Forest Research
Technical Report
Vancouver Forest Region
2100 Labieux Road, Nanaimo, BC, Canada, V9T 6E9, 250-751-7001

TR-002 Geomorphology September 1999

Debris Flow Initiation in Coastal British Columbia Gullies

by
Thomas Millard
Research Geomorphologist

Research Disciplines: Ecology ~ Geology ~ Geomorphology ~ Hydrology ~ Pedology ~ Silviculture ~ Wildlife

TABLE OF CONTENTS

COVER PHOTO: Gullies in Gordon River watershed, Vancouver Island, British Columbia.

EXECUTIVE SUMMARY

This study investigates debris flow initiation hazard in Coastal British Columbia gullies. Field assessments were conducted in four geographic areas: north of Nitinat Lake on Vancouver Island, south of Nitinat Lake, the Squamish River and Mamquam River drainages in the Coast Mountains (southwestern mainland), and the Deena Creek and Ghost Creek drainages in the Queen Charlotte Islands. A total of 286 slope failures – of which 75 were debris flows – were analysed.

Information was collected on gully and slope failure characteristics, including slope failure location (headwall or sidewall), gully wall slope angle, gully wall slope distance, channel gradient, surficial material and surficial material depth, soil drainage, slope failure dimensions, the volume of slope failure debris delivered to the channel, the planimetric angle of entry of the slope mass into the channel, and whether the slope failure continued to transport as a debris flow down the gully channel.

Two types of analysis were carried out: the first to identify any factor that may have affected the initiation of channelized debris flow, and the second to identify factors that could be used in pre-logging assessments to identify gully locations that are prone to debris flow. Both single and multivariate analyses were used to identify factors in debris flow initiation.

The study found that slope failures in gully headwalls were much more likely to initiate a debris flow than slope failures in gully sidewalls. Headwall debris flows started on lower gradient slopes than did sidewall debris flows. The minimum initial failure volume required to initiate a headwall debris flow was about half the volume required to initiate a sidewall debris flow (11 m^3 compared with 25 m^3). Angle of entry is highly associated with location. The median headwall slope failure angle of entry is 0°, compared with the median sidewall slope failure angle of entry of 74°.

In addition to location within the gully (headwall or sidewall), the initial failure volume and the volume of debris delivered to the channel were the most important factors in determining whether a slope failure would result in a debris flow. Larger initial failures, and larger amounts of debris delivered to the channel, were much more likely to initiate debris flows than small slope failure volumes. Larger volume slope failures are associated with deeper surficial materials on sidewalls but not headwalls. Surficial material depth, or terrain type, divided into shallow and deeper classes, is significant in the prediction models. About 90% of debris flows had at least 80% of the initial failure volume delivered to the gully channel.

For both headwall and sidewall locations, a set of minimum criteria could be stated for debris flow initiation in this study. Below these criteria, debris flows did not occur. Above these criteria, debris flows occurred, but not all slope failures resulted in debris flows.

For headwalls, minimum debris flow initiation criteria were:

- Initial slope failure area of at least 30 m^2
- Initial slope failure volume of at least 10 m^3
- Debris volume delivered to the channel of at least 10 m^3
- Gully wall slope angle of at least 26° for till slopes
- Gully wall slope angle of at least 32° for colluvial slopes.

For sidewalls, minimum debris flow initiation criteria were:

- Initial slope failure area of at least 50 m^2
- Initial slope failure volume of at least 25 m^3
- Debris volume delivered to the channel of at least 25 m^3
- Gully wall slope angle of at least 35° for till slopes
- Gully wall slope angle of at least 39° for colluvial slopes (with one exception)
- A gully wall slope distance of at least 7 m.

The likelihood of debris flow initiation increased with the following factors:

- For both headwalls and sidewalls, an increase in volume of debris delivered to the channel
- For both headwalls and sidewalls, an increase in initial slope failure size
- For both headwalls and sidewalls, an increase in surficial material depth
- For sidewall slope failures, an increase in channel gradient

Although three of the geographic areas (South Nitinat, Squamish, and Queen Charlotte Islands) did not have significant differences in debris flow initiation, the fourth area, North Nitinat, was different from the other three areas. The most likely explanation for this difference was the presence at North Nitinat of highly sheared bedrock within gullied areas.

The results show that debris flow initiation is a complex process. As with most geomorphic processes, a significant degree of uncertainty exists. Although this study better defines the factors which are associated with debris flow initiation, there are limitations to this type of research. Therefore, caution must be used when applying these results. Terrain scientists should examine relationships between local slope failures and debris flows in gullies before applying these results to specific locations within Coastal British Columbia.

KEYWORDS:

gullies, debris flow, slope failure, terrain stability, Coastal British Columbia

REGIONAL CONTACT

For further information contact: Tom Millard, Research Geomorphologist, Vancouver Forest Region, BCMOF, (250) 751-7115; Tom.Millard@gems8.gov.bc.ca

ACKNOWLEDGMENTS

Funding for this project was provided by the Research Program of Forest Renewal British Columbia, administered by Nana Zolbrod at the Science Council of British Columbia. Steve Herold and his field crews from J.M. Ryder and Associates carried out the field work. Peter Ott provided much-needed statistical advice and review. Doug VanDine, Brent Ward and Rick Guthrie provided technical review of draft reports. Terry Rollerson provided advice throughout the project as well as reviewing draft versions. Shirley Mahood tried to explain verb tense to me.

1.0 INTRODUCTION

Gullies are a common feature of the mountainous Coastal British Columbia landscape. A subset of the channel system, gullies are incised, usually first- or second-order hillslope channels. Fluvial transport and mass movements, most significantly debris flows, are the major geomorphic processes in gullies. Debris flows consist of a combination of water, rock, mud, and large and small organic debris moving rapidly down the gully, with most of the debris depositing in the valley bottom in fans or cones. Debris flows within gully systems are significant ecological disturbances, with some effects lasting decades and even centuries. In addition, they can pose a serious safety hazard to forest users.

The Forest Practices Code of British Columbia requires an assessment of landslide-prone terrain, and part of the assessment includes evaluation of how far a slope failure will travel before deposition. In gullies, a critical point occurs when a slope failure enters the gully channel: if the slope failure continues to move down the gully channel as a debris flow, the result is usually a much larger and more destructive event than if the slope failure stops where it enters the channel.

If gullies prone to debris flow are not identified prior to development, increased numbers of damaging debris flows will occur. Conversely, if forest management is overly cautious and no gullies are harvested in order to avoid environmental damage, then timber harvesting opportunities will be lost. Clearly, accuracy in identification of debris flow prone gullies is important to forest management in Coastal British Columbia.

This study investigates debris flow initiation in Coastal British Columbia gullies. It is an empirical study designed to identify factors which are commonly associated with debris flow initiation. There are two objectives:

1. To better define the factors that affect debris flow initiation,
2. To develop more accurate methods of predicting gully reaches prone to debris flow initiation.

This study does not address all hazards in gullies. Debris flows are usually the largest and most destructive type of slope failure that occurs in gullies, and therefore this study seeks to explain debris flow initiation. However, debris flows are not the only slope failures that cause significant environmental damage in gullies. Loss of timber and soil, and deposition of sediment and debris into streams, may result from other types of slope failures that occur in gullies. In addition, fluvial events can cause significant disturbance.

2.0 PREVIOUS STUDIES

Several Coastal British Columbia slope failure studies identify gullies as hazardous terrain. A number of these studies examine slope failure rates and terrain types in logged terrain (Howes, 1987; Rollerson, 1992; Rollerson et al., 1997). In each of these studies, gullied terrain has the highest or among the highest slope failure rates of all logged terrain, with Rollerson (1992) identifying gullied headwater basins and stream escarpments as particularly susceptible to slope failures. Within gullies, the headwalls and sidewalls are particularly susceptible to slope failure. The headwall is the steep uppermost reach of a gully system, equivalent to a zero-order channel (Dietrich and Dunne, 1978). The sidewalls are located along the transport zone, or middle reaches, of a gully system. Sidewalls are the steep hillslope facet that connects the gully channel to the open slopes outside of the gully.

Debris flow initiation in Coastal British Columbia gullies is usually a two-step process. Initially, a slope failure occurs on a headwall of a gully or along a sidewall of a gully. (A third possible location is from outside of the gully.) Secondly, if the failure mass reaches the gully channel, it may continue moving down the gully channel as a debris flow, or it may deposit within the channel. Rollerson (1984) found 98% of gully debris flows initiate from slope failures on gully headwalls, sidewalls, or from slope failures outside of the gully. Rood (1990) found 15% of gully debris flows originate from gully sidewalls, 57% initiate from gully headwalls, and 14% initiate from failures outside of the gully. Debris flows that initiate in the gully channel are very rare in Coastal British Columbia gullies.

