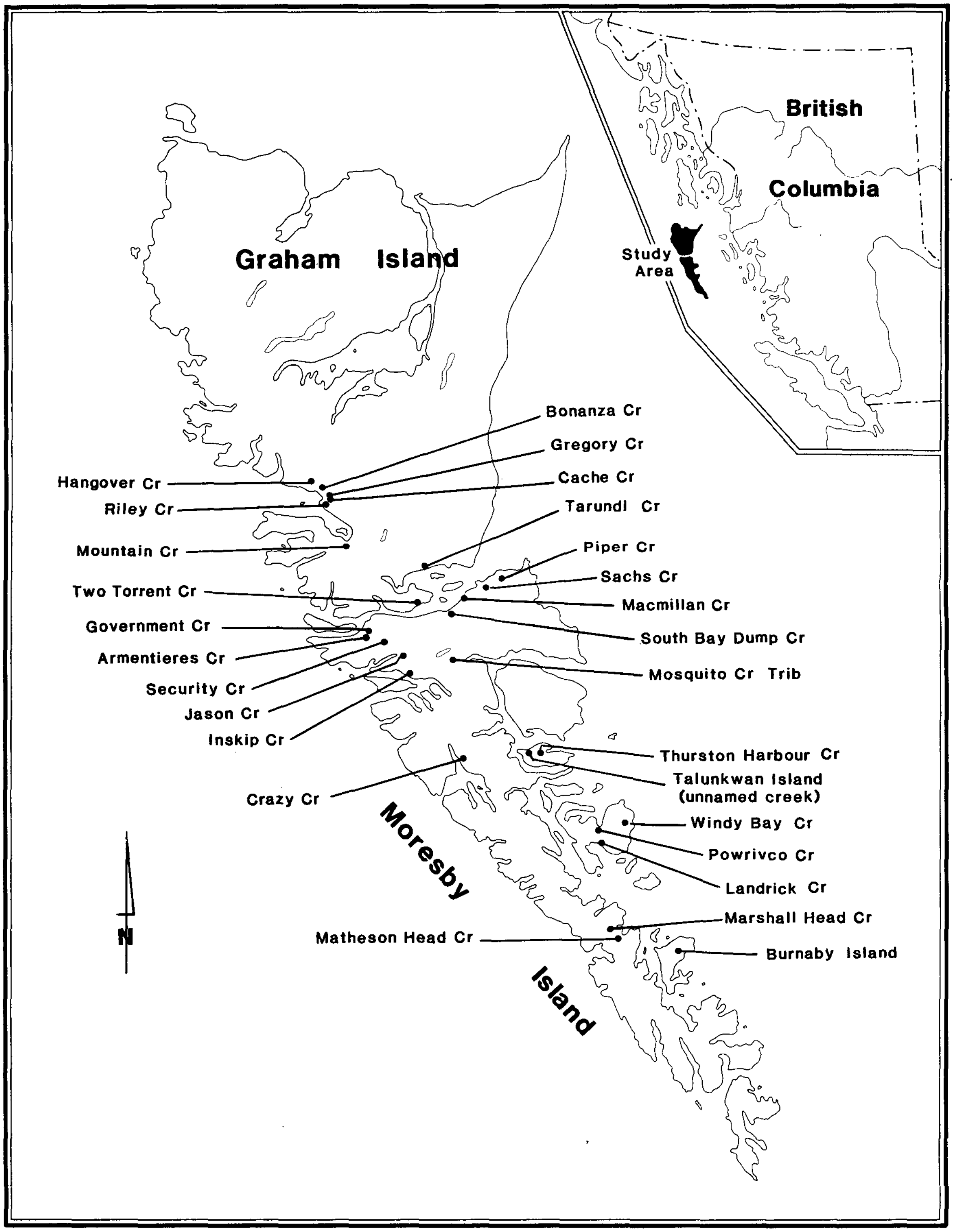


FIGURE 1. Location of study basins on the Queen Charlotte Islands.

TABLE 1. Dominant geology and physiography of the study basins, Queen Charlotte Islands

| Basin name | Drainage area ($km^2$) | Logged[a] Area ($km^2$) | Steepland Area[b] Forested ($km^2$) | Steepland Area[b] Logged[a] ($km^2$) | Physiographic[c] region | Geologic[d] formation Major | Geologic[d] formation Minor |
|---|---|---|---|---|---|---|---|
| Hangover Creek | 21.2 | 0 | 11.6 | 0 | SP | Masset | - |
| Bonanza Creek | 47.4 | 6.1 | 20.4 | 2.5 | SP | Masset | - |
| Gregory Creek | 36.7 | 0.8 | 14.5 | 0.3 | SP | Masset | - |
| Cache Creek | 1.5 | 0.5 | 0.4 | 0.03 | SP | Masset | - |
| Riley Creek | 28.7 | 3.5 | 10.6 | 1.4 | SP | Yakoun | Masset |
| Mountain Creek | 12.8 | 1.2 | 9.8 | 0.4 | QCR | PTP | Longarm |
| Tarundl Creek | 11.3 | 4.0 | 2.7 | 0.5 | SP | Skidegate | Masset |
| Piper Creek | 4.2 | 0.4 | 0.2 | 0 | SP | Haida? | - |
| Sachs Creek | 17.8 | 11.4 | 3.6 | 3.2 | SP | Haida | Honna |
| MacMillan Creek | 6.2 | 4.0 | 1.8 | 1.3 | SP | Haida | Honna |
| South Bay Dump Creek | 4.0 | 3.2 | 0.6 | 1.4 | SP | Honna | Haida |
| Mosquito Cr. Tributary | 5.4 | 1.1 | 3.8 | 0.5 | QCR | Karmutsen | - |
| Government Creek | 16.1 | 0 | 7.7 | 0 | QCR | Karmutsen | PTP, Kunga |
| Armentieres Creek | 4.0 | 0.8 | 2.8 | 0.4 | QCR | Karmutsen | - |
| Security Creek | 33.9 | 1.0 | 16.7 | 0.3 | QCR | Karmutsen | - |
| Jason Creek | 11.9 | 0 | 8.9 | 0 | QCR | Karmutsen | - |
| Inskip Creek | 13.0 | 0 | 10.3 | 0 | QCR | Karmutsen | - |
| Crazy Creek | 6.0 | 0.3 | 2.8 | 0 | QCR | Haida | Kunga |
| Talunkwan Island | 4.5 | 1.9 | 2.0 | 1.3 | QCR | Masset | - |
| Powrivco Creek | 4.3 | 1.5 | 1.7 | 1.2 | QCR | Masset | Yakoun |
| Windy Bay Creek | 20.7 | 0 | 13.1 | 0 | QCR | Masset | Longarm |
| Landrick Creek | 2.1 | 1.0 | 1.1 | 0.9 | QCR | Masset | - |
| Marshall Head Creek | 8.7 | 0 | 5.1 | 0 | QCR | Karmutsen | - |
| Matheson Head Creek | 6.7 | 0 | 5.0 | 0 | QCR | Karmutsen | - |
| Burnaby Island | 12.0 | 0 | 5.8 | 0 | QCR | PTP | Kunga |
| Two Torrent Creek | 3.9 | 0.3 | 2.4 | 0.2 | QCR | Haida | Longarm |
| Thurston Harbour Creek | 6.1 | 3.9 | 1.3 | 1.9 | QCR | Masset | - |

a Includes clearcut and road areas.
b Watershed area steeper than 20°. Determined from 1:50 000 NTS Maps.
c QCR is the Queen Charlotte Ranges; SP, the Skidegate Plateau (Holland 1976).
d Geologic formations are from Sutherland Brown (1968). Rock types are (Lewis 1982): Masset - soft volcanics; Yakoun - soft volcanics; Karmutsen - hard volcanics; Haida - clastic sedimentaries; Honna - clastic sedimentaries; Kunga - limestones and argillites; Longarm - clastic sedimentaries; PTP (post tectonic plutons) - granites and granite-like rocks. Major and minor distinctions reflect the geologies that have the majority and minority of mass wasting occurrence in a particular basin.

## 2.2 The Land Base

The steepland logged areas were clearcut between 1 and 17 years prior to the date of aerial photography. The total areas for the different ages are shown on Figure 2. The steepland forested terrain includes only old-growth forest.

Steepland areas were defined on 1:50 000 NTS maps. For each basin the distance between the contours was used to separate areas steeper than 20° from those less steep. The location and age of logged areas were extracted from the Fish/Forestry Interaction Program (FFIP) Data Catalogue[1] and overlain on the contour map.

Where the logged areas were small or the FFIP catalogue was known to be inaccurate steepland logged areas were extracted from 1:5 000 working drawings of the basins. Road areas were determined from road lengths measured on 1:5000 working drawings, multiplied by a standard width of 20 m.

## 2.3 Calculation of Frequency and Yield

Frequency and yield calculations require the number and volume of landslides, the steepland area, and the number of years during which mass wasting occurs.

The mass wasting events observed on the aerial photographs in forested terrain range from 1 year to 100 or more years in age. However, older events have progressively higher percentage ground cover, and a point is reached where the detailed information discussed in Sections 2.3.2 and 2.3.3 can no longer be accurately collected. The sighting of the ground through the vegetation in the initiation and transport zones -- necessary for data collection -- is typically lost for events exceeding 40-60 years in age (Smith _et_ _al_. 1983). A review of older events dated by Smith _et_ _al_. (their Table 1) showed that events 36 and 48 years old had sufficiently open vegetation to be included in this study, while events 64, 87, and 99 years old were excluded. The time period for mass wasting

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[1] Unpublished data catalogues are available from, Fish/Forestry Interaction Program, 2153 West 46th Avenue, Vancouver, B.C. V6M 2L2.

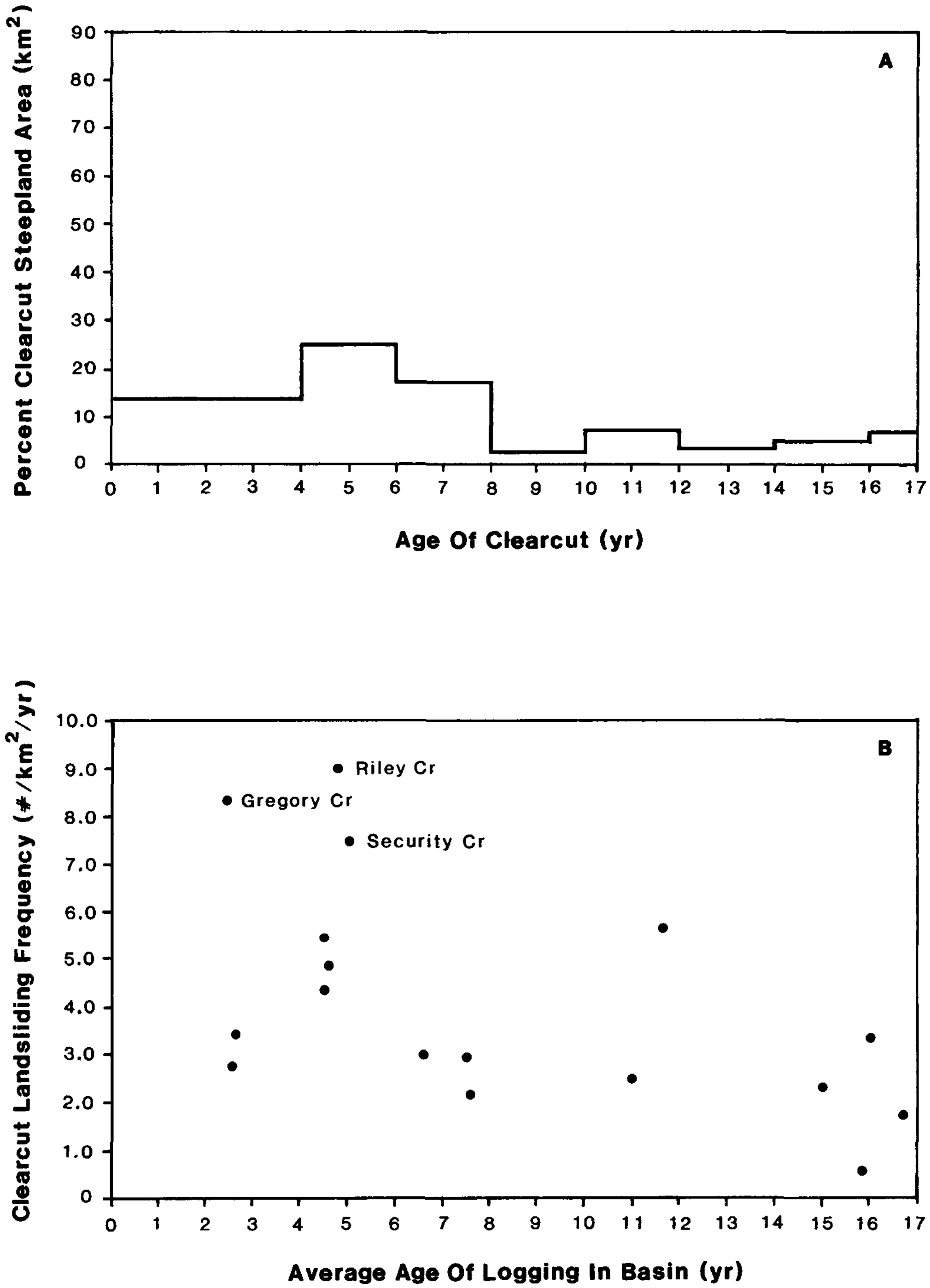


FIGURE 2. The characteristics of logged areas sampled in this study.
(A) The proportion of clearcut steeplands of different ages.
(B) The landsliding frequency of clearcut steeplands in the study basins related to the average age of logging in the study basins.

in the forested areas -- that is, the average or typical age of the oldest events included in the sample -- was estimated to be 40 years.