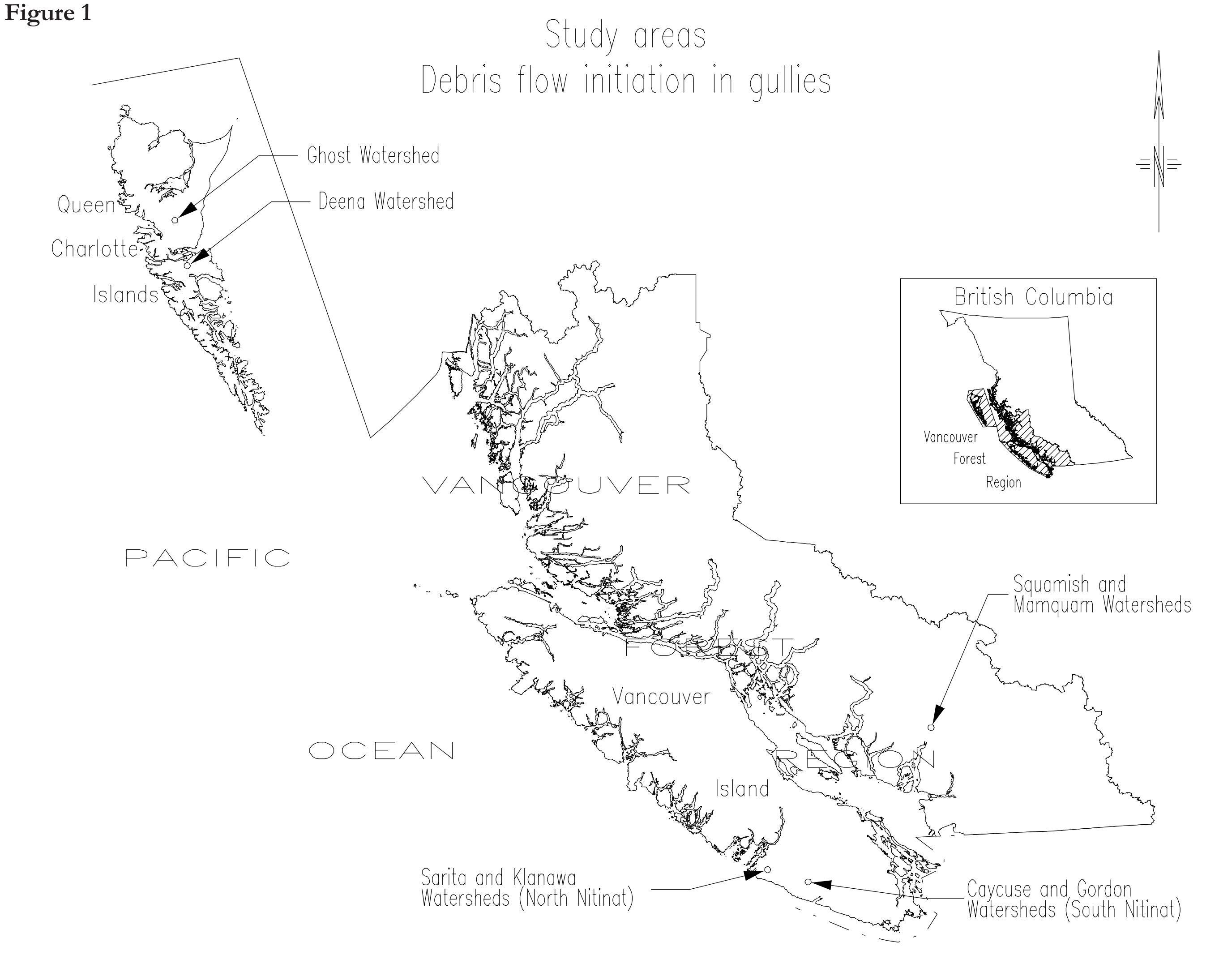
Bovis and Dagg (1992) use an impulsive loading model to describe the second step of debris flow initiation. Terrain and failure characteristics used in their model include the length of the slide path to the channel, the slope angle of the slide path, the mass of the slide, the planimetric angle of entry between the trend of the slope failure path and the trend of the channel, and channel gradient. With the exception of angle of entry, the likelihood of debris flow initiation increases as each of these variables increase. Although the case studies used by Bovis and Dagg tend to have much larger input volumes than typical forestry slope failures, this model appears to be applicable for forestry related debris flows.

The Gully Assessment Procedure (Anonymous, 1995a) uses a two step procedure for rating debris flow initiation hazard. Initially, surficial material and gully wall slope angle are used to rate the slope failure hazard. The second step uses channel gradient and the gully wall slope distance to evaluate the likelihood of a slope failure developing into a debris flow. Debris flow initiation hazard increases as either channel gradient or gully wall slope distance increases.

Brayshaw (1997), who examined gullies near Chilliwack, B.C, suggests few parameters are strongly correlated with debris flow initiation. His research found surficial material, gully wall gradient and length, and channel gradient the most important factors affecting debris flow initiation. In addition, the initial failure volume, the amount of sediment stored in the channel, and the planimetric angle of entry were important. Overall predictive ability was fair using surficial material, gully wall gradient, gully wall length, and channel gradient.

VanDine (1996) reports channel gradients greater than 25° are usually necessary to initiate a debris flow, and the channel gradient needed for debris flow initiation increases as watershed area decreases.

Figure 1



Several studies examine the deposition of debris flows. These studies indicate lower limits at which a slope failure entering a channel should not initiate a debris flow. Benda and Cundy (1990) examine 73 channelized debris flows in non-glaciated Oregon terrain, and an additional six channelized debris flows in glaciated Washington terrain. Their model uses channel gradient and planimetric tributary junction angle to predict deposition. For straight reaches, their model predicts deposition in channels with gradients of 3.5°. For channel gradients between 3.5° and 20°, debris flows that enter the channel with a tributary junction angle of 70° or greater will deposit. Their model predicts all debris flows on channel gradients greater than 20° will continue.

VanDine (1996) identifies several factors which are likely to result in debris flow deposition. Channel gradients less than 10° usually result in the onset of deposition. Unconfined channels encourage deposition. Finer grained sediments and greater amounts of water within the debris usually result in lower angles of deposition and thus longer travel distances.

Fannin and Rollerson (1993) use a channel width to channel gradient ratio with units of m/degrees to identify the onset of debris flow deposition. Deposition usually occurs when the ratio exceeds a value of one, and usually occurs when the channel gradient is less than 20°.

3.0 METHODS

3.1 DATA COLLECTION

Data was collected from four geographic areas to determine the extent of variation in debris flow behaviour in Coastal British Columbia (Figure 1). The four areas are:

- **South Nitinat**: south of Nitinat Lake on the west coast of Vancouver Island, with most of the gullies located within the Gordon River and the Caycuse River drainages. This area is part of the Vancouver Island Mountains (Holland, 1976). Bedrock in this area is primarily composed of diorites of the Island Intrusives, with some Bonanza Group volcanics and Quatsino

Formation limestone (Muller, 1977). The biogeoclimatic zone is Coastal Western Hemlock, very wet maritime subzone (Nuszdorfer and Boetger, 1994a).

• **North Nitinat**: north of Nitinat Lake, primarily in the Klanawa River and the Sarita River drainages. The geology and biogeoclimatic zone of this area are similar to the South Nitinat area.

• **Squamish**: the Squamish River and Mamquam River drainages. These areas are within the granitic rock of the Pacific Ranges of the Coast Mountains (Holland, 1976). The main biogeoclimatic zone is Coastal Western Hemlock, with subzones very wet maritime, moist maritime, and dry maritime. Some gullies are in the Mountain Hemlock moist maritime zone (Nuszdorfer and Boetger, 1994b).

• **Queen Charlotte Islands (QCI):** the Deena Creek Drainage on Moresby Island and the Ghost Creek drainage on Graham Island. The Deena Creek area is within the Queen Charlotte Ranges and Ghost Creek is within the Skidegate Plateau. Bedrock is comprised of volcanics and sedimentary rocks (Holland, 1976). The biogeoclimatic zone is Coastal Western Hemlock, wet hypermaritime subzone (Nuszdorfer and Boetger, 1994c).

In each area, almost all gullies meeting the following criteria were visited in the field:

• The gully was logged from 5 to 15 years ago. This time frame is commonly chosen for studies of slope failures in logged terrain (Rollerson, 1992).

• At least one slope failure had occurred in the gully.

• There was reasonable access to the gully.

Analysed slope failures met the following criteria:

• Only hillslope failures were analysed – no road prism slope failures, or slope failures likely affected by road drainage, were included.

• The slope failure initiated on either a gully headwall or a gully sidewall.

• The initial slope failure was at least 25 m^2 in area. All initial slope failures which result in debris flows were assumed to be at least this large.

For each slope failure, the following data were collected:

Gully characteristics at the failure site

• *Location:* either a gully headwall or a gully sidewall.

• *Gully wall slope angle (GWSA):* the slope angle from the base of the gully wall to the top of the gully wall, measured along the fall line.

• *Gully wall slope distance (GWSD):* the slope distance measured from the base of the gully wall to the top of the gully wall, measured along the fall line.

• *Channel gradient (CG):* for sidewalls, measured where the slope failure entered the channel, unless the slope failure deposit locally reduced the channel gradient, in which case the channel gradient was measured upstream of the slope failure. For headwall locations, the channel gradient was measured in the gully reach immediately downstream of the headwall.