The comparable time period for mass wasting in logged areas is the age at the time of photography. This is the period over which landsliding due to clearcutting or road construction could have occurred.

Within any basin, the yield or frequency from logged areas was determined from the total number or volume of landslides, the steepland logged area, and the average age of logging in that basin. This was calculated by weighting the ages of steepland logging with the steepland area of that particular age (Table 2).

## 2.4 Comparison of Forested and Logged Terrain

The best estimate of the natural rate of landsliding on the Queen Charlotte Islands is based on the total volume or number of forested events, the forested steepland area, and the estimated 40-year record. To assess the overall impact of logging on natural rates of mass wasting, a similar value is required for logged areas. This was calculated from the total volume or number of landslides, the clearcut or road steepland area, and the average age of logging. The average age of logging was calculated from an areally weighted average of the age of logging in the individual basins.

The overall rate of mass wasting from logged areas is sensitive to the age distribution of the individual clearcut areas (Figure 2), since their yield or frequency varies with age and depends on:

1. whether a major storm capable of initiating mass wasting has occurred since logging; and
2. if a major storm has occurred, when it occurred in the sequence of clearcut, root deterioration, and establishment of second growth.

In the Queen Charlottes, large storms of an approximately 5-year recurrence interval are sufficient to initiate landslides in most areas (Schwab 1983). Major storms occurred in 1974 and 1978 (Wilford and Schwab 1982; Schwab 1983). Localized events that also caused significant mass wasting occurred in 1975 and 1976. As such, all of the logged areas

TABLE 2. The frequency of mass wasting on forested and logged terrain in the study basins, Queen Charlotte Islands

| Basin name | Steepland area[c] Forest[c] ($km^2$) | Clearcut ($km^2$) | Road[d] ($km^2$) | Logging age (yr) | Number of failures by process Slides | Flows | Number of failures[f] by land class Forest | Logged | Clearcut | Roads | Failure frequency (no./$km^2$/yr) Forest | Logged | Clearcut | Roads | Failure rate relative to forest Logged | Clearcut | Roads |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hangover[a] | 11.6 | 0 | 0 | - | 65 | 3 | 68 | - | - | - | 0.15 | - | - | - | - | - | - |
| Bonanza[a] | 20.4 | 2.2 | 0.30 | 4.6 | 148 | 14 | 104 | 58 | 49 | 9 | 0.13 | 5.0 | 4.8 | 6.5 | x40 | x38 | x51 |
| Gregory[a] | 14.5 | 0.25 | 0.05 | 2.4 | 91 | 12 | 98 | 5 | 5 | 0 | 0.17 | 6.9 | 8.3 | 0 | x41 | x49 | 0 |
| Cache[a] | 0.4 | 0.03 | 0 | 6 | 1 | 1 | 0 | 2 | 2 | 0 | 0 | 11.1 | 11.1 | 0 | ------ | undefined | ------ |
| Riley[a] | 10.6 | 1.2 | 0.20 | 4.9 | 90 | 12 | 39 | 63 | 53 | 10 | 0.09 | 9.2 | 9.0 | 10.2 | x99 | x98 | x111 |
| Mountain[be] | 9.8 | 0.4 | 0 | 16 | 35 | 1 | 25 | 11 | 11 | 0 | 0.06 | 1.7 | 1.7 | 0 | x27 | x27 | 0 |
| Tarundl[b] | 2.7 | 0.5 | 0.07 | 7.6 | 11 | 0 | 2 | 9 | 8 | 1 | 0.02 | 2.1 | 2.1 | 1.9 | x112 | x113 | x102 |
| Piper[b] | 0.2 | 0 | 0 | - | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Sachs[b] | 3.6 | 3.0 | 0.20 | 7.5 | 88 | 13 | 20 | 81 | 68 | 13 | 0.14 | 3.4 | 3.0 | 8.7 | x24 | x22 | x62 |
| MacMillan[b] | 1.8 | 1.2 | 0.08 | 4.5 | 29 | 5 | 3 | 31 | 24 | 7 | 0.05 | 5.4 | 4.4 | 19.4 | x129 | x107 | x467 |
| South Bay[b] Dump | 0.6 | 1.3 | 0.07 | 6.6 | 32 | 7 | 6 | 33 | 26 | 7 | .25 | 3.6 | 3.0 | 15.2 | x15 | x12 | x61 |
| Mosquito[be] Tributary | 3.8 | 0.5 | 0 | 17 | 9 | 1 | 5 | 5 | 5 | 0 | 0.03 | 0.59 | 0.59 | 0 | x18 | x18 | 0 |
| Government[b] | 7.7 | 0 | 0 | - | 31 | 6 | 37 | - | - | - | 0.12 | - | - | - | - | - | - |
| Armentieres[be] | 2.8 | 0.4 | ? | 15 | 47 | 1 | 34 | 14 | 14 | 0 | 0.30 | 2.3 | 2.3 | 0 | x8 | x8 | 0 |
| Security[b] | 16.7 | 0.3 | 0.03 | 5 | 102 | 9 | 101 | 10 | 10 | 0 | 0.15 | 6.7 | 7.4 | 0 | x44 | x49 | 0 |
| Jason[b] | 8.9 | 0 | 0 | - | 52 | 10 | 62 | - | - | - | 0.17 | - | - | - | - | - | - |
| Inskip[b] | 10.3 | 0 | 0 | - | 74 | 3 | 77 | - | - | - | 0.19 | - | - | - | - | - | - |
| Crazy[b] | 2.8 | 0 | 0 | ? | 13 | 0 | 13 | - | - | 0 | 0.12 | - | - | - | - | - | - |
| Talunkwan[b] | 2.0 | 1.2 | 0.09 | 11.6 | 98 | 11 | 3 | 106 | 85 | 21 | 0.04 | 7.1 | 5.7 | 20.1 | x189 | x151 | x536 |
| Powrivco[b] | 1.7 | 1.1 | 0.10 | 2.6 | 10 | 3 | 3 | 10 | 8 | 2 | 0.04 | 3.2 | 2.8 | 7.7 | x73 | x63 | x174 |
| Windy Bay[b] | 13.1 | 0 | 0 | - | 24 | 1 | 25 | - | - | - | 0.05 | - | - | - | - | - | - |
| Landrick[b] | 1.1 | 0.9 | 0.03 | 2.6 | 12 | 5 | 9 | 8 | 8 | 0 | 0.20 | 3.3 | 3.4 | 0 | x16 | x17 | 0 |
| Marshall[b] Head | 5.1 | 0 | 0 | - | 15 | 6 | 21 | - | - | - | 0.10 | - | - | - | - | - | - |
| Matheson[b] Head | 5.0 | 0 | 0 | - | 11 | 0 | 11 | - | - | - | 0.06 | - | - | - | - | - | - |
| Burnaby[b] | 5.8 | 0 | 0 | - | 14 | 3 | 17 | - | - | - | 0.07 | - | - | - | - | - | - |
| Two Torrent[b] | 2.4 | 0.2 | 0.02 | 16.0 | 30 | 4 | 23 | 11 | 11 | 0 | 0.24 | 3.1 | 3.4 | 0 | x13 | x14 | 0 |
| Thurston[b] Harbor | 1.3 | 1.7 | 0.02 | 11.0 | 61 | 13 | 1 | 73 | 46 | 27 | 0.02 | 3.5 | 2.5 | 12.3 | x182 | x128 | x638 |
| Total | 166.7 | 16.4 | 1.44 | 7.3 | 1193 | 144 | 807 | 530 | 433 | 97 | 0.12 | 4.1 | 3.6 | 9.2 | x34 | x30 | x76 |

[a] Data from air photographs flown in summer 1981.
[b] Data from air photographs flown in fall 1982.
[c] Watershed area steeper than 20°.
[d] Road areas are calculated from an average road width of 20 m.
[e] Inventory for these basins compiled by Bert Roberts.
[f] Only failures greater than .02 ha in area are recorded.

may not have experienced a rainfall event of sufficient magnitude to initiate mass wasting.

Because of root decay and the loss of support from the root mat, maximum frequencies of debris sliding from clearcut areas occur from 5 to 20 years following logging (Nakano 1971; Megahan et al. 1979; Yoshinori and Osamu 1984). These data suggest that those areas logged prior to 1973 (approximately 8 years old) may have exhibited peak or near maximum frequencies of mass wasting during the 1978 storm; a lower response may be expected from more recently logged areas. The effect of the average age of logging in individual basins on mass wasting frequency (Table 2) is shown on Figure 2(B).

### 2.5 Photography

The data for this study were collected from two different sets of aerial photographs, which covered 20 study basins on Moresby Island and seven on Graham Island. The locations of the basins are shown in Figure 1.

Data for the Rennell Sound basins (1-5 in Table 2, p. 9) were extracted from British Columbia Government black and white aerial photographs (BC81059 and BC81083) flown on July 22 and 24, 1981. Photographs were taken with a 305.09-mm focal length aerial camera from an altitude of 3500 m, and have a nominal scale of 1:11 000. Photo quality and basin coverage generally were very good.

Colour photographs (BCC325 and BCC326) were taken for basins 6-27 (Table 2) between August 27 and September 3, 1982. A 152.18-mm focal length camera was used at a flying height of approximately 2000 m. The photographs have a nominal scale of 1:13 000.[2] The quality of the prints varied (from very poor to very good) and depended on cloud conditions and time of day. Some lines of photography were flown in the early morning and have deep shadows in valley bottoms and on north, northeast, and northwest slopes as a result. Additional problems for

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[2] Aerial photographs are available from Map and Air Photo Sales, Survey and Mapping Branch, B.C. Ministry of Environment, Victoria, B.C.

interpretation were introduced by incomplete coverage of some basins (particularly Security Creek, Government Creek, and Thurston Harbour Creek).

## 2.6 Data Collection

Quantitative data were extracted from overlapping pairs of photographs set up in a WILD A6 stereoplotter. The WILD A6 is a precision instrument that rectifies aerial photographs from perspective projection to orthogonal projection. This allows true and precise measurement of horizontal distances, heights, and angles in the model formed by the overlapping aerial photographs. Rectification is achieved through interior and relative orientation procedures.

Measurements were taken after the stereo pair was relatively oriented -- a point at which a natural model, with a common vertical and horizontal scale, is created. As the stereo model is not absolutely leveled (that is, tied to surveyed ground control), it may be tilted or tipped relative to a geodetic zero datum, and the scale is not known exactly.

Because analysis was conducted basin by basin, all photo pairs covering the area within a given basin were viewed consecutively. For any given photo pair the area visible for classification and measurement was roughly 1 km wide by 2 km long. Most individual landslides were contained within a single stereo model.

Each failure was traced onto a mylar base sheet. Plan measurements of width and length were made directly from this tracing. The height of the terrain at changes of slope was recorded on the same sheet. Slopes were determined from tangents calculated from the difference in elevation and the distance between any two points.

Measurement inaccuracies can be due either to the inherent imprecision of the stereoplotter or to the error introduced by lack of absolute orientation, including both uncontrolled scale variation and tips or tilts. The machine limitations on accuracy are approximately 0.05 mm for vertical scale and 0.5 mm (ruler accuracy) for horizontal measurement, which, at a working map scale of 1:5000, translate to 0.3 m vertical error and 2.5 m horizontal error.

Error in the absolute tip or tilt of an individual stereo model relative to geodetic zero datum was less than 2° for almost all models. Although such errors did affect the accuracy of slope measurements, this error was small compared to the slopes measured -- ranging from 25 to 50° -- in the initiation zone of slides. Tips or tilts in the model had an insignificant effect on measurement of horizontal distance.