• *Terrain type:* Terrain classes were grouped into seven types, with similar terrain classes clustered together. The types are:

1) Morainal (till) veneers and morainal veneers with some rock (Mv/R or Mv//R).

2) Colluvial veneers and colluvial veneers with minor amounts of morainal veneer (Cv//Mv).

3) Colluvial veneers with some rock (Cv/R or Cv//R).

4) Rock dominated terrain with some colluvial veneer (R/Cv or R//Cv).

5) Non-veneer morainal deposits (Mb, Mvb, Mw) that may have included some rock (eg, Mw/R or Mw//R).

6) Non-veneer colluvial deposits (Cb, Cvb, Cw) that may have included some rock (eg, Cw/R or Cw//R).

7) Combinations of non-veneer morainal and colluvial deposits that may have included some rock.

• *Soil drainage class:* rapid, well, moderately well and imperfectly. No poorly or very poorly drained classes were recorded. In some cases intermediate classes were recorded. In these cases the drainage class was assumed to the dominant drainage class.

• *Surficial depth:* the depth of the surficial material.

• *Soil depth:* the depth of the weathered, or developed, soil profile.

Slope failure characteristics

• *Slope failure type:* For the purposes of this report the term "slope failure" is used as a generic term for all types of slope failures that occurred on headwalls and along sidewalls. The term "NochDF" is used for slope failures that deposited in or near the channel and did not initiate a channelized debris flow. The term "ChDF" is used for slope failures that either initiated a channelized debris flow, or for debris flows that entered the gully channel and continued to travel down the gully channel as a debris flow.

• *Initial slope failure length, width, and depth:* the dimensions of the initial failure before it entered the channel. Initial slope failure area and volume were calculated from these measurements.

• *Debris volume into channel:* the volume of slope failure debris that reached the channel from the failure site, accounting for erosion or deposition along the failure path.

• *Slope origin:* the original slope of the ground surface before the failure occurred. Measured at the margin of the slope failure initiation zone.

• *Failure plane slope:* the slope angle along the surface of the initial failure plane.

• *Angle of entry (AOE):* the planimetric angle between the trend of the slope failure path and the trend of the channel.

3.2 ANALYTICAL METHODS

Initial analysis examined the gully and slope failure characteristics of NochDF and ChDF events, and investigated simple relationships evident from the data. Presentation of these data relies on tabular and graphical output.

The second step of analysis used logistic regression for multivariate analysis of the data. Logistic regression uses a binomial distribution to model the stochastic component of the outcome, in this case whether a NochDF or a ChDF occurred (Bergerud, 1996). It runs through a series of iterations to fit the model to the data, using the -log likelihood as the fitting criteria. The analysis constructs a model of the form:

$$\text{Probability of a ChDF} = \frac{e^{\beta_0+\beta_1 x_1+\ldots+\beta_p x_p}}{1+e^{\beta_0+\beta_1 x_1+\ldots+\beta_p x_p}}$$

Where $x_1, x_2, \ldots, x_p$ are predictor variables, and $\beta_1, \beta_2, \ldots, \beta_p$ are the unknown coefficients to be estimated.

Logistic regression required identifying variables that were correlated with each other. First, the Pearson product moment correlation coefficient was calculated for all pairs of continuous variables to determine which variables were correlated with one another. After the correlation analysis, separate two sample t-tests were run for each continuous variable using debris flow outcome (ChDF or NochDF) as the classification variable. Log transforms were used for highly skewed data. In general, only one continuous variable from each highly correlated set was selected for the logistic regression model based on the significance of its associated t-test. Last, a logistic regression model was constructed commencing with the selected continuous variables and all of the nominal and ordinal variables.

Backward elimination was then used to select the most parsimonious multiple logistic model. Initially all selected variables were included in the model; after running the model, the least significant variable (using the likelihood ratio test) was eliminated. The model was run again, once more with the least significant variable being eliminated. The number of effects in the model was reduced until all variables were significant at $\alpha = 0.05$.

In logistic regression, the Whole Model Test indicated whether all the variables used in the model significantly improved the model compared to the intercept only model. The Effects Likelihood Ratio Test compared two models: one that included the indicated variable, and a second that excluded only that variable. If the variable had a significant effect, the test reported a low *p*-value (Anonymous, 1995b). The Hosmer-Lemeshow goodness of fit test was used to compare the slope failure outcomes with the fitted model. The Hosmer-Lemeshow statistic was compared to a Chi-Square distribution; if the Chi-square value was not significant, the model had a good fit (Hosmer and Lemeshow, 1989).

Two types of models were constructed:

- **Best Models,** which provided the best explanation of debris flow initiation. These models included the use of variables that could only be determined after the slope failure has occurred.
- **Predictive Models,** which could be used in a pre-logging assessment to predict the likelihood of a debris flow. These models excluded variables that could only be determined after a slope failure occurred.

4.0 RESULTS

This study analysed data from a total of 286 slope failures. Table 1 summarizes the data, separating the slope failures into NochDF and ChDF. In addition, the table separates slope failures by sidewall or headwall location.

Sidewall slope failures (a total of 227) accounted for the majority of the events investigated, but headwall slope failures (a total of 59) produced slightly more debris flows. Two-thirds (66%) of headwall failures resulted in a debris flow compared to 16% of sidewall slope failures. A Chi-Square test showed this difference significant to 0.001. The data were split into headwall and sidewall data sets since there was a very significant difference between debris flow initiation in headwall locations compared with sidewall locations, and for future assessments, headwall and sidewall location is easily identified in the field.

4.1 INITIAL DATA INVESTIGATION

Tables 2 to 6 show the results for gully characteristics at the slope failure locations. Channel gradient, gully wall slope angle, gully wall slope distance, terrain type, and soil drainage are summarized. The distributions for channel gradient, gully wall slope angle and gully wall slope distance were skewed, and therefore the minimum, median, and maximum are reported.

Table 1 Summary of slope failure events

		Headwall		Sidewall		Total		
Geographic area	No. of gullies	NochDF	Ch DF	NochDF	Ch DF	NochDF	Ch DF	Total
S. Nitinat	45	8	15	73	9	81	23	104
N. Nitinat	34	1	12	30	11	31	23	54
QCI	42	9	10	57	9	67	19	86
Squamish	23	2	2	30	8	32	10	42
Total	144	20	39	190	37	211	75	286

Table 2 shows the median headwall channel gradients were steeper than the median sidewall channel gradients, an expected result since channel gradient tends to increase towards the upper reaches of a gully. There was a 2° difference between the median channel gradient for headwall NochDF and ChDF, and a 4° difference for sidewall NochDF and ChDF. In both cases, the median ChDF channel gradient was the greater of the two. A Wilcoxon test showed this difference was not significant for headwalls, but was significant for sidewalls at $\alpha = 0.05$ (Anonymous, 1995b).

Table 3 shows slightly steeper median sidewall slope angles than headwall slope angles. A Wilcoxon test showed the difference between headwall and sidewall slope angles was significant. Within headwall locations, there was no slope angle difference between NochDF and ChDF. Similarly, there was little difference in the median sidewall slope angles for NochDF and ChDF. However, there was a large difference between the minimum sidewall slope angle of NochDF and ChDF events, indicating that a greater sidewall slope angle was required for a ChDF.

Table 5 shows some differences in terrain type and debris flow outcome. For both headwall and sidewall locations, terrain types 5, 6, and 7 had a higher percentage of ChDF than terrain types 1, 2, 3, and 4. Terrain types 5, 6, and 7 are deeper surficial materials compared to the other four terrain types. When terrain types 1, 2, 3, and 4 were grouped together and terrain types 5, 6, and 7 were grouped together, a Chi-square test showed no significant difference in debris flow outcome for headwalls, but did show a significant difference for sidewalls. For both headwall and sidewall locations, morainal veneers (terrain type 1) had no debris flows, however this result should be viewed with caution given the low sample numbers.

Table 6 may show some difference between headwall and sidewall locations in debris flow outcome as a function of soil drainage. There was little difference in the percentage of headwall slope failures that resulted in a debris flow based on the different soil drainage classes. However, in sidewall locations there was some indication that the likelihood of a ChDF increased with moderately and imperfectly drained slopes compared with rapidly and well drained slopes.

Tables 7 to 10 summarize slope failure characteristics. The minimum, median and maximum are reported as the data were

Table 2 Channel Gradient (CG)

	Headwall		Sidewall	
CG (deg)	NochDF	ChDF	NochDF	ChDF
minimum	20	20	3	10
median	30	32	18	22
maximum	45	48	85	45

Table 3 Gully Wall Slope Angle (GWSA)

	Headwall		Sidewall	
GWSA (deg)	NochDF	ChDF	NochDF	ChDF
minimum	29	27	19	34
median	39	39	43	42
maximum	51	52	56	54

Table 4 Gully Wall Slope Distance (GWSD)

	Headwall		Sidewall	
GWSD (m)	NochDF	ChDF	NochDF	ChDF
minimum	5	4	2	7
median	23	28	25	26
maximum	90	90	160	60

Table 5 Terrain type

Terrain type	Headwall			Sidewall		
(Dominant material)	NochDF	ChDF	% ChDF	NochDF	ChDF	% ChDF
1 (Mv, Mv/R, Mv//R)	2	0	0	13	0	0
2 (Cv and Cv//Mv)	7	14	67	30	2	6
3 (Cv/R and Cv//R)	4	9	69	43	7	14
4 (R/Cv and R//Cv)	2	3	60	15	1	6
5 (Non veneer M)	1	7	88	58	19	25
6 (Non veneer C)	1	3	75	15	4	21
7 (Non veneer M & C)	1	3	75	15	4	21

Table 6 Soil drainage

	Headwall			Sidewall		
Soil drainage	NochDF	ChDF	% ChDF	NochDF	ChDF	% ChDF
Rapid	2	3	60	3	0	0
Well	10	13	57	135	17	11
Moderately well	5	20	80	49	19	28
Imperfectly	3	2	40	3	1	25

strongly skewed. There were substantial differences in the angle of entry between both headwall and sidewall categories, and between NochDF and ChDF categories (Table 7). The median angle of entry for headwall NochDF was 22°, and the median angle of entry for headwall ChDF was 0°. In contrast, the sidewall NochDF median angle of entry was 75°, and the median angle of entry of sidewall ChDF was somewhat less at 67°.

Angle of entry was clearly different in headwall locations compared with sidewall locations. A Wilcoxon test showed this difference is significant to 0.0001. For both headwall and sidewall locations, the median ChDF angle of entry was lower than the median NochDF angle of entry. The difference was significant at the 0.01 level for both the headwall data and the sidewall data.

For initial failure size characteristics and the debris volume into channel, the data clearly show that larger events were more likely to initiate debris flows. In both headwall and sidewall locations, the median ChDF was much larger than the median NochDF. This was true whether the initial failure area (Table 8), or initial failure volume (Table 9), or the debris volume into the channel (Table 10) was the criteria. The difference was significant to 0.0001 for each variable. Headwall ChDF could initiate from smaller initial slope failures than sidewall ChDF. The minimum initial failure area that resulted in a headwall ChDF was 33 m^2 compared to the minimum sidewall ChDF of 50 m^2 (Table 8).

Similarly, the minimum initial failure volume that resulted in a headwall ChDF was 11 m^3 compared to the minimum sidewall ChDF initial failure volume of 25 m^3 (Table 9). Table 10 also shows differences between the minimum headwall ChDF event and the minimum sidewall ChDF event.

Figures 2 and 3 show plots of terrain type compared to the initial failure volume.

For headwalls, Figure 2 shows little relationship between the size of initial failure and the terrain type. However for sidewalls, Figure 3 shows a difference between terrain types. Terrain types that are primarily veneers (terrain types 1, 2, 3, and 4) had few slope failures with an initial volume greater than 100 m^3. In contrast, deeper surficial materials (terrain types 5, 6, and 7) had several slope failures greater that 100 m^3. Even small headwall slope failures were likely to result in a debris flow, and so there appears to be little effect from terrain type in headwall debris flow initiation. In contrast, sidewall slope failures were much more likely to result in debris flow initiation if the initial slope failure was large, and deeper surficial materials were more likely to have large initial failure volumes.

Table 7 Angle of entry (AOE)

	Headwall		Sidewall	
AOE (deg)	NochDF	ChDF	NochDF	ChDF
minimum	0	0	0	30
median	22	0	75	67
maximum	70	54	90	87

Table 8 Initial failure area

Failure area	Headwall		Sidewall	
(m^2)	NochDF	ChDF	NochDF	ChDF
Minimum	25	33	26	50
Median	74	230	70	200
Maximum	2400	2600	800	1300

Table 9 Initial failure volume

Failure volume	Headwall		Sidewall	
(m^3)	NochDF	ChDF	NochDF	ChDF
Minimum	3	11	3	25
Median	17	100	24	92
Maximum	720	3400	460	720

Table 10 Debris volume into the channel

Volume into	Headwall		Sidewall	
channel (m^3)	NochDF	ChDF	NochDF	ChDF
Minimum	0	11	0	25
Median	8	100	13	83
Maximum	720	3400	520	700

Figure 2

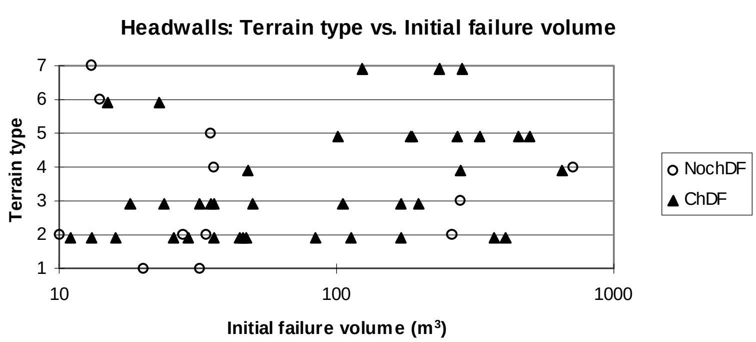
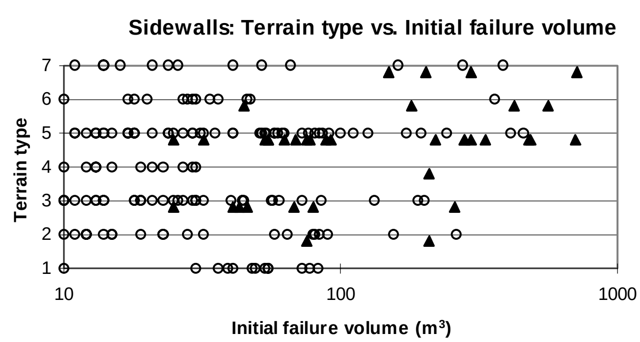


Figure 3



An important aspect of debris flow initiation is whether the initial failure volume is delivered to the channel, as is shown in Figures 4 and 5. Most ChDF events lost little of the initial failure volume before the slope failure entered the channel. All but one headwall ChDF had greater than 90% of the initial failure volume delivered to the channel. Of the 37 sidewall ChDF, only eight delivered less than 80% of the initial failure volume to the channel. Many of the sidewall failures with initial failure volumes between 10 and 100 m^3 deposited much of the debris before reaching the channel, and this usually resulted in no debris flow initiation. The proportion of debris delivered to the channel from a slope failure may partially depend on the gully cross-sectional geometry, however this study did not investigate this factor.

Figures 6 to 11 compare the variables channel gradient, angle of entry, and the volume of debris delivered to the channel. Figure 6 shows most headwall ChDF had an angle of entry of 0°, no matter what the channel gradient. It also suggests, for slope