As mentioned earlier, measurements were made at an assumed scale of 1:5000. This scale was not determined for each model from known ground control points, but rather for several models, and a similar enlargement was applied to the remaining models. Consequently, scale may vary by as much as ±5% from one model to the next. This variation principally affects the measurement of distance and exceeds the inherent measurement error when distances over 50 m are measured. Scale variation has no influence on the determination of slope, as both vertical and horizontal measurements are affected equally.

## 2.7 Failure Description

The original intention of the project was to collect detailed information on all identifiable mass wasting events, but this was impractical in the case of revegetated slides and small events for two reasons. First, although slides may remain recognizable from the vegetation pattern for many years, once they are revegetated it is difficult to measure some important parameters, such as slopes, widths, and lengths in the initiation and transport zones. Additionally, large features may remain visible for a long time, while no record may remain of smaller events of a similar age. Because of the potential for age bias and the difficulty of extracting accurate data, detailed information was not collected for substantially revegetated landslides.

Second, because small slides can become obscured by vegetation in forested areas, it was necessary to impose a 200-$m^2$ minimum size limit on landslides to avoid bias in distinguishing between logged and forested areas. Also, those events less than 200 $m^2$ are less than 8 $mm^2$ at the working scale of 1:5000 -- a size at which it is difficult to distinguish events or collect quantitative data.

Consequently, the detailed information discussed in this report applies to those landslides larger than 200 $m^2$, with visible initiation and transport zones. The visibility requirement means that revegetation has not obscured the ground - (implying ages of approximately 40 years or less), and that the feature is clearly visible on both overlapping aerial photographs and is not badly shadowed.

### 2.7.1 Types of landslides

Episodic mass wasting events include rock slides, rotational slumps, earth flows, debris slides, and debris flows (Church 1983). Only debris slides and flows were numerically significant in the study basins.

Debris slides are shallow, rapid, downslope movements of unsaturated surficial material and organic debris (Varnes 1978). These events are initiated on steep slopes and often deposit material at changes in slope, on debris cones, or in valley bottoms. They include the debris avalanches and debris slides discussed by Swanston (1969), Swanston and Swanson (1976), Alley and Thomson (1978), and Wilford and Schwab (1982).

Debris flows are saturated or supersaturated flows of material, typically restricted to gullies (Varnes 1978). Debris flows, as used in this paper, are the debris torrents discussed by Swanston (1969), Swanston and Swanson (1976), and Wilford and Schwab (1982).

Slides and flows, as used in this paper, were distinguished on the aerial photographs by the appearance of the debris (signs of flowage or log levees), where the debris was deposited (slope, length of deposit), and the nature of the deposit. This simple classification was used because more subtle differences are often ambiguous on air photographs.

Debris slides were further subdivided according to the environment where they occur: open slope failures, gully headwall failures, gully sidewall failures, and active wall failures. The gully headwall was defined as the distinct land facet upslope of the incised portion of the gully. This area contributes water and materials to the gully and is, in effect, the gully drainage area. Gully sidewall failures initiate on the wall of the incised portion of the gully. Active wall failures include those events where the debris is not visible and the scar may represent a debris slide, an exposure of bedrock, or a laterally extensive portion of ravelling gully wall.

A common situation in the study area was for a debris flow to be initiated by a gully headwall or sidewall debris slide. Both the flow and the slide were listed and described separately when they could be distinguished.

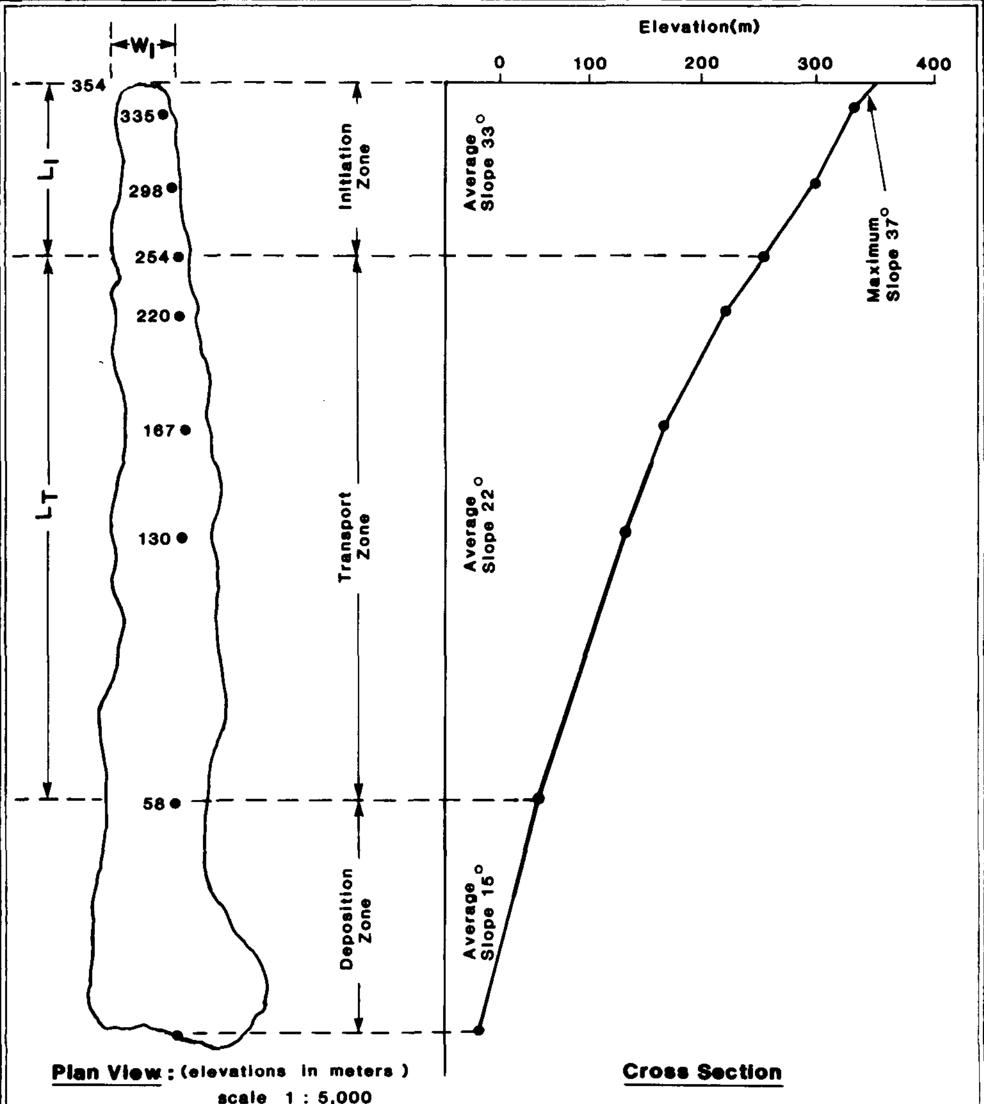
#### 2.7.2 Environmental descriptors

Slides were classified as either clearcut or forested failures. Clearcut logging is the only silvicultural system used on the Queen Charlotte Islands.

Events were further divided into open slope or gully categories. Those landslides occurring in logged areas were classified as clearcut, road-related, or cut boundary failures. Clearcut failures included all events not related to roads or cut boundaries. Road-related failures included failures in fill and cut, and also failures associated with drainage diversion where these could be identified.

#### 2.7.3 Failure descriptors

For the purposes of estimating volumes and describing slides, failures were subdivided into initiation, transport, and deposition zones (Figure 3). Generally, the initiation zone is an area of complete scour, typically including the steepest part of the




**Example Calculation:**

From Initiation Zone $= \dfrac{L_I \cdot \overline{W}_I \cdot D_I}{\cos \theta_I} = \dfrac{155\,m \cdot 50\,m \cdot 0.5\,m}{\cos 33^\circ} = 4600\,m^3$

From Transport Zone $= \dfrac{L_R \cdot \overline{W}_R \cdot D_R}{\cos \theta_R} = \dfrac{475\,m \cdot 80\,m \cdot 0.25\,m}{\cos 22^\circ} = 10200\,m^3$

Total Volume $= 4600 + 10200 = 14800\,m^3$

FIGURE 3. Volume estimation from a typical debris slide.

failure. The transport zone is an area of lower gradient and for debris slides may be an area of deposition and scour. For debris flows, the transport zone is the scoured portion of the channel. The deposition zone is where material from the initiation and transport zones is deposited.

In some cases these zones were distinct; in others they were not. Often the division between the initiation and transport zone is based simply on changes of slope along the failure. For smaller features these zones are often indistinguishable and measurements were often recorded as belonging to the initiation zone.

### 2.7.4 Volume of events

The total volume entering the depositional zone was determined from measurement of the volume in the depositional zone or, more commonly, from a combination of widths, lengths, and estimated depths of the initiation and transport zones. The volume exiting the initiation zone was estimated as:

$$\text{length} \times \text{width} \times \text{depth} \times 1/\cos\theta.$$

The volume contributed from the transport zone was calculated in a similar manner. Lengths, widths, and slopes were measured from the 1:5000 working maps. Depths were:

Initiation depth: Smith *et al*. (1983), from measurements on 45 failures, determined the average depth of soil removal from the initiation zone to be 0.44 m. As this depth corresponded roughly to the vertical resolution of the stereoplotter, it was not possible to estimate directly the depth of soil removal on different failures. The initiation depth was assumed to be 0.5 m for almost all events. Occasionally, the general appearance of the landslide indicated depths different than average and, for these events, depths were estimated as either 0.25, 1.0, or 2.0 m.

Field investigations by the author in January and May 1983, and by the Forest Engineering Research Institute of Canada (FERIC) in the summer of 1983, were used to confirm some depth estimates from the aerial photography.

Transport depth: For debris slides the transport zone is an area of mixed scour and deposition. The transport depth was assumed to be equal to one-half the depth in the initiation zone. For debris flows the transport depth was calculated from the volume in the deposition zone and the approximate surface area of the transport zone, or an average value based on other flows was used.

When the volume of material in the depositional zone could be measured from the aerial photographs, this was used in conjunction with the surface area of the failure to calculate the depth of material yielded by the failure. These calculations were used to confirm the depth estimates previously discussed. Note that estimates of the volume of deposited material included organic debris, which in some cases can comprise a large portion of the total debris. This organic component was not directly included in volume estimates calculated from measurement of the initiation and transport zones.

2.7.5 Volume entering streams

Streams were defined as channel reaches with gradients less than 10% (6°). Consequently, the headward extensions of the stream net were referred to as "gullies" and failure material that entered and remained in a gully was not considered to have entered the "stream". Only the larger materials involved in the slide were considered, as information concerning the disposition of fine materials and fluvial reworking of materials could not be obtained from this scale of photography.

Reaches of stream were classified into three groups on the basis of gradient: 0.1-1%; 1-3%; and 3-10%. The classification follows Church (1983) in part, but differs in the gradient classes and in the emphasis on gradient. Gradient was used to categorize different reaches rather than valley flat width or the presence of a footslope.

Failure volumes entering streams were estimated to be either 1/10, 1/3, 2/3, or all of the landslide volume.

## 2.8 Ground Confirmation

In the summer and fall of 1983, FERIC personnel collected field measurements on a subset of the clearcut failures identified from the aerial photographs. Field observations were collected from the Bonanza Creek, Talunkwan Island, Tarundl Creek, MacMillan Creek, South Bay Dump Creek, and Sachs Creek watersheds. These data were used to confirm the location and volume of failures examined on the aerial photographs.

### 2.8.1 Location of failures

A total of 66 failures are available for comparison of the location of the initiation zone of the failures. Event types include open slope debris slides, gully headwall debris slides, gully sidewall debris slides, active wall debris slides, and debris flows. Events in logged areas were classified into four categories:

Road-related: Of the 19 events identified by FERIC as road-related, 13 were identified as such from the aerial photographs, five as clearcut gully failures, and one as an open slope failure. The underestimation of the number of road-related events in this study appears to be related to the description of some events distant from the road right-of-way as initiated by drainage diversion. These events are difficult to identify in the field, and very difficult to identify on the aerial photography.

Clearcut gully: Of their 20 clearcut gully failures, 18 were identified on the aerial photographs as such, while the other two failures were identified as road-related. On the aerial photographs these two failures appeared to occur on road fill, but they apparently began beyond this zone.

Clearcut open slope: Of the 24 open slope failures identified by FERIC, in this study 13 were identified as open slope, eight as clearcut gully failures, one as road-related, and two as boundary-related. FERIC outlined a very limited headwall area; many of their open slope events passed into gullies.

Cut boundary-related: There appears to be a problem with events identified as boundary-related failures. Of the five events that this study identified as boundary-related, and that were subsequently examined by FERIC personnel, three began above the boundary in the forested area and two began below the boundary in the clearcut area.

The field survey of failures carried out by FERIC indicated a satisfactory classification of failure locations from the aerial photography. The number of road-related failures due to drainage diversion were probably underestimated. In addition, many of the boundary-related failures identified on the aerial photographs may have begun above the boundary in forested terrain or below the boundary in clearcut.

### 2.8.2 Volume of failures

The 66 failures include events of the following types: open slope debris slides (24), gully headwall debris slides (18), gully sidewall debris slides (7), active wall debris slides (14), and debris flows (3). Of this total data set, 40 failures were selected for comparison of volumes (Figure 4).

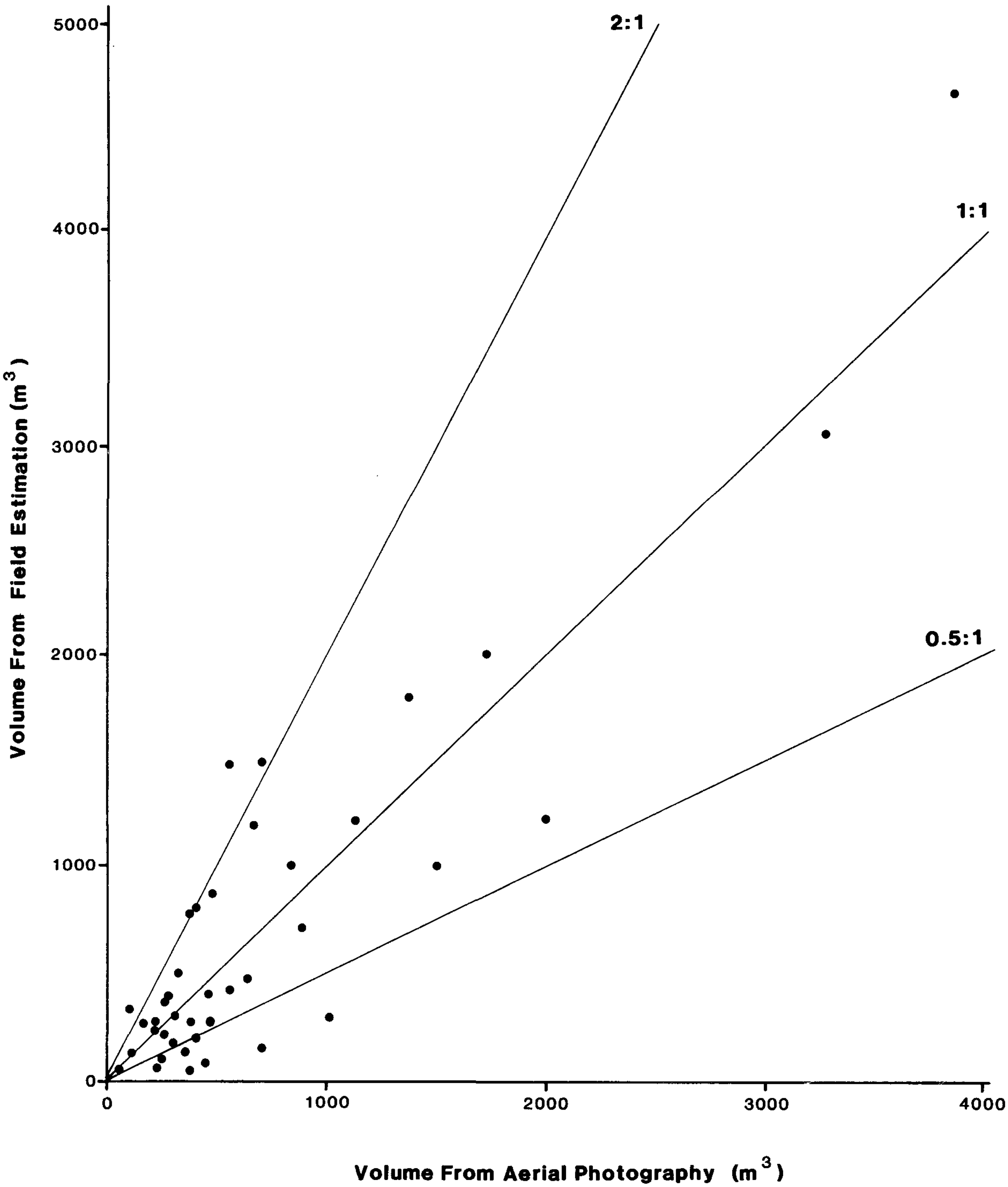



FIGURE 4. The relation between the volume of failures, determined from field surveys and air photograph estimations.

The data set was reduced for the following reasons: first, active wall events were not included because they are often areas of dry ravel for which it is not possible to estimate the yield of material from aerial photographs. An additional 12 failures were not included, in some cases because volumes estimated in the field and from the aerial photographs were for different slide areas; and in other cases, where a debris slide initiated a debris flow, because the field and air photograph measurements often attributed different portions of the total volume to the slide and to the debris flow.

The various statistical measures calculated for the total data and portions of the data set are described in Table 3. These include:

Average difference: The average difference -- the mean of the differences between the volumes determined by FERIC and those from air photographs -- was calculated for two sets of slides. For those slides where the field-determined volume was less than 1000 $m^3$, the average volume determined from air photography exceeded that from field measurement by 84 $m^3$. For the total data set the average difference declined to -15 $m^3$. Overall, the average volume determined from aerial photographs tends to slightly underestimate that determined from field measurements.

Standard deviation: This measure gives extra weight to extremes and provides approximate confidence bounds for the average differences. The standard deviation was determined for two sets of slides. For the smaller slides (FERIC volume less than 1000 $m^3$) the calculated RMS error was 291 $m^3$. An assumed normal distribution of average differences implies that 70% of the average differences are between -207 and 375 $m^3$ for these smaller slides. For the total data set the observed RMS error was 399 $m^3$. For all failures the bulk of the average differences lies between -414 and +384 $m^3$.

TABLE 3. Statistical measures used to compare the volume estimates of failures from aerial photography and field surveys

Variables

O = volume observed from aerial photography

E = volume observed in the field

N = number of events

Average difference:

$$A.D. = \frac{\sum_{i=1}^{N} (O-E)}{N}$$

Standard deviation:

$$\sigma = \left\{ \frac{\sum_{i=1}^{N} (O-(E+A.D.)}{N} \right\}^{1/2}$$

Bias ratio:

$$B.R. = \frac{\sum_{i=1}^{N} \frac{(O-E)}{E}}{N}$$

Table of values

| Range of volumes | N | A.D. | $\sigma$ | B.R. |
|---|---|---|---|---|
| $45 > E > 1000\ m^3$ | 30 | +84 | 283 | - |
| all slides | 40 | -15 | 390 | - |
| $45 \geq E > 500\ m^3$ | 24 | - | - | 1.26 |
| $500 \geq E > 1000\ m^3$ | 6 | - | - | -0.20 |
| $E \geq 1000\ m^3$ | 10 | - | - | -0.17 |

Bias ratio: This is a relative measure and is the sum of the average differences divided by the volume determined from field measurement for each failure. In essence, the measure represents the average percentage overestimate or underestimate of the field-determined volume.

For the small slides (field volume less than 500 $m^3$), the average bias measure was 1.26. For these small slides the biases are large and positive and the air photograph estimates exceed those determined from field measurement. For mid-size failures (field volume between 500 and 1000 $m^3$) and the larger failures (field volume greater than 1000 $m^3$), the average bias measures are similar -- both approximately -0.2. For these size of events the average bias measure implies that air photograph estimates are typically 20% smaller than the volumes determined from field estimates.

The following conclusions are drawn from the ground confirmation of volumes:

1. Total volumes determined from aerial photographs for a reasonable number and size range of failures are equivalent to the field measurements.
2. The bulk of the differences between the volumes estimated from aerial photographs and from field measurements for all failures should typically be between $\pm 400$ $m^3$. The average difference of smaller events is positive, suggesting that air photograph estimates often exceed field estimates for smaller failures.
3. Different biases are observed for different size ranges of events. For small events the volume determined from air photographs is larger than from field estimate. For mid-size and larger events, air photograph estimates of volume are, on average, less than the field estimates. Bias estimates are variable for individual slides.

# 3 RESULTS

## 3.1 Mass Wasting Frequency

### 3.1.1 The number of mass wasting events

A total of 1573 features were enumerated in the 350 $km^2$ of logged and forested terrain examined. Of these 1573 features, 1337 were included in the detailed inventory that comprises the data set discussed in this section. Of the remaining 236 events, 179 were revegetated and 57 were either shadowed or occurred outside the area of stereo coverage for the basins.

The overall frequency of mass wasting events in the study area, based on the 1573 events, was 4.5 failures per square kilometre. This is 70% greater than the estimate of 2.6 failures per square kilometre obtained by Gimbarzevsky (1983), based on his average frequency calculated on UTM cells. His land base was 2500 $km^2$ and included only 1-$km^2$ blocks of terrain where failures were observed. His regional data were extracted from 1:50 000 scale photography and the minimum detectable size was much larger than in this study.

### 3.1.2 The frequency of mass wasting in the study basins

The frequencies (number per square kilometre per year) of landsliding for each drainage basin are summarized in Table 2.

The failure frequency from forested steeplands ranged from a low of 0.02 events per square kilometre per year (Tarundl and Thurston Harbor creeks) to maximum values of 0.25 and 0.30 landslides per square kilometre per year (South Bay Dump Creek and Armentieres Creek, respectively). High values are observed in South Bay Dump Creek, since nearly all the basin has been clearcut and only unstable terrain is left forested. Mass wasting frequency from forested terrain in 12 of the remaining 23 basins varied between 0.09 and 0.20 events per square kilometre per year.

The frequency of failures on clearcut steeplands, ranged from a minimum of 0.59 (Mosquito Creek Tributary), to maximums of 9.0 (Riley Creek) and 11.1 (Cache Creek) events per square kilometre per year. Ten of the remaining basins had failure frequencies ranging from 2.1 to 5.4 events per square kilometre per year. The distribution of forested and steepland areas with different mass wasting frequencies is shown on Figure 5. Note that the minimum observed frequency from clearcuts is approximately twice as large as the maximum from forested steeplands.

Road-related failure frequencies in the study basins are more variable than those from either forested or clearcut terrain. Of the 17 logged basins, nine have no road-related failures. In some of the basins -- Mosquito Creek Tributary and Armentieres and Mountain creeks -- roads were only built on the valley bottoms. Failure frequencies in basins that have steepland roads range from 1.9 events per square kilometre per year (Tarundl Creek) to 20.1 events per square kilometre per year (Talunkwan Creek).

### 3.1.3 Mass wasting frequency of different event types

Table 4 summarizes the frequency of failure for different event types in forested, clearcut, and roaded terrain. In the clearcut portion of the logged areas, accelerations for the four types of debris slides are very similar, varying from 23 to 31 times. Schwab (1983) observed an acceleration of 28 times following the 1978 multi-day rainstorm at Rennell Sound for clearcut debris avalanches yielding greater than 100 $m^3$.