Figure 4

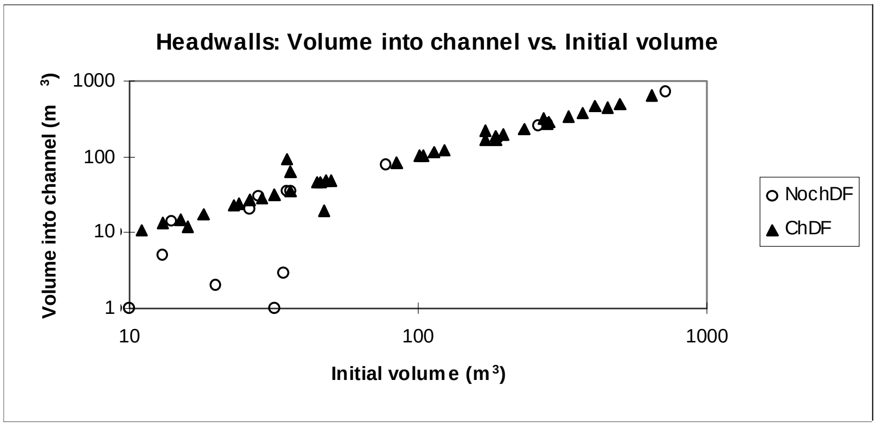


Figure 5

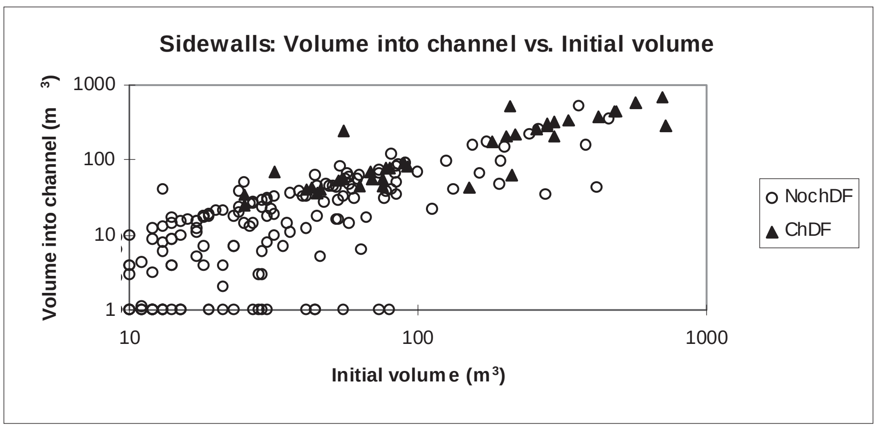
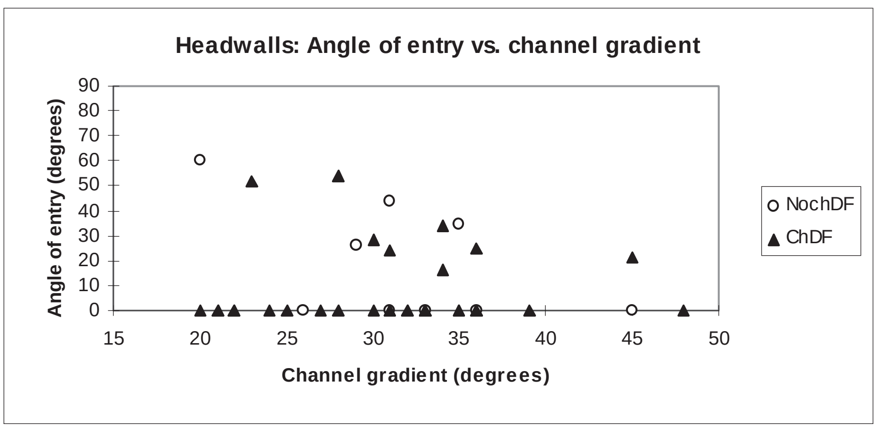


Figure 6



failures with an angle of entry greater than 0°, a trend of decreased angle of entry as channel gradient increased. Figure 7 shows a trend of decreased angle of entry as channel gradient increased for sidewall slope failures. Figure 7 also shows very few sidewall slope failures entered the channel with an angle of entry of less than 30°.

Both Figures 8 and 9 show minimum channel gradients were required to initiate a ChDF. Headwall ChDF initiated at a minimum channel gradient of 20°, regardless of the volume of debris delivered to the channel. However, the minimum headwall channel gradient measured was 20°, and so it is unlikely that this is a true minimum – if headwalls with channel gradients less

Figure 7

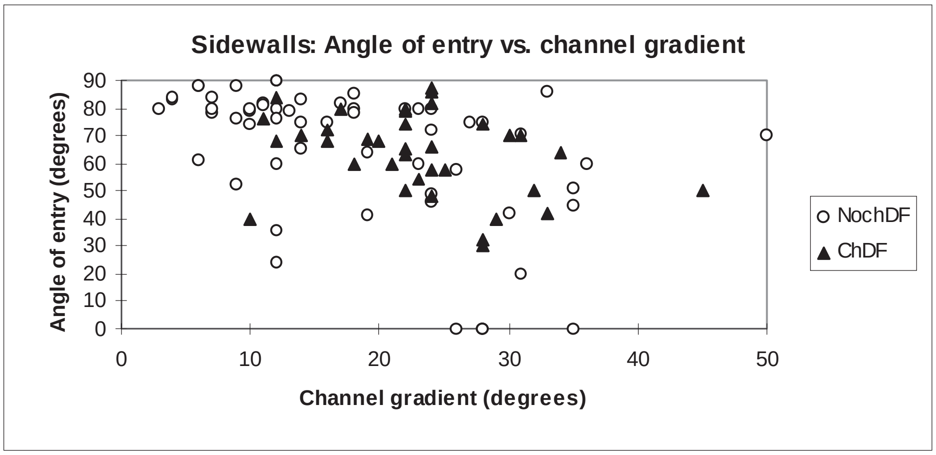


Figure 8

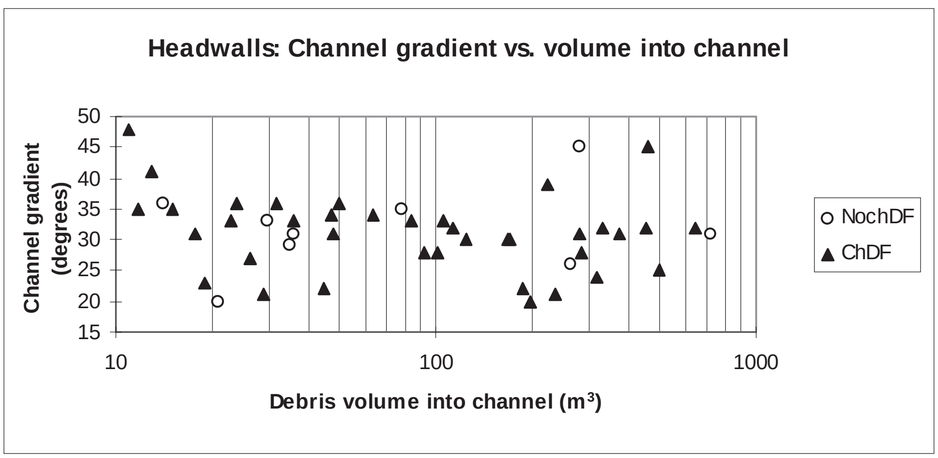
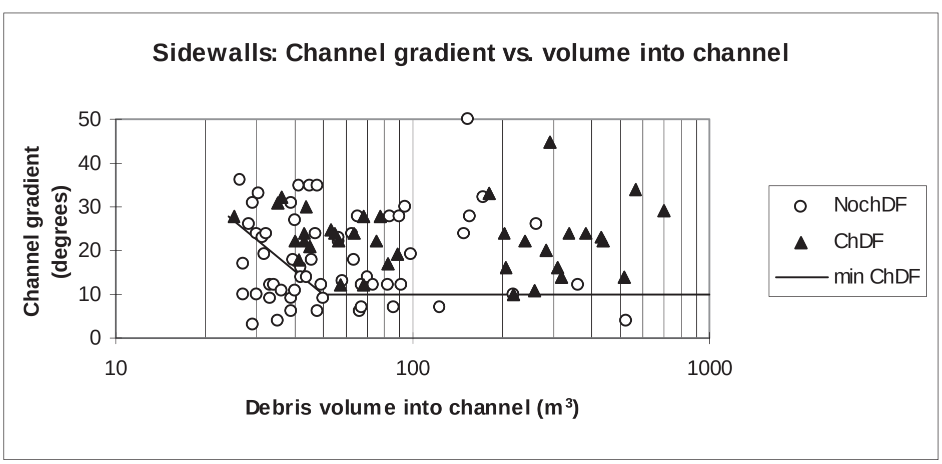


Figure 9



than 20° exist, they may initiate debris flows. Figure 9 shows a minimum boundary line for sidewall ChDF. Sidewall ChDF occurred in channel gradients greater than 10° if the debris volume delivered to the channel was greater than 50 m^3 (Figure 9). The data also show that for sidewall ChDF with a debris volume delivered to the channel of less than 50 m^3, minimum channel gradient increased as debris volume delivered to the channel decreased.

Combinations of terrain type and slope gradient are often used to identify potentially unstable terrain in Coastal British Columbia (Rollerson, 1992; Anonymous, 1995a). Figures 10 and 11 show terrain type and slope gradient combinations for headwall and sidewall slope failures. One sidewall – NochDF, terrain type 5 with a GWSA of 19° – is not shown in Figure 11.

Several trends are evident in Figures 10 and 11. Figure 10 shows headwall slope failures occurred on slopes as low as 26°, while Figure 11 shows all but one sidewall slope failures occurred on slopes greater than 31°. Both Figures 10 and 11 show there were no slope failures on terrain types 3 and 4 (veneers of colluvium combined with rock) if the gully wall slope angle was less than 37°. Headwall slope failures in terrain types 1, 5, and 7 (those which contain till) had a minimum gully wall slope angle between 26° and 28°, but sidewall slope failures in these terrain types had minimum gully wall slope angles of 31° to 35°. For sidewall slope failures, only nine NochDF and one ChDF of the 226 slope failures occurred on slopes less than 35°, so slope failures, and particularly debris flows, were rare if the sidewall slope angle was less than 35°. For both headwall and sidewall slope failures, the maximum gully wall slope angle was about 55°.

A combination of channel gradient and gully wall slope distance is used in the Gully Assessment Procedure (Anonymous, 1995a) to evaluate whether a debris flow is likely to initiate in a gully when a slope failure occurs. Figure 12 shows the headwall data from this study using the same parameters. To clarify the plot, only headwall slope failures with a minimum initial failure volume of 11 m^3 are shown (the minimum size for a headwall ChDF).