Clearcutting accelerated the frequency of debris flows 41 times. Comparable values from other Pacific Northwest regions follow:

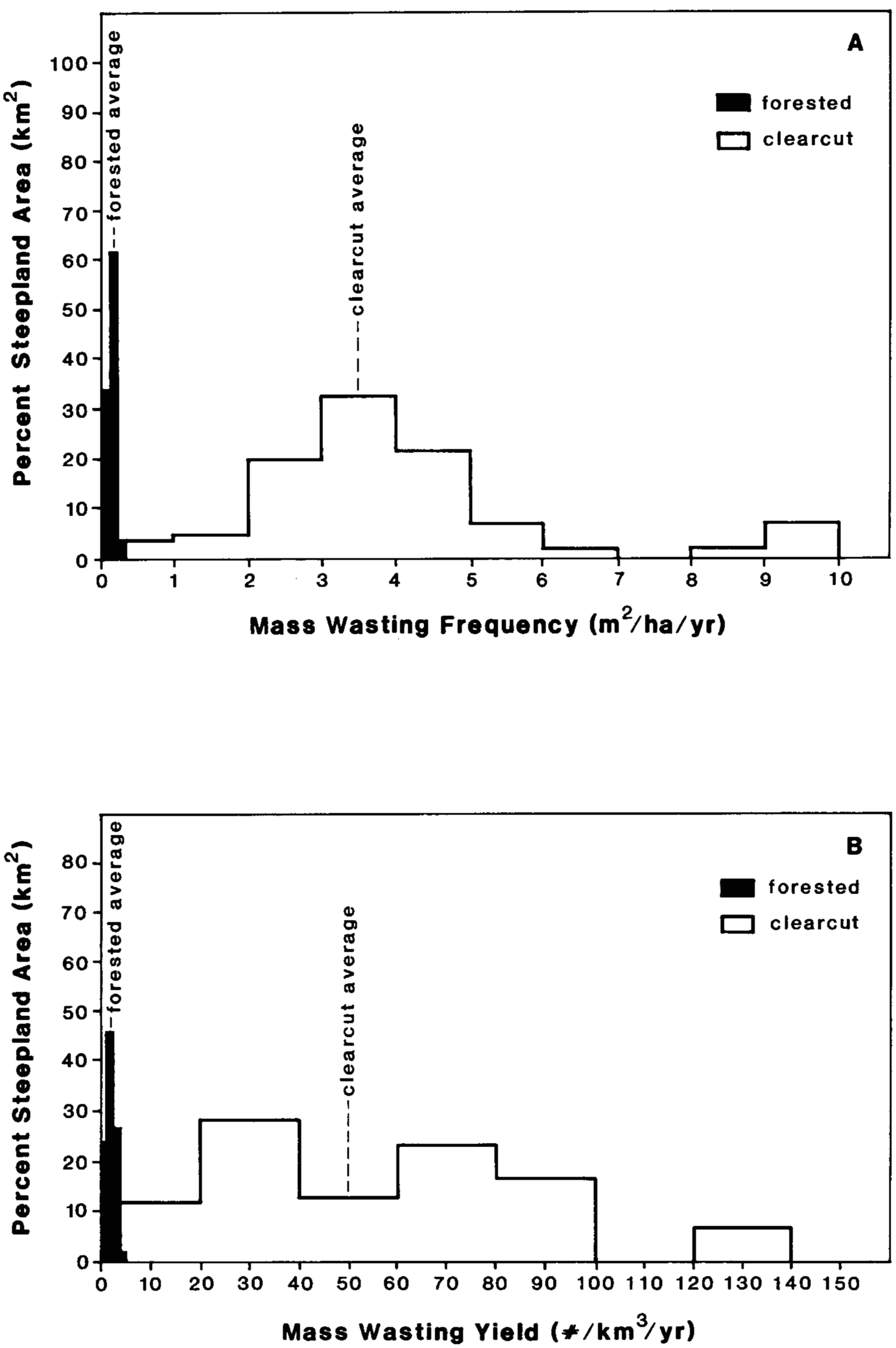



FIGURE 5. The distribution of mass wasting frequency and yield for forested and clearcut areas. (A) Proportion of steepland areas with different frequencies. (B) Proportion of steepland areas with different yields.

TABLE 4. The number and frequency of mass wasting events by failure location and type in forested and logged terrain, in the Queen Charlotte Islands study basins

| | Forested area[a] | | | Logged area[bc] | | | Clearcut area[c] | | | Road area[c] | | | Rate relative[d] to forested area | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. | No./km$^2$ | No./km$^2$/yr | No. | No./km$^2$ | No./km$^2$/yr | No. | No./km$^2$ | No./km$^2$/yr | No. | No./km$^2$ | No./km$^2$/yr | Logged | Clearcut | Road |
| Debris slide open slope | 295 | 1.77 | 0.044 | 239 | 13.4 | 1.84 | 165 | 10.1 | 1.38 | 74 | 5.14 | 7.04 | x42 | x31 | x159 |
| Debris slide gully headwall | 186 | 1.12 | 0.028 | 104 | 5.83 | 0.78 | 92 | 5.61 | 0.77 | 12 | 8.33 | 1.14 | x29 | x28 | x41 |
| Debris slide gully sidewall | 146 | 0.88 | 0.022 | 62 | 3.48 | 0.48 | 61 | 3.72 | 0.51 | 1 | 0.69 | 0.10 | x22 | x23 | x4 |
| Debris slide active wall | 102 | 0.61 | 0.015 | 58 | 3.25 | 0.45 | 57 | 3.48 | 0.48 | 1 | 0.69 | 0.10 | x29 | x31 | x6 |
| Debris flow | 78 | 0.47 | 0.012 | 67 | 3.76 | 0.51 | 58 | 3.53 | 0.48 | 9 | 6.25 | 0.86 | x43 | x41 | x73 |
| Total | 807 | 4.84 | 0.12 | 530 | 29.7 | 4.1 | 433 | 26.4 | 3.6 | 97 | 67.4 | 9.2 | x34 | x30 | x76 |

a Forested area assumes 40-year record.
b Man-modified terrain (clearcuts plus roads).
c Assumes average 7.3 years of record.
d Acceleration based on no./km$^2$ per yr.

| | Frequency of debris flows | | Acceleration |
|---|---|---|---|
| | Forested (No./km$^2$/yr) | Clearcut (No./km$^2$/yr) | |
| Morrison (1975) | .005 | .044 | x8.8 |
| Swanston and Swanson (1976) | .008 | .036 | x4.5 |
| This study | .012 | 0.48 | x41 |

Frequencies of debris flows in forested terrain are similar for the three studies. The larger accelerations observed on the Queen Charlotte Islands are a result of the greater frequency of debris flows in clearcut terrain. This may be due, in part, to the greater increase in triggering events -- open slope and gully debris slides -- which occurs with clearcutting in the Queen Charlotte Islands (Section 3.2.4).

Road areas also accelerate the occurrence of open slope debris slides and debris flows. The frequency and acceleration of debris flows from roads in the Queen Charlotte Islands are comparable to those of Morrison (1975) and Swanston and Swanson (1976). They observed debris flow frequencies of 0.67 and 0.34 events per square kilometre per year; accelerations were 133 and 42 times.

The frequency of events entering streams (Table 5) is accelerated by logging, but not to the same extent as logging accelerates the overall frequency of landsliding. The frequency of events observed in logged terrain, relative to forested terrain, was 34 times greater; the frequency of events entering streams from logged areas was accelerated 23 times.

In forested terrain 40% of the events entering streams are open slope slides. Gully headwall slides and debris flows accounted for approximately 40% of the remaining events entering streams each year. In clearcut and road areas a nearly equal contribution to streams was observed for these three event types. Gully sidewall and

TABLE 5. The number and frequency of mass wasting events entering streams, by failure location and type, for forested and logged terrain, in the Queen Charlotte Islands study basins

| | Forested area[a] | | | Logged area[bc] | | | Clearcut area[c] | | | Road area[c] | | | Rate relative[d] to forested area | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. | No./$km^2$ | No./$km^2$/yr | No. | No./$km^2$ | No./$km^2$/yr | No. | No./$km^2$ | No./$km^2$/yr | No. | No./$km^2$ | No./$km^2$/yr | Logged | Clearcut | Road |
| Debris slide open slope | 109 | 0.65 | .016 | 39 | 2.19 | 0.30 | 27 | 1.65 | 0.23 | 12 | 8.33 | 1.14 | x18 | x14 | x70 |
| Debris slide gully headwall | 58 | 0.35 | .009 | 36 | 2.02 | 0.28 | 30 | 1.83 | 0.25 | 6 | 4.17 | 0.57 | x31 | x29 | x66 |
| Debris slide gully sidewall | 21 | 0.13 | .003 | 6 | 0.34 | 0.05 | 6 | 0.37 | 0.05 | 0 | 0 | 0 | x15 | x16 | 0 |
| Debris slide active wall | 31 | 0.19 | .005 | 9 | 0.50 | 0.07 | 9 | 0.55 | 0.08 | 0 | 0 | 0 | x15 | x16 | 0 |
| Debris flow | 45 | 0.27 | .007 | 29 | 1.63 | 0.22 | 24 | 1.34 | 0.18 | 5 | 3.47 | 0.48 | x33 | x27 | x70 |
| Total | 264 | 1.58 | .040 | 119 | 6.67 | 0.91 | 96 | 5.85 | 0.80 | 23 | 15.97 | 2.19 | x23 | x20 | x55 |

[a] Forested area assumes 40-year record.
[b] *Man-modified terrain* (clearcuts plus roads).
[c] Assumes average 8 years of record.
[d] Acceleration based on no./$km^2$ per yr.

active wall debris slides contributed few of the events entering streams from forested and clearcut areas, and none from roads.

Despite a large contribution to the number of failures entering streams, the lowest acceleration for events entering streams from clearcut areas occurred for the open slope debris slides. The acceleration of debris flows entering streams from clearcuts was twice that of open slope debris slides.

Only open slope debris slides, gully headwall debris slides, and debris flows entered streams from road areas. Similar accelerations, ranging from 66 to 70 times, were observed for each type.

## 3.2 Debris Volumes Associated with Failure Events

Table 6 shows the average annual volume yield from each of the study basins. This data set is based on the 1337 failures discussed in Section 2.1.1.

### 3.2.1 Annual volume yields

The total estimated volume of material delivered from the forested steeplands was 1 097 350 $m^3$, or 6600 $m^3/km^2$. This amounts to approximately 9900 tonnes/$km^2$, based on an assumed density of 1500 $kg/m^3$. For forested slopes, the average rate of mass wasting by episodic processes was found to be 1.6 $m^3$/ha per year or 2.5 tonnes/ha per year.

The total volume of mass wasting from the logged area was estimated to be 757 750 $m^3$. This represents a yield of 41 500 $m^3/km^2$, or 63 700 tonnes/$km^2$. Annual landsliding from the logged portion of the study basins involved 58.2 $m^3$/ha per year or 87 tonnes/ha per year. By comparison, Pierson (1977) observed a yield of 0.2 tonnes/ha per year from logged areas in the Oregon Coast Range.

TABLE 6. Mass wasting annual volume yield for the study basins on the Queen Charlotte Islands

| Basin name | Forested area | | Logged area[a] | | Clearcut area | | Road area[b] | | Effect of logging on yield | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Logged[a] | | Clearcut | | Roads | |
| | Total yield ($m^3$/ha/yr) | Yield to streams ($m^3$/ha/yr) | Total yield ($m^3$/ha/yr) | Yield to streams ($m^3$/ha/yr) | Total yield ($m^3$/ha/yr) | Yield to streams ($m^3$/ha/yr) | Total yield ($m^3$/ha/yr) | Yield to streams ($m^3$/ha/yr) | Total | Streams | Total | Streams | Total | Streams |
| Hangover | 1.4 | 0.6 | - | - | - | - | - | - | - | - | - | - | - | - |
| Bonanza | 1.3 | 0.4 | 43.6 | 4.3 | 40.3 | 4.8 | 67.4 | 0 | x33 | x12 | x30 | x13 | x51 | 0 |
| Gregory | 2.6 | 1.0 | 23.6 | 9.7 | 28.3 | 11.7 | 0 | 0 | x9 | x10 | x11 | x12 | 0 | 0 |
| Cache | 0 | 0 | 66.7 | 0 | 66.7 | 0 | 0 | 0 | undefined | | | | | |
| Riley | 1.5 | 0.5 | 114.3 | 46.4 | 124.7 | 54.1 | 52.0 | 0 | x77 | x92 | x84 | x108 | x35 | 0 |
| Mountain | 0.9 | 0.2 | 7.5 | 0.2 | 7.5 | 0.2 | 0 | 0 | x8 | x.7 | x8 | x.7 | 0 | 0 |
| Tarundl | 0.1 | 0.07 | 6.0 | 1.8 | 6.8 | 1.8 | 3.8 | 1.9 | x59 | x25 | x67 | x25 | x37 | x25 |
| Piper | 0 | 0 | - | - | - | - | - | - | - | - | - | - | - | - |
| Sachs | 1.8 | 0.8 | 45.1 | 20.0 | 32.0 | 7.9 | 240.7 | 202 | x25 | x26 | x18 | x10 | x132 | x257 |
| MacMillan | 0.3 | 0.2 | 78.3 | 50.0 | 74.6 | 53.1 | 133.3 | 2.8 | x282 | x277 | x269 | x294 | x480 | x15 |
| South Bay Dump | 4.8 | 3.3 | 61.9 | 35.1 | 35.9 | 11.2 | 545.5 | 478.4 | x13 | x11 | x7 | x3 | x114 | x147 |
| Mosquito Tributary | 0.8 | 0.1 | 2.7 | 0.2 | 2.7 | 0.2 | 0 | 0 | x3 | x2 | x3 | x2 | 0 | 0 |
| Government | 1.2 | 0.5 | - | - | - | - | - | - | - | - | - | - | - | - |
| Armentieres | 4.8 | 3.5 | 6.0 | 0.5 | 6.0 | 0.5 | 0 | 0 | x1 | x0.1 | x1 | x0.1 | 0 | 0 |
| Security | 1.8 | 0.3 | 67.9 | 0 | 74.7 | 0 | 0 | 0 | x38 | 0 | x42 | 0 | 0 | 0 |
| Jason | 2.4 | 0.8 | - | - | - | - | - | - | - | - | - | - | - | - |
| Inskip | 2.7 | 1.2 | - | - | - | - | - | - | - | - | - | - | - | - |
| Crazy | 1.3 | 0.04 | - | - | - | - | - | - | - | - | - | - | - | - |
| Talunkwan | 0.9 | 0.3 | 94.4 | 43.2 | 73.9 | 29.2 | 368.3 | 229.9 | x102 | x150 | x80 | x101 | x398 | x800 |
| Powrivco | 0.1 | 0 | 95.8 | 20.2 | 97.2 | 18.2 | 80.8 | 42.3 | x652 | - | x661 | - | x549 | - |
| Windy Bay | 0.6 | 0.4 | - | - | - | - | - | - | - | - | - | - | - | - |
| Landrick | 3.2 | 2.3 | 63.3 | 44.3 | 65.4 | 45.7 | 0 | 0 | x20 | x19 | x20 | x20 | 0 | 0 |
| Marshall Head | 2.2 | 1.0 | - | - | - | - | - | - | - | - | - | - | - | - |
| Matheson Head | 0.7 | 0.06 | - | - | - | - | - | - | - | - | - | - | - | - |
| Burnaby | 2.1 | 1.2 | - | - | - | - | - | - | - | - | - | - | - | - |
| Two Torrent | 3.4 | 2.5 | 57.4 | 49.7 | 63.1 | 54.7 | 0 | 0 | x17 | x20 | x19 | x22 | 0 | 0 |
| Thurston Harbour | 1.5 | 0 | 97.9 | 59.9 | 83.1 | 60.1 | 135.9 | 4.5 | x65 | - | x55 | - | 91 | - |
| Total | 1.6 | 0.6 | 58.2 | 27.6 | 50.7 | 23.5 | 143.6 | 74.9 | x35 | x43 | x31 | x37 | x87 | x117 |