Figure 10

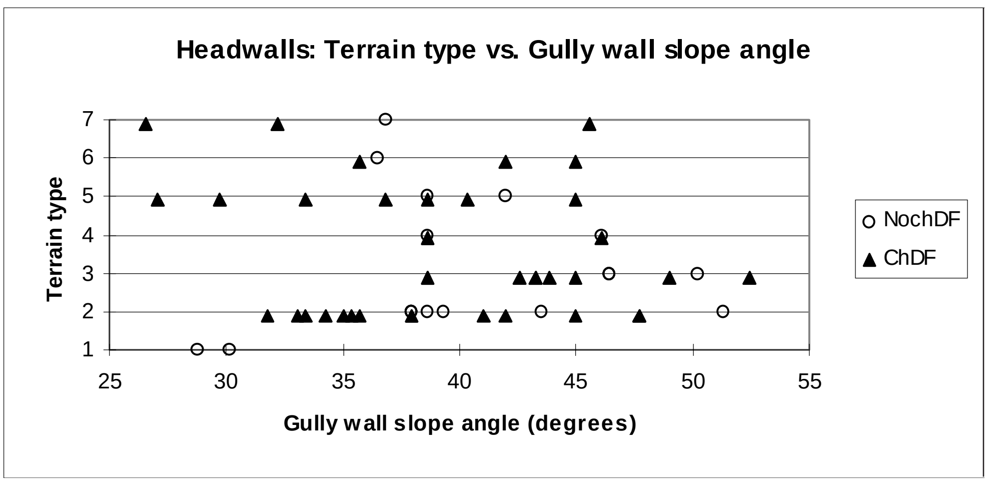


Figure 11

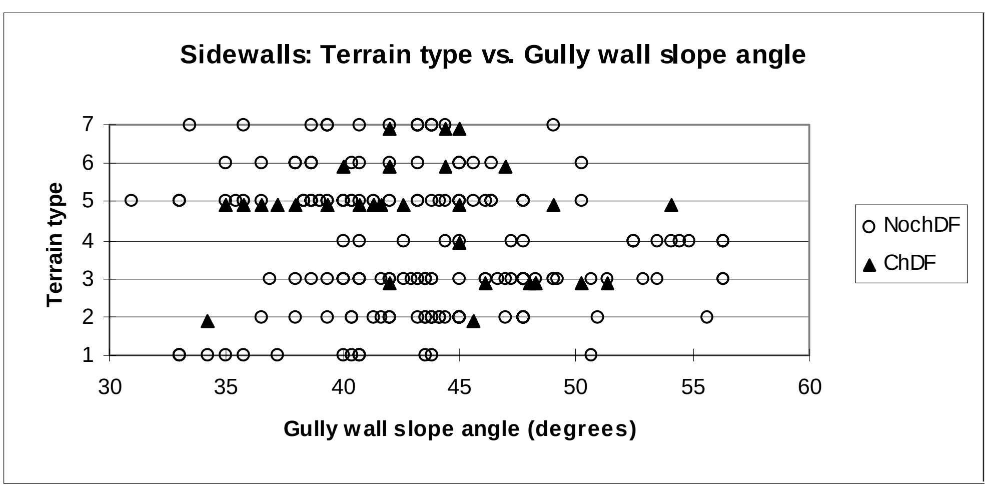


Figure 12

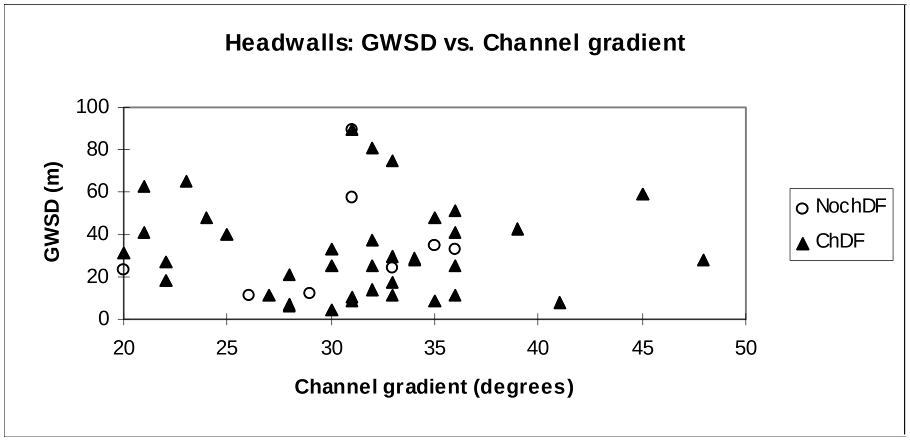


Figure 13

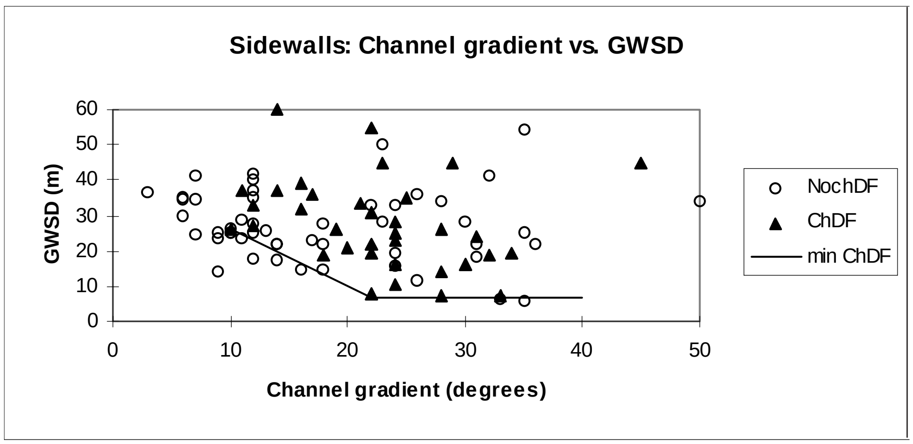


Figure 13 shows the same plot for the sidewall data. Only sidewall slope failures with a minimum initial failure volume of 25 m^3 are shown (the minimum size for a sidewall ChDF).

Six NochDF with gully wall slope distances greater than 60 m are not shown in Figure 13.

All headwall ChDF initiated with a channel gradient greater than 20° (Figure 12). However, there was no obvious increased likelihood of debris flow initiation as headwall channel gradient increased, nor was it evident that increased gully wall slope distance resulted in an increased likelihood of debris flow. Figure 13 includes a minimum boundary line or envelope curve for sidewall ChDF initiation. For channel gradients from 10° to about 20°, the data indicates a decrease in the gully wall slope distance required to initiate a debris flow as channel gradient increased. Of the 11 ChDF with channel gradients less than 20°, all but one had a volume delivered to the channel of at least 50 m^3, and seven had a volume delivered to the channel of over 100 m^3, indicating that if a larger volume of debris was delivered to a channel with a gradient less than 20°, a debris flow was more likely to develop. If the channel gradient was greater than about 20°, then ChDF occurred with a minimum sidewall slope distance of 7m.

4.2 LOGISTIC REGRESSION

The analysis considered three sets of data: the entire data set (gully data), the headwall data set, and the sidewall data set. The gully data set was analysed to determine the variables that had overall significance. The headwall and sidewall data sets were analysed separately since location had a very significant effect on debris flow outcome. Best Models (those that used post-slope failure information), and Predictive Models (those that used only pre-slope failure information) were developed for each of the data sets.

4.2.1 CORRELATION ANALYSIS AND T-TESTS.

Two major types of variables were correlated using a criterion of $r = 0.50$:

1. Slope failure dimensions and the derived values of failure area, failure volume, and the debris volume into the channel were generally correlated. For the entire data set, the headwall data set, and sidewall data set, the log transform (base 10) of the debris volume into the channel (log channel volume) was the most significant variable using a t-test. The log transform of the debris volume into the channel was used in model construction.

Table 11 Gully Best Model

	p-value	Parameter estimate
Whole model test	0.0001	
Hosmer-Lemeshow test	0.44	
Intercept	0.0001	-5.31
Geographic area	0.004	
Geographic area: North Nitinat		0.80
Geographic area: South Nitinat, Squamish, QCI		-0.80
Channel gradient	0.02	0.054
GWSD	0.01	-0.023
Location	0.0000	
Headwall		1.14
Sidewall		-1.14
log channel volume	0.0000	3.09

2. Most slope gradients were correlated. These variables were path slope, slope origin, slope failure plane, and gully wall slope angle. For the entire data set and the headwall data set, path slope was the most significant of these variables, and was therefore used for the Gully Best Model and the Headwall Best Model. Gully wall slope angle was the most significant of these variables for the sidewall set and was therefore used for the Sidewall Best Model. For the Predictive Models gully wall slope angle was used, as the others could only be determined after a slope failure.

4.2.2 GULLY BEST MODEL

The Gully Best Model combined the headwall and sidewall data together. Cases with an initial failure volume of less than 11 m^3 were excluded, as this was the minimum size that initiated a ChDF. The variables selected for analysis in the Gully Best Model were geographic area, location, terrain type, drainage class, path slope, gully wall slope distance, channel gradient, angle of entry, and the log channel volume.

After the model was run, geographic area, location, channel gradient, gully wall slope distance and log channel volume were all significant to 0.05. However, a repeated run of the model that excluded the North Nitinat data showed no significant difference between the remaining three geographic areas. The South Nitinat, Squamish, and QCI geographic areas were then combined into one group, the North Nitinat data were once more included, and the model run again. Table 11 shows the results of the analysis.

Figure 14 shows the effect of the variables in the Gully Best Model. Each chart shows four lines: one of North Nitinat headwalls (N. Nit. HW), one of North Nitinat sidewalls (N. Nit. SW), headwalls of South Nitinat, Squamish, and the Queen Charlotte Islands (3Area HW), and sidewalls of South Nitinat, Squamish, and the Queen Charlotte Islands (3Area SW). Headwalls had a greater probability of failure than sidewalls, a result which confirms the significance of location. The North Nitinat area had a greater probability of failure than the other three areas.

Figure 14 also shows the probability of a ChDF increased with increased channel gradient and increased debris volume into the

Figure 14 Gully Best Model

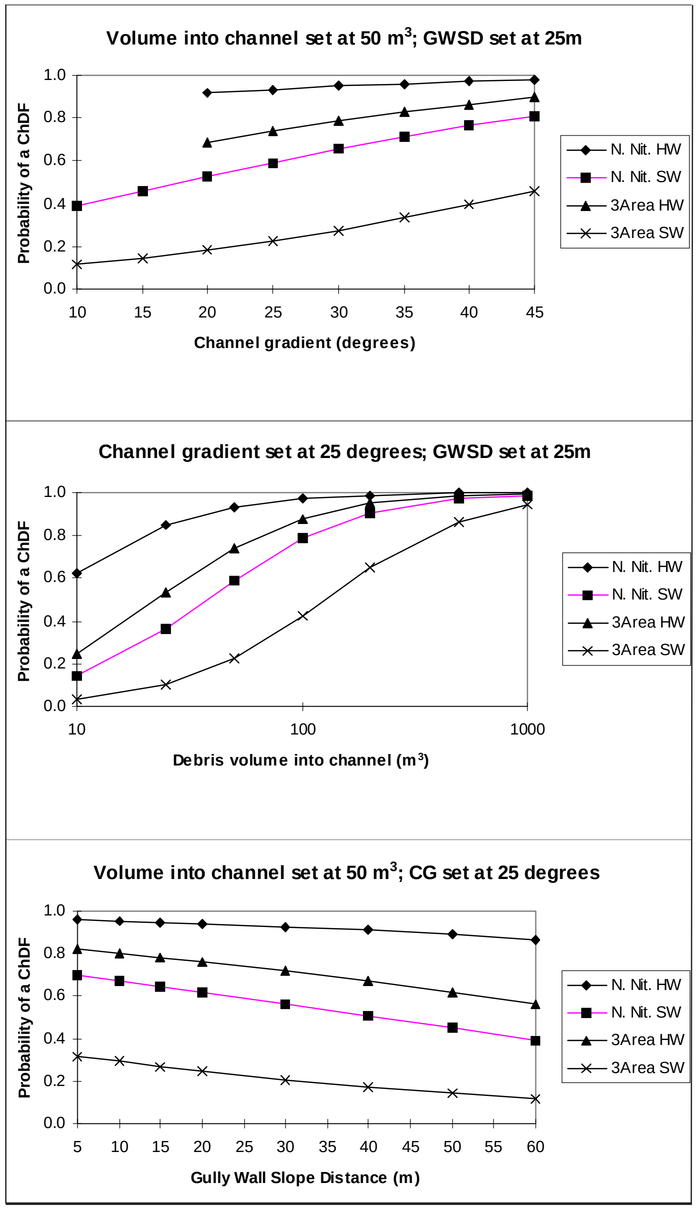


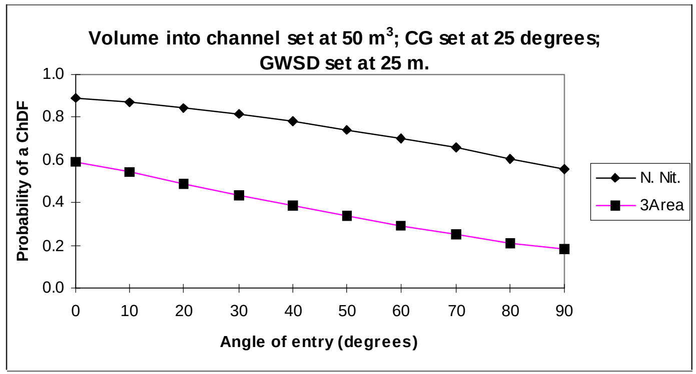
Table 12 Gully Best Model using Angle of entry

	p-value	Parameter estimate
Whole model test	0.0001	
Hosmer-Lemeshow test	0.28	
Intercept	0.0002	-4.8
Geographic area	0.001	
Geographic area: North Nitinat		0.87
Geographic area: South Nitinat, Squamish, QCI		-0.87
Channel gradient	0.011	0.057
GWSD	0.012	-0.021
Angle of entry	0.004	-0.021
log channel volume	0.0000	3.03

channel. However, the probability of a ChDF decreased as gully wall slope distance increased, a surprising result. The effect from gully wall slope distance was not strong - as slope distance increased from 5 m to 60 m, the decrease in ChDF probability was an average of 21%.

The Gully Best Model rejected the variable angle of entry as not significant. However, angle of entry was strongly associated with location, and therefore another model was run, this time replacing location with angle of entry. In this model, angle of entry was shown to be significant, as shown in Table 12. Figure 15 shows the effect of angle of entry in this model (the other effects are similar to those shown in Figure 14).

Figure 15 Angle of entry effect in the Gully Best Model



4.2.3 GULLY PREDICTIVE MODEL

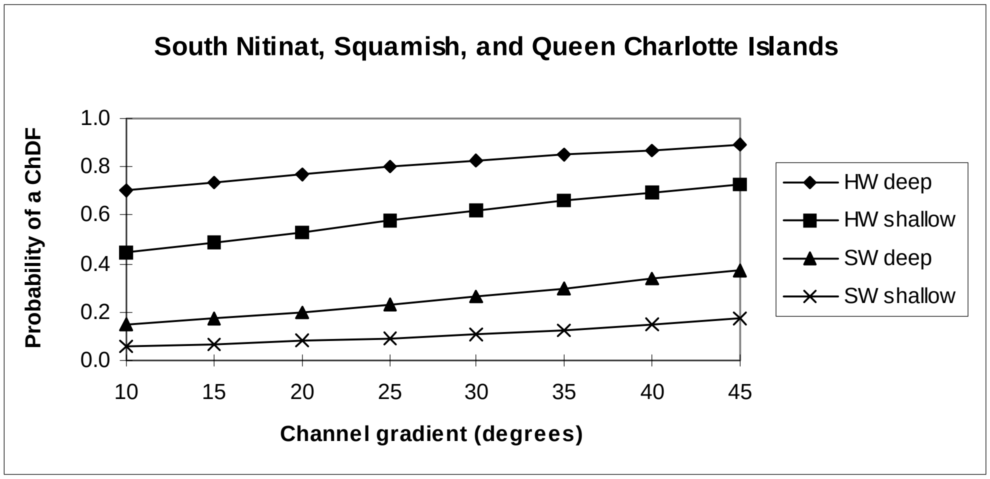
The variables used in the construction of the Gully Predictive Model were location, geographic area, terrain type, drainage class, gully wall slope angle, gully wall slope distance, and channel gradient. Once again geographic area was significant, but no significant difference between South Nitinat, Squamish, and Queen Charlotte Islands was found. Geographic area was regrouped into North Nitinat and 3Areas (South Nitinat, Squamish, and Queen Charlotte Islands). Terrain type was found to be significant, but the parameter estimates were unstable. Terrain type was regrouped into two types: shallow (terrain types 1, 2, 3, and 4), and deep (terrain types 5, 6, and 7). The results in Table 13 show this classification to be significant. The Hosmer-Lemeshow statistic almost showed significance at the 0.05 level, which would have indicated the model did not fit the data well.

Figure 16 shows the effects in this model. The first chart in

Table 13 Gully Predictive Model

	p-value	Parameter estimate
Whole model test	0.0001	
Hosmer-Lemeshow test	0.08	
Intercept	0.13	-0.67
Geographic area	0.0026	
Geographic area: North Nitinat		0.61
Geographic area: South Nitinat, Squamish, QCI		-0.61
Channel gradient	0.028	0.034
Location	0.0000	
Headwall		1.36
Sidewall		-1.36
Terrain - 2 types	0.0009	
Deep terrain types		0.58
Shallow terrain types		-0.58

Figure 16 Gully Predictive Model



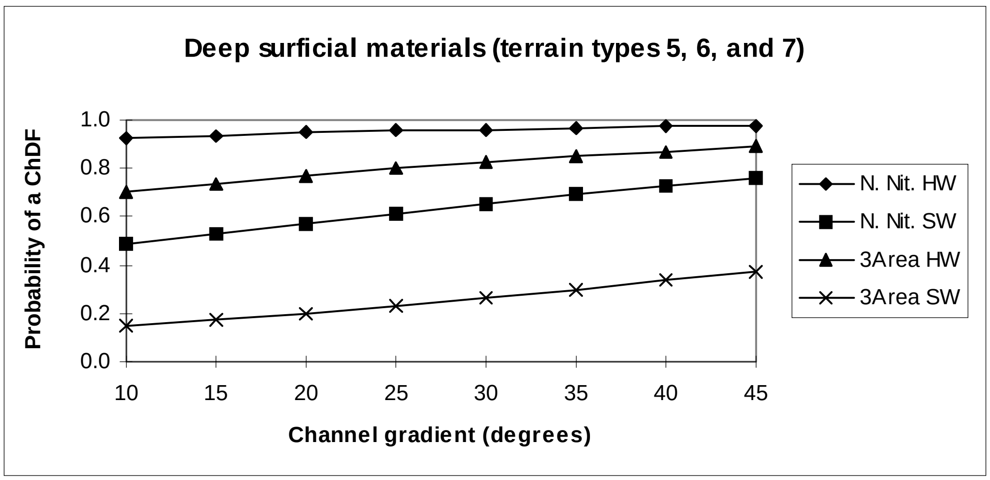


Figure 16 shows the differences in geographic area (North Nitinat compared to the three other areas) and the difference between headwall and sidewall locations. The second chart in Figure 16 shows the differences between deep and shallow terrain and headwall and sidewall locations for the three areas of South Nitinat, Squamish, and the Queen Charlotte Islands.