[a] Logged area includes all man-modified terrain (clearcut plus roads).
[b] Road areas are calculated from an average road width of 20 m.

The total annual volume of mass wasting from logged areas was apparently 35 times larger than from forested areas. Of the total volume from logged areas, approximately 606 800 $m^3$ were from clearcuts and 150 950 $m^3$ were from road-related failures. The volume observed from clearcut areas was approximately 4 times that from roads. On an areal basis, clearcut steeplands yielded 50.7 $m^3$/ha per year; roads yielded 143.6 $m^3$/ha per year, based on an assumed 20-m road right-of-way width. Accelerations associated with clearcut and roads were thus calculated at 31 and 87 times, respectively.

The overall annual volume yield to streams from forested steeplands was estimated to be 0.6 $m^3$/ha per year. From logged areas the yield was 27.6 $m^3$/ha per year; from clearcut areas, 23.5 $m^3$/ha per year; and from road areas, 74.9 $m^3$/ha per year. The accelerations of yield to streams from logged area (43 times), clearcut areas (37 times), and roads (117 times) were slightly larger than the observed accelerations for the same land categories for total yield. As noted in Section 3.1.1, the acceleration of frequency of events entering streams as a result of logging was smaller than the acceleration of frequency of the total number of events. This in turn suggests that to produce the greater accelerations of yield to streams, the events entering streams from logged areas must be larger in size than those from forested terrain (see Section 3.2.4).

Annual yields from forested, clearcut, and road areas for each of the 27 basins are summarized in Table 6 (also Figure 5). The acceleration of mass wasting as a result of clearcutting ranges from minimums in Armentieres (1 times) and Mosquito Tributary (3 times) to maximums in Powrivco Creek (661 times) and MacMillan Creek (269 times). Other areas with low accelerations are South Bay Dump Creek (7 times) and Mountain Creek (8 times). Yields from logged areas in these basins were similar to other nearby basins, and accelerations were low due to the high yield from forested areas. Accelerations of total yield from roads ranged from a low in Tarundl Creek (35 times) to a maximum in Powrivco Creek (549 times). Road-related failures were observed in nine of the 12 basins with steeplands roads.

### 3.2.2 Geology and yield from forested steeplands

The influence of the different geologic formations (Table 1) on the yield from forested steeplands is shown in Table 7.

TABLE 7. The influence of geologic formation on the yield from forested terrain in the Queen Charlotte Islands study basins

| Formation | No. of basins | Steepland forested area ($km^2$) | Weighted average yield ($m^3$/ha/yr) | Minimum yield ($m^3$/ha/yr) | Maximum yield ($m^3$/ha/yr) |
|---|---|---|---|---|---|
| Masset (soft volcanics) | 8 | 64.4 | 1.5 | 0.6 | 2.6 |
| Karmutsen (hard volcanics) | 8 | 60.3 | 2.0 | 0.7 | 4.8 |
| Haida (sedimentaries) | 4 | 7.6 | 2.0 | 0.3 | 4.8 |
| PTP (granites) | 2 | 15.6 | 1.3 | 0.9 | 2.1 |

Basins dominated by the Masset formation include those in Rennell Sound -- Hangover, Bonanza, Gregory, and Cache creeks -- and those from Talunkwan and Lyell islands. Those basins dominated by the Karmutsen formation are on Moresby Island, as are those with the Haida formation as their dominant geology.

Weighted average yields for the different formations vary from a minimum of 1.3 $m^3$/ha per year from the PTP, to a maximum of 2.0 $m^3$/km per year from the Karmutsen and Haida. However, the variation of yields observed for the different basins dominated by each formation suggests that the average yields are not significantly different and that these different formations produce similar yields. Similarly, there is no difference between yields from the two physiographic regions.

This, in turn, simplifies the interpretation of changes in mass wasting frequencies and yields following clearcut logging. If similar yields are derived from different regions and geologies, then the comparison of logging data from all clearcuts with the overall set of mass wasting events from forested terrain is not confounded by differences in the proportions of geologic formations or physiographic regions.

### 3.2.3 Mass wasting annual yields of different event types

In both the logged and forested steepland area, the majority of the total yield is from open slope debris slides and debris flows (Table 8). These features contributed 73% of the total annual yield in forested terrain and 86% in logged areas.

The overall average size of a mass wasting event varies only slightly from forested to clearcut terrain: from 1360 to 1400 $m^3$. However, within each event category the change in the average size of failures is quite variable. Debris slides in clearcut areas averaged 42% of their size in forested terrain. This smaller average size may reflect, in part, the ease of identifying smaller events in clearcut terrain. As well, root mat strength may impose a higher areal threshold for failure in forested terrain. Gully headwall debris slides showed a similar variation in average size between forested and logged terrain. The average size of gully sidewall and active wall debris slides were unchanged following logging.

There was a large difference in the average size of debris flows in forested and logged terrain. The average flow in logged terrain yielded 50% more debris and sediment than in forested terrain. This increase may have been due to a number of factors, such as an increased amount of debris in gullies (from logging slash, road fills, and destabilized gully walls) following logging, or an increase in the number of larger failures occurring. Increases in the average size of debris flows did not appear to be related to increased transport lengths in logged areas (Table 9).

TABLE 8. Mass wasting volume and yield, by failure location and type, in forested and logged terrain, in the Queen Charlotte Islands study basins

| | No. | Forested area[a] | | | No. | Logged area[b] | | | No. | Clearcut area[b] | | | No. | Road area[b] | | | Rate relative to forested area[c] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total volume ($m^3$) | Average volume ($m^3$) | Yield ($m^3$/ha/yr) | | Total volume ($m^3$) | Average volume ($m^3$) | Yield ($m^3$/ha/yr) | | Total volume ($m^3$) | Average volume ($m^3$) | Yield ($m^3$/ha/yr) | | Total volume ($m^3$) | Average volume ($m^3$) | Yield ($m^3$/ha/yr) | Logged | Clearcut | Road |
| Debris slide open slope | 295 | 426 350 | 1450 | 0.6 | 239 | 174 000 | 730 | 13.4 | 165 | 100 500 | 610 | 8.4 | 74 | 73 500 | 990 | 69.9 | x21 | x13 | x109 |
| Debris slide gully headwall | 186 | 167 150 | 900 | 0.3 | 104 | 50 950 | 490 | 3.9 | 92 | 41 500 | 450 | 3.5 | 12 | 9 450 | 790 | 9.0 | x16 | x13 | x36 |
| Debris slide gully sidewall | 146 | 55 700 | 380 | 0.1 | 62 | 18 600 | 300 | 1.4 | 61 | 17 700 | 290 | 1.5 | 1 | 900 | 900 | 0.9 | x17 | x18 | x10 |
| Debris slide active wall | 102 | 78 350 | 770 | 0.1 | 58 | 41 500 | 720 | 3.2 | 57 | 41 300 | 720 | 3.4 | 1 | 200 | 200 | 0.2 | x27 | x29 | x2 |
| Debris flow | 78 | 369 800 | 4740 | 0.6 | 67 | 472 700 | 7060 | 36.3 | 58 | 405 800 | 7000 | 33.9 | 9 | 66 900 | 7430 | 63.6 | x65 | x61 | x114 |
| Total | 807 | 1 097 350 | 1360 | 1.6 | 530 | 757 750 | 1430 | 58.2 | 433 | 606 800 | 1400 | 50.7 | 97 | 150 950 | 1560 | 143.6 | x35 | x31 | x87 |

a Yields in forested areas are calculated from 40-year record.
b Yields in logged areas are calculated from 7.3 year average age .
c Accelerations based on yield.

TABLE 9. Length of scour by debris flows from forested and logged terrain in the Queen Charlotte Islands and other Pacific Northwest regions

| | Forested area | | Clearcut area | | Road area | |
|---|---|---|---|---|---|---|
| | Average length (m) | Range (m) | Average length (m) | Range (m) | Average length (m) | Range (m) |
| Swanston and Swanson (1976) | 610 | 100-2280 | - | - | - | - |
| Schwab (1983) | 420 | 60-1000 | 380 | 120- 800 | 470 | 75-610 |
| This study | 370 | 75-1200 | 330 | 35-1400 | 280 | 50-660 |

Accelerations of the different event types varied around the average acceleration of 31 times in clearcut areas. The accelerations of the debris slides were all below the average, and ranged between 13 (open slope and gully headwall) and 29 (active wall) times. The acceleration of the yield of debris flows was 61 times, due to the highest acceleration of frequency of occurrence (41 times), combined with the increased average size of events. The acceleration of yield of debris slides in clearcut terrain is much lower despite a similar acceleration of frequency of occurrence (approximately 30 times) because of the decreased average size of open slope and gully debris slides in clearcut terrain.

A large variation occurred in the accelerations of the different event categories for road areas. Nearly all the total yield from this land category was from open slope debris slides and debris flows. Accelerations for these event types were 109 times for open slope debris slides and 114 times for debris flows.

The annual yield to streams in forested terrain was derived primarily from open slope debris slides and debris flows (Table 10). In logged terrain the annual yield entering streams was derived primarily from debris flows and, to a much lesser extent, from open slope debris slides. Debris flows contributed 37% of the material

TABLE 10. Mass wasting volume and yield entering streams, by failure location and type, in forested and logged terrain, in the Queen Charlotte Islands study basins

| | No. | Forested area[a] | | | No. | Logged area[b] | | | No. | Clearcut area[b] | | | No. | Road area[b] | | | Rate relative to[c] forested area | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total volume ($m^3$) | Average volume ($m^3$) | Yield ($m^3$/ha/yr) | | Total volume ($m^3$) | Average volume ($m^3$) | Yield ($m^3$/ha/yr) | | Total volume ($m^3$) | Average volume ($m^3$) | Yield ($m^3$/ha/yr) | | Total volume ($m^3$) | Average volume ($m^3$) | Yield ($m^3$/ha/yr) | Logged | Clearcut | Road |
| Debris slide open slope | 109 | 15 6200 | 1430 | 0.23 | 39 | 27 200 | 700 | 2.1 | 27 | 11 900 | 440 | 1.0 | 12 | 15 300 | 1 300 | 14.6 | x9 | x4 | x62 |
| Debris slide gully headwall | 58 | 38 900 | 670 | 0.06 | 36 | 16 700 | 460 | 1.3 | 30 | 11 100 | 370 | 0.9 | 6 | 5 600 | 930 | 5.3 | x21 | x16 | x91 |
| Debris slide gully sidewall | 21 | 4 800 | 230 | 0.01 | 6 | 1 500 | 250 | 0.1 | 6 | 1 500 | 250 | 0.1 | 0 | 0 | 0 | 0 | x16 | x17 | 0 |
| Debris slide active wall | 31 | 24 700 | 800 | 0.04 | 9 | 3 400 | 380 | 0.3 | 9 | 3 400 | 380 | 0.3 | 0 | 0 | 0 | 0 | x7 | x8 | 0 |
| Debris flow | 45 | 202 900 | 4510 | 0.30 | 29 | 309 100 | 10660 | 23.7 | 24 | 251 300 | 10470 | 21.0 | 5 | 57 800 | 11 560 | 55.0 | x78 | x69 | x181 |
| Total | 264 | 427 500 | 1620 | 0.6 | 119 | 357900 | 3010 | 27.6 | 96 | 279 200 | 2910 | 23.5 | 23 | 78 700 | 3 420 | 74.9 | x43 | x37 | x117 |

a Yields in forested areas are calculated from 40-year record.
b Yields in logged areas are calculated from 7.3 year average age .
c Accelerations based on yield.

entering streams from forested areas and 67% of the material entering streams from clearcut areas.

The average sizes quoted in Table 10 for events entering streams are the average sizes of the portion of the volume that entered a stream from a particular event. Since, in many cases, not all of a slide or flow entered a stream, the average size of the event necessary to produce these average yields to streams per event would have been larger than this quoted value.

The pattern of changes induced by logging in the average yield per event entering a stream follows the pattern of change in total yield. The average volume contributed to a stream by an open slope debris slide from clearcut areas was only 31% of that from forested areas; the average from a gully headwall slide was 55% of that from forested areas. This reflects the smaller average size of debris slides following logging. That is, slides in logged areas have a similar probability of entering streams as those in forested areas, but contribute less volume per slide because of their smaller average size. From road areas a different pattern occurs. The average contributions from open slope and gully headwall debris slides are similar to forested events.

The average volume contributed to streams from debris flows in logged areas was 236% larger than from forested areas. This exceeds the increase induced in the overall average size of debris flows by logging and is due, in part, to the greater mobility of flows from clearcut terrain. That is, flows from clearcuts are more likely to enter stream reaches with gradients of less than 10%.

### 3.2.4 The distribution of failures by volume class

Table 11 shows the number of events in different volume categories, by land class, for all events and for those events that enter streams.

TABLE 11. The volume distribution of failures from forested and logged terrain

| All events | Total set | Volume class ($m^3$) 100-500 | 500-1000 | 1000-5000 | 5000-10 000 | 10 000 |
|---|---|---|---|---|---|---|
| Forested | 807 | 372 | 179 | 212 | 31 | 13 |
| | (100%) | (46%) | (22%) | (26%) | (4%) | (2%) |
| Logged | 530 | 310 | 90 | 99 | 20 | 11 |
| | (100%) | (58%) | (15%) | (19%) | (4%) | (2%) |
| **Events entering streams** | | | | | | |
| Forested | 264 | 83 | 56 | 88 | 24 | 13 |
| | (100%) | (31%) | (21%) | (33%) | (12%) | (5%) |
| Logged | 119 | 49 | 17 | 29 | 14 | 10 |
| | (100%) | (41%) | (14%) | (24%) | (12%) | (8%) |
| **Probability of events entering streams by volume class** | | | | | | |
| Forested | 33% | 22% | 31% | 42% | 77% | 100% |
| Logged | 22% | 16% | 19% | 29% | 70% | 91% |

In both forested and logged terrain the majority of failures involved less than 1000 $m^3$ of material; 68% of the forested events and 75% of the logged events were less than this size. A similar percentage of both logged and forested failures were larger than 10 000 $m^3$. The smaller average size of clearcut debris slides is reflected in the greater proportion of events less than 500 $m^3$: 58% in logged terrain, 46% in forested areas.

When events that directly enter the stream system are considered in both forested and logged terrain, the percentage of smaller events is reduced. Only 52% of the landslides entering streams from forested areas are less than 1000 $m^3$, while for logged terrain 55% of the landslides entering streams are less than 1000 $m^3$. These changes simply indicate that smaller events have a smaller probability of entering streams than do mid-size or large events.

The probability of a landslide entering a stream for both logged and forested terrain is directly proportional to the size of the failure (Table 11). For failures between 100 and 500 $m^3$ , approximately 22% of the events from forested areas and 16% from logged areas enter streams. For the larger events involving more than 5000 $m^3$ of material, the probability of entering a stream is greater than 70% for both forested and logged terrain.

3.2.5 Comparison with mass wasting yields from the Pacific Northwest

Table 12 lists mass wasting yields from other regions in the Pacific Northwest extracted from Swanston and Swanson (1976) and Sidle _et al_. (1985). The yields from O'Loughlin (1972), Fiksdahl (1974), Morrison (1975), Swanson and Dyrness (1975) and Swanson _et al_.[3] are total mass erosion rates by debris avalanches. The yield from this study is the total of open slope, gully headwall,

[3] Swanson, F.J., M. Swanson, and C. Woods. 1977. Inventory of mass erosion in the Mapleton Ranger District, Suislaw National Forest Ranger District, Suislaw National Forest final report. A co-operative report of the Suislaw National Forest and the Pacific Northwest Forest and Range Experimental Station. Unpublished report.

TABLE 12. Mass wasting yields from studies in the U.S. Pacific Northwest and British Columbia

| Source | Location | Study area ($km^2$) | Forested area | | | Clearcut area | | | Acceleration | Road area | | | Acceleration |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | No. of events | Yield ($m^3$/ha/yr) | Period of record (yr) | No. of events | Yield ($m^3$/ha/yr) | Period of record (yr) | | No. of events | Yield ($m^3$/ha/yr) | Period of record (yr) | |
| Swanson and Dyrness (1975) | Cascade Mtns Oregon | 64.2 | 31 | 0.36 | 25 | 30 | 1.32 | 25 | x3.7 | 69 | 17.7 | 25 | x49 |
| Morrison (1975) | Cascade Mtns Oregon | 17.4 | 7 | 0.45 | 25 | 18 | 1.17 | 15 | x2.6 | 75 | 155.7 | 15 | x346 |
| Swanson et al. (1977) | Coast Ranges Oregon | - | 42 | 0.32 | 15 | 317 | 0.62 | 10 | x1.9 | 89 | 15.9 | 15 | x50 |
| Swanson et al. (1977) | Coast Ranges Oregon (Mapleton only) | - | 34 | 0.28 | 15 | 186 | 1.13 | 10 | x4.0 | 41 | 34.9 | 15 | x125 |
| Fiksdahl (1974) | Olympic Pen Washington | 24.4 | 25 | 0.70 | 84 | 0 | 0 | 6 | 0 | 83 | 117.7 | 6 | x168 |
| O'Loughlin (1972) | Coast Mtns B.C. | 276.7 | 29 | 0.11 | 32 | 18 | 0.25 | 32 | x2.3 | 11 | 2.83 | 32 | x26 |
| This study | QCI, B.C. | 350 | 729 | 1.1 | 40 | 375 | 16.8 | 7 | x15 | 88 | 80.0 | 7 | x73 |

gully sidewall, and active wall debris slides. These are comparable sets of failure events.

The average annual debris slide yield from forested steeplands in the Queen Charlotte Islands is larger than the yields reported in the Pacific Northwest by other authors. The average annual yields in Table 12 can be compared to the Queen Charlotte Islands rate if the debris slide yields from the 27 study basins are used to estimate the standard error of the average annual debris slide yield. The yields from the study basins were converted to logarithms to remove positive skew from the distribution. A difference of means test (Blalock 1972) applied to the logarithms of the annual yields ($p=0.05$) indicates that only the average annual yield observed by Fiksdahl (1974) was not smaller than the yield observed in this study.

A similar rationale can be used to compare debris slide yields from clearcut areas in the Queen Charlotte Islands to other areas in the Pacific Northwest. Application of a difference of means test ($p=0.05$) indicates that the yield from clearcut areas in the Queen Charlotte Islands is significantly larger than from other areas in the Pacific Northwest. The larger debris slide yields from clearcut areas and the larger accelerations (v. Schwab 1983) observed in the Queen Charlotte Islands indicate that significantly more instability is induced by vegetation removal from steeplands in the Queen Charlotte Islands than elsewhere in the Pacific Northwest.

Sediment and debris yields from road-related debris slide failures fall in the middle of the range of the yields observed from other studies in the Pacific Northwest. Accelerations and yields from roads are extremely variable over the 17 logged basins and, as a result, no statistical comparison of yields was made.

## 3.3 Mass Wasting Volumes Entering Different Reach Types

Table 13 lists the total volume and yield, and the volume and yield entering each of three reach types (stream gradient class). Of the total volume eroded from hillslopes, 47% from logged and 39% from forested terrain directly entered the stream system. Most of the material directly

TABLE 13. Volume and yield of material entering streams classified on the basis of gradient

| Stream gradient class (reach type) | Number of events | | Volume ($m^3$) | | Percent volume ($m^3$) | | Average yield per event ($m^3$) | | Yield ($m^3$/ha/yr) | | Logged rate relative to forest |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Logged | Forest | Logged | Forest | Logged | Forest | Logged | Forest | Logged | |
| 0.1-1% | 12 | 2 | 38 100 | 200 | 9 | 0 | 3180 | 100 | 0.06 | 0.02 | x0.3 |
| 1-3% | 38 | 18 | 60 100 | 46 600 | 14 | 13 | 1580 | 2590 | 0.09 | 3.6 | x40 |
| 3-10% | 214 | 99 | 329 300 | 311 100 | 77 | 87 | 1540 | 3140 | 0.49 | 23.9 | x48 |
| Total | 264 | 119 | 427 500 | 357 900 | 100 | 100 | 1620 | 3010 | 0.6 | 27.6 | x43 |



TABLE 14. The influence of location on the number, volume, and yield of mass wasting events in logged areas

| Location | No. of failures | | Volume of failures | | Yield ($m^3$/ha/yr) | No. entering streams | | Volume entering streams | | Yield to streams ($m^3$/ha/yr) 3 |
|---|---|---|---|---|---|---|---|---|---|---|
| | Number | Percentage of total | Volume ($m^3$) | Percentage of total | | Number | Percentage of total | Volume ($m^3$) | Percentage of total | |
| Clearcut open slope failures | 188 | 35 | 147 300 | 19 | 12.3 | 36 | 30 | 42 000 | 12 | 3.5 |
| Clearcut gully failures | 245 | 46 | 459 500 | 61 | 38.4 | 60 | 50 | 237 200 | 66 | 19.8 |
| Road open slope failures | 79 | 15 | 96 900 | 13 | 92.2 | 14 | 12 | 32 000 | 9 | 30.4 |
| Road gully failures | 18 | 3 | 54 050 | 7 | 51.4 | 9 | 8 | 46 700 | 13 | 44.4 |
| Total | 530 | 100% | 757 750 | 100% | 58.2 | 119 | 100% | 357 900 | 100% | 27.6 |

entered the higher gradient stream reaches in the upper portions of the watershed. The difference between the total volume and the volume entering streams represents the amount of material stored in gullies, on fans, and on slopes.

### 3.3.1 Comparison of proportions by reach type

Differences between the numbers of landslides entering streams in forested and logged terrain can be examined with a difference of proportions test (Blalock 1972). The test indicates that a significantly larger proportion of landslides enter streams from logged areas ($p=0.01$). Second, results indicate that a greater proportion of events enter higher gradient streams from logged areas than from forested areas ($p=0.01$).

### 3.3.2 The lowest gradient reaches

A much larger proportion of the yield to streams from forested areas directly entered the lowest gradient portion of streams. The average contribution of events directly entering the lowest gradient reaches from forested terrain was twice the size of either of the higher gradient reach classes. The material delivered from forested areas to reaches with gradients from 0.1 to 1% came primarily from three basins: Burnaby Island, Inskip Creek, and Security Creek. The lower portions of these streams were all affected by open slope debris slides.

Differences in the distribution of material by reach type for logged and forested areas may be due to only a small number of logged areas being in a suitable position to affect lower gradient reaches. Also, the total volumes entering mid- and lower gradient reaches were underestimated for logged areas. Because they could not be accurately measured, torrents entering the lower portions of Sachs, MacMillan, South Bay Dump, and Two Torrent creeks were not included in the totals in Table 13. These torrents influenced reaches with gradients between 1 and 3%.

### 3.4 The Location of Failures

Table 14 divides the volume from landsliding and the volume of material entering streams from logged areas on the basis of the location of the initiation zone of the failure. Location was divided into open slope and gully clearcut failures and open slope and gully road failures. Boundary-related failures are included in either the clearcut open slope or gully classes and are not treated separately because of the identification difficulties discussed in Section 2.4.1. In any event, the identified boundary-related failures were of little importance to mass wasting in logged terrain, contributing less than 5% of the total volume and 0.1% of the material entering streams.

Clearcut open slope failures comprised 35% of the total number of events and contributed 19% of the total volume of mass wasting and approximately 12% of the volume entering streams. Clearcut gully failures included 46% of the total failures, and supplied 61% of the total volume of mass wasting and 66% of the material entering streams.

Of the total number of road-related failures, 79 occurred on the open slope portion of roads, and 18 were gully-related road failures. Nearly all of these failures occurred in the road fill. The open slope road failures contributed 13% of the total volume of mass wasting, while the gully road failures contributed 7%. Conditions were reversed for the volumes entering streams, with a larger percentage of the total (13%) entering from gullies and a smaller percentage (9%) from open slope failures.

There appeared to be some changes over time in the volume of material derived from roads. Road construction techniques gradually changed after 1976 when backhoes came into use. (Prior to this date, roads were constructed by bulldozer ["cat-constructed"].) In South Bay Dump, Talunkwan, Thurston Harbour, and Sachs creeks where roads were built before 1976, the road-related yield averaged 317 $m^3$/ha per year. The remaining logged areas contributed 33 $m^3$/ha per year.

The largest yields to streams came from the open slope (14.2 $m^3$/ha per year) and gully (9.8 $m^3$/ha per year) road failures. While yields are instructive for comparing sources of failures, the total volume entering stream systems is of greater importance to streams. Seventy-eight percent of the landslide volume directly entering streams was from clearcut failures. Road area failures contributed the remaining 22%.

The predominance of road-related to other sources of failures in logged areas, as reported in various studies from the Pacific Northwest, is shown in Table 15. Results are divided. Some studies indicate that road-related failures account for a relatively greater proportion of logged failures -- both by number and by volume -- than is observed in this study; while others report of road-related failures in similar proportions to this study's. The proportion of road-related events observed in this study is significantly smaller (difference of proportion test, p=0.01; Blalock 1972) than those observed by other authors, particularly in studies from the Cascade Mountains in Oregon; and also smaller than those reported by Greswell et al. (1979) and Wilford and Schwab (1982). Similar proportions were observed by O'Loughlin (1972), Chatwin and Rollerson (1983), and Swanson et al.[4]

Results of this study and Chatwin and Rollerson's suggest that clearcut failures are more important in the Queen Charlotte Islands than in some other areas of the Pacific Northwest. Wilford and Schwab's data (1982) may differ because of the inclusion of minor failures (less than 200 $m^2$ surface area) in road fill. The lesser importance of road-related failures is not due to decreased mass wasting from roads in the Queen Charlotte Islands (Table 12), but rather to larger numbers and volumes from clearcut areas. This change is due to the high rates of failures induced by the removal of vegetation under conditions that promote high rates of mass wasting.

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[4] Swanson et al., 1977.

TABLE 15. Comparison of road-related failures to other sources of failures in logged areas, as reported in studies from the U.S. Pacific Northwest and British Columbia

| Location | No. failures on forested terrain | No. failures on logged terrain | Logged failures: Percent roads No. | Logged failures: Percent roads Volume | Logged failures: Percent other No. | Logged failures: Percent other Volume |
|---|---|---|---|---|---|---|
| Coast Ranges, Oregon | | | | | | |
| Fredriksen (1970) | 15 | 17 | 35 | 97 | 65 | 3 |
| Swanson et al. (1977) | 42 | 406 | 22 | - | 78 | - |
| Schroeder and Brown (1984) | 67 | 164 | - | 29 | - | 71 |
| Greswell et al. (1979) | 47 | 198 | 36 | - | 64 | - |
| Cascade Mtns., Oregon | | | | | | |
| Swanson and Dyrness (1975) | 32 | 107 | 66 | 67 | 34 | 33 |
| Dyrness (1967) | 5 | 44 | 81 | - | 19 | - |
| Morrison (1975) | 7 | 93 | 81 | - | 19 | - |
| Swanson and Grant (1982) | 43 | 125 | 66 | - | 34 | - |
| Southwestern British Columbia | | | | | | |
| O'Loughlin (1972) | - | - | 18 | - | 82 | - |
| Queen Charlotte Islands, B.C. | | | | | | |
| Wilford and Schwab (1982) | 322 | 113 | 39 | 43 | 61 | 57 |
| Chatwin and Rollerson (1983) | - | 114 | 17 | 22 | 83 | 78 |
| This study | 807 | 530 | 19 | 20 | 81 | 80 |

### 3.5 Surface Areas Associated with Failure Events

Table 16 shows the surface area of debris slides that occur on open slope and gully headwall and sidewall slope positions in forested and logged terrain. The area of gully and stream channel scoured by debris flows is also included. The surface areas of debris slides included in Table 16 are based on the surface areas of the initiation and transport zones only; the portion of the landscape affected by deposition is not included.

In forested steeplands, 195.3 ha of a land base of 166.7 $km^2$ were affected by debris slides on open slopes, gully headwalls, and gully sidewalls. For the time period of the events examined in forested terrain this represents 1.17 $ha/km^2$ affected directly by debris slides, or a rate of .036 $ha/km^2$ per year affected by debris slides over the 40 years of record.

In logged terrain, 68.8 ha of a land base of 17.8 $km^2$ were affected by debris slides. Failures had a direct impact on 3.88 $ha/km^2$ (or 3.88% of the land base) in logged steeplands. Soil was lost to debris sliding at a rate of 0.53 $ha/km^2$ per year based on an average logging age of 7.3 years. This represents an increase of 15 times over the rate observed in forested terrain.

Accelerations of the rate of surface area affected by debris slides and debris flows in logged areas vary according to landscape position. Accelerations on open slope and gully headwall positions were 17 and 15 times, respectively. A higher acceleration of 27 times was observed for gully sidewall positions, reflecting yarding impacts in basins such as Bonanza Creek in Rennell Sound. The largest accelerations occurred for gullies and streams scoured by debris flows. The acceleration of 50 times reflects the significant effect of logging on debris flows.

TABLE 16. The surface area of failures in forested and logged terrain for open slope and gully positions, Queen Charlotte Islands

| | Forested area[a] | | | Logged area[b] | | | Rate[c] relative to forested area |
|---|---|---|---|---|---|---|---|
| | Area impacted (ha) | Failure area per km$^2$ (ha/km$^2$) | Rate of area affected (ha/km$^2$/yr) | Area impacted (ha) | Failure area per km$^2$ (ha/km$^2$) | Rate of area affected (ha/km$^2$/yr) | |
| Open slope | 134.7 | .81 | .021 | 46.0 | 2.6 | .35 | x17 |
| Gully headwalls | 39.9 | .24 | .006 | 11.8 | .66 | .09 | x15 |
| Gully sidewalls | 20.7 | .12 | .003 | 11.0 | .62 | .08 | x27 |
| Gully stream scour by debris flows | 43.3 | .26 | .006 | 42.5 | 2.4 | .33 | x50 |
| Total | 238.6 | 1.4 | .036 | 111.3 | 6.2 | .85 | x24 |

a Forested area is 166.7 km$^2$. Rates are based on an average age of 40 years.
b The logged area (clearcut and road right-of-ways) is 17.8 km$^2$. Rates are based on an average age of logging of 7.3 years.
c Accelerations are calculated from the rates of surface area affected by debris slides and debris flows.

## 4 CONCLUSIONS

The purpose of this report was to examine the impact of timber harvesting on landsliding in steepland areas in the Queen Charlotte Islands. Harvesting impacts were assessed by comparing the frequency and yield of landsliding in clearcut and road areas to forested terrain.

The generality of the calculated accelerations depends on the representativeness of the sample of forested and, more particularly, logged terrain. Examination of sampled steepland areas indicates that neither physiographic region or bedrock geology exerts a strong influence over frequencies or yields of landsliding. As a result the averages determined in this report are appropriate for a large proportion of Queen Charlotte Island steeplands.

In logged areas the rate of landsliding also varies with the history of storm activity and the age of the logged area. The accelerations, frequencies and yields reported in this study are averaged over logged areas ranging from less than 1 to 16 years in age. While the duration of accelerated erosion from clearcuts is not known for the Queen Charlotte Islands other authors (Yoshinori and Osamu 1984) suggest it may continue for at least 25 years following logging. For a given logged area, when mature vegetation is re-established, rates return to the natural or forested level.

The accelerations, frequencies, and yields from clearcuts quoted in this study are appropriate averages for large areas of steepland logging ranging from several to 25 years old. Lesser accelerations are appropriate at the lower and upper ends of this age range; greater rates are expected for steeplands from 5 to 15 years in age (Figure 2; Nakano 1971; Megahan et al. 1978; Swanston and Swanson 1976; Yoshinori and Osamu 1984).

In forested terrain, landsliding occurred at a frequency of 0.12 events per square kilometre per year; the observed yield was 1.6 $m^3$/ha per year. Debris slides and debris flows contributed approximately 60 and 40% of the total yield, respectively.

The yield from debris sliding in forested terrain was 1.1 $m^3$/ha per year. This value is significantly larger than yields observed from most other

Pacific Northwest areas. The average debris slide from forested areas in the Queen Charlotte Islands yielded 1000 $m^3$. Average volumes of debris avalanches in forested areas in other Pacific Northwest regions range from 1540 to 4600 $m^3$ (Swanston and Swanson 1976).

Road building and the removal of vegetation accelerate the overall frequency and yield of landsliding. As well, logging alters the average size of debris slides and debris flows and their relative importance to the total yield. Debris slides in clearcut are accelerated 30 times in frequency, but only approximately 15 times in yield. The lower acceleration of yield is associated with a 50% decrease in the average size of open slope and gully headwall slides in clearcuts. Smaller debris avalanches in clearcuts were also observed by O'Loughlin (1972), Morrison (1975) and Schwab (1983). This change may be caused by a lower areal threshold for failure from logged terrain, the result of lowered root mat strength.

The yield of debris sliding from clearcut of 16.8 $m^3$/ha per year was significantly larger than other rates observed in the Pacific Northwest. The acceleration of 15 times was much larger than the typically observed range of 2-4 times. The removal of vegetation on Queen Charlotte Islands steeplands has a greater impact on mass wasting than it does in other Pacific Northwest regions.

The 41-fold acceleration in the frequency of debris flows on the Queen Charlotte Islands exceeds the reported range of 5-10 times (Swanston and Swanson 1976). Since debris flows are typically triggered by debris slides, the greater acceleration reflects the greater increase in debris slides.

Debris flows contributed 33.9 $m^3$/ha per year from clearcuts -- approximately two-thirds of the total yield. The increased contribution is due to a 150% increase in the average size of flows. The increase in average size is due to increased debris in gullies and an increased probability of larger failures, rather than to changes in the average length of channel scour.

The overall yield from roads in steepland logged areas is 143.6 $m^3$/ha per year -- approximately 3 times the rate observed from clearcut terrain. However, the use of yield values distorts the relative importance of clearcut and road erosion to the total volume of mass wasting. Approximately 80% of the total is from clearcuts and 20% from roads.

Debris slides contribute 80 $m^3$/ha per year, or 55%, of the yield from roads. This yield and the acceleration of 73 times fall into the middle of the range of values observed in other Pacific Northwest regions.

The frequency of debris flows from roads was 0.86 events per square kilometre per year; the comparable acceleration, 73 times. Swanston and Swanson (1976) report frequencies of 0.34 and 0.67, and accelerations of 42 and 133 times. The total yield from steepland roads in the Queen Charlotte Islands differs for areas constructed prior to and after 1976. Prior to 1976, roads were "cat-constructed" and yields were 371 $m^3$/ha per year. Following 1976, roads were constructed by backhoe and yields were 33 $m^3$/ha per year. The large difference in yields may also be influenced by the relative age of the road systems at the time of photography.

Of the total volumes eroded from slopes, 47% from logged and 39% from forested terrain enter the stream system. More than three-quarters of the volume delivered to streams enters reaches with gradients of 3-10°.

From forested terrain, 80% of the events entering streams are debris slides, which contribute 50% of the yield to streams. In clearcut terrain, debris slides comprise 75% of events entering streams and 10% of the total yield. The lower contribution to yield from clearcuts is due to a decreased average contribution to streams. Slides in clearcuts have a smaller probability of entering streams and also contribute less volume per slide because of their smaller average size.

The average contribution to streams from debris flows in clearcuts is 2.3 times as large as that from forested terrain. This increase is due to the greater size of debris flows from clearcuts and, in part, to increased mobility of flows in logged terrain.

The probability of a landslide entering a stream is directly proportional to its size. Events involving more than 5000 $m^3$ have a greater than 70% chance of entering a stream. Landslides less than 1000 $m^3$ -- which account for more than half of the total events -- have a 17% probability in logged areas and 25% in forested areas of entering a stream.

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