The Gully Best Model and the Gully Predictive Model both confirmed location as one of the two most important variables. The volume of debris delivered to the channel was shown to be very significant in the Gully Best Model. Geographic location was shown to be significant in both models, with the North Nitinat area significantly different from the other three areas. Channel gradient was significant in both models. Both terrain type and gully wall slope distance were shown to be significant in one of the models but not the other, suggesting these were not strong effects.

To determine whether different variables were useful for evaluating debris flow initiation in the two different locations, the headwall data were separated from the sidewall data and models were constructed for both data sets.

4.2.4 HEADWALL BEST MODEL

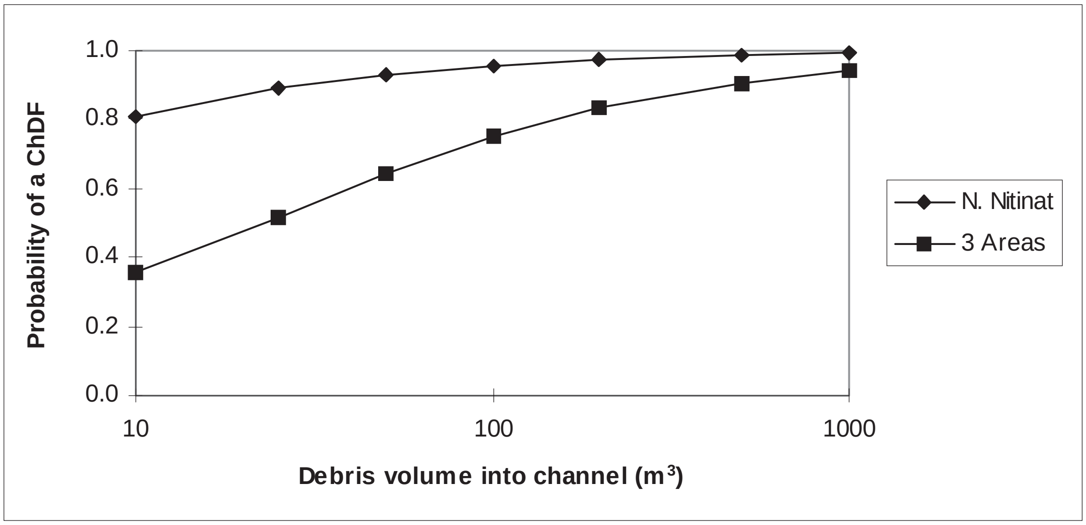
The variables chosen for analysis in the Headwall Best Model were the same as the variables in the Gully Best Model: geographic area, location, terrain type, drainage class, path slope, gully wall slope distance, channel gradient, angle of entry, and the log channel volume. Terrain types were combined into shallow terrain (terrain types 1, 2, 3, and 4), and deep terrain (terrain types 5, 6, and 7). Soil drainage classes rapid and well drained were combined, as were moderately well and imperfectly.

The analysis showed two variables significant to 0.05 – log channel volume and geographic area. Geographic area did not

Table 14 Headwall Best Model results

	p-value	Parameter estimate
Whole model test	0.0002	
Hosmer-Lemeshow test	0.31	
Intercept		-1.26
Geographic area	0.028	
Geographic area: North Nitinat		1.02
Geographic area: South Nitinat, Squamish, QCI		-1.02
log channel volume	0.0006	1.69

Figure 17 Headwall Best Model



show as significant unless divided into two classes (North Nitinat compared with the three other areas). Table 14 shows the statistical results. Figure 17 shows the effect of channel volume and geographic area on debris flow initiation probability, as determined by the logistic regression equation and the parameter estimates shown in Table 14.

4.2.5 HEADWALL PREDICTIVE MODEL

This model used only variables which could have been identified prior to logging: geographic area, terrain class, drainage class, surficial depth, gully wall slope distance, and channel gradient. Instead of path slope, gully wall slope angle was included.

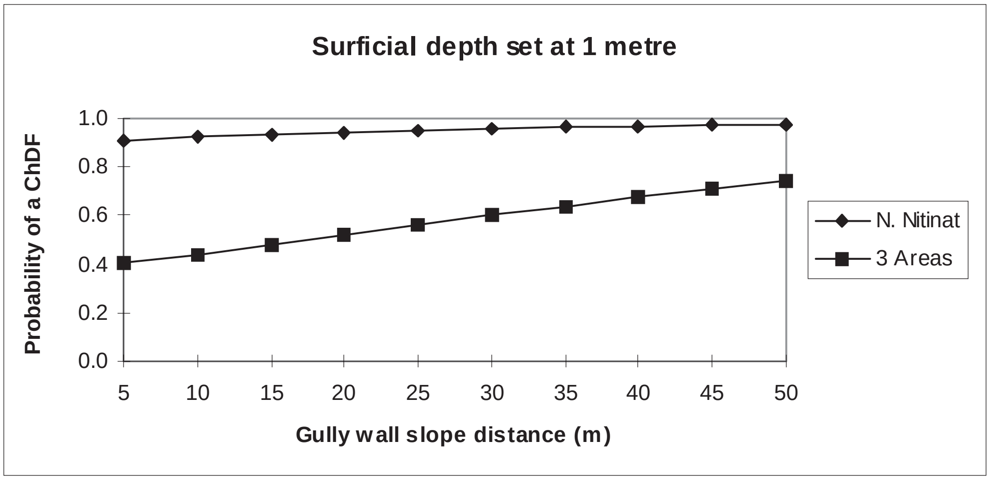
The analysis yielded three variables (geographic area, gully wall slope distance, and surficial depth) significant to 0.05. A separate analysis excluded the North Nitinat data and indicated the remaining three areas were not significantly different, and therefore the model was run again using the two-class geographic area variable. Table 15 shows the statistical results. Figure 18 shows the effects of geographic area, gully wall slope distance, and surficial depth.

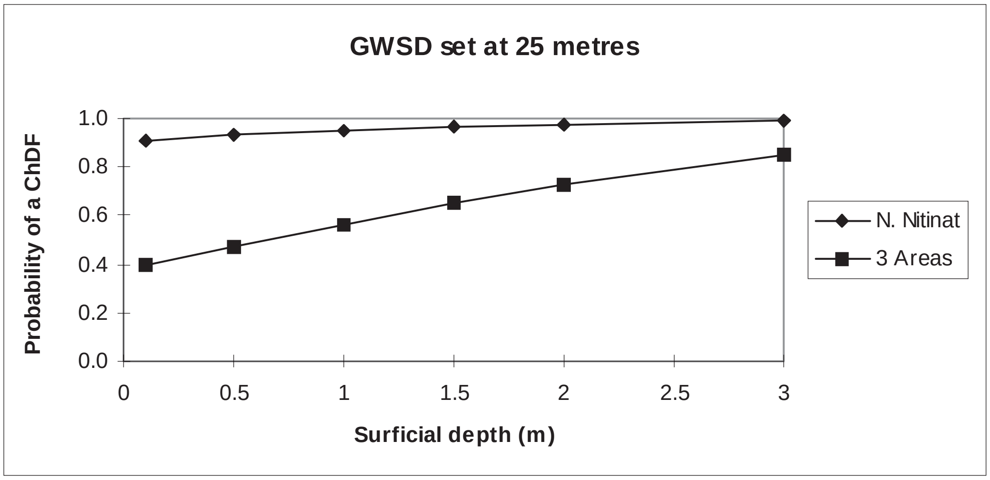
The North Nitinat area had a greater probability of a debris flow than the other areas. Gully wall slope distance is shown to be directly proportional to debris flow probability, the reverse of the role of gully wall slope distance in the Gully Best Model.

Table 15 Headwall Predictive Model results

	p-value	Parameter estimate
Whole model test	0.003	
Hosmer-Lemeshow test	0.52	
Intercept	0.054	
Geographic area	0.002	
Geographic Area: North Nitinat		1.37
Geographic Areas: S. Nitinat, Squamish, QCI		-1.37
Surficial depth	0.048	0.75
GWSD	0.025	0.032

Figure 18 Headwall Predictive Model





Terrain type was not shown to be significant, however surficial depth, which is related to terrain type, was significant. Neither gully wall slope distance nor surficial depth had much effect on debris flow probability in the North Nitinat area.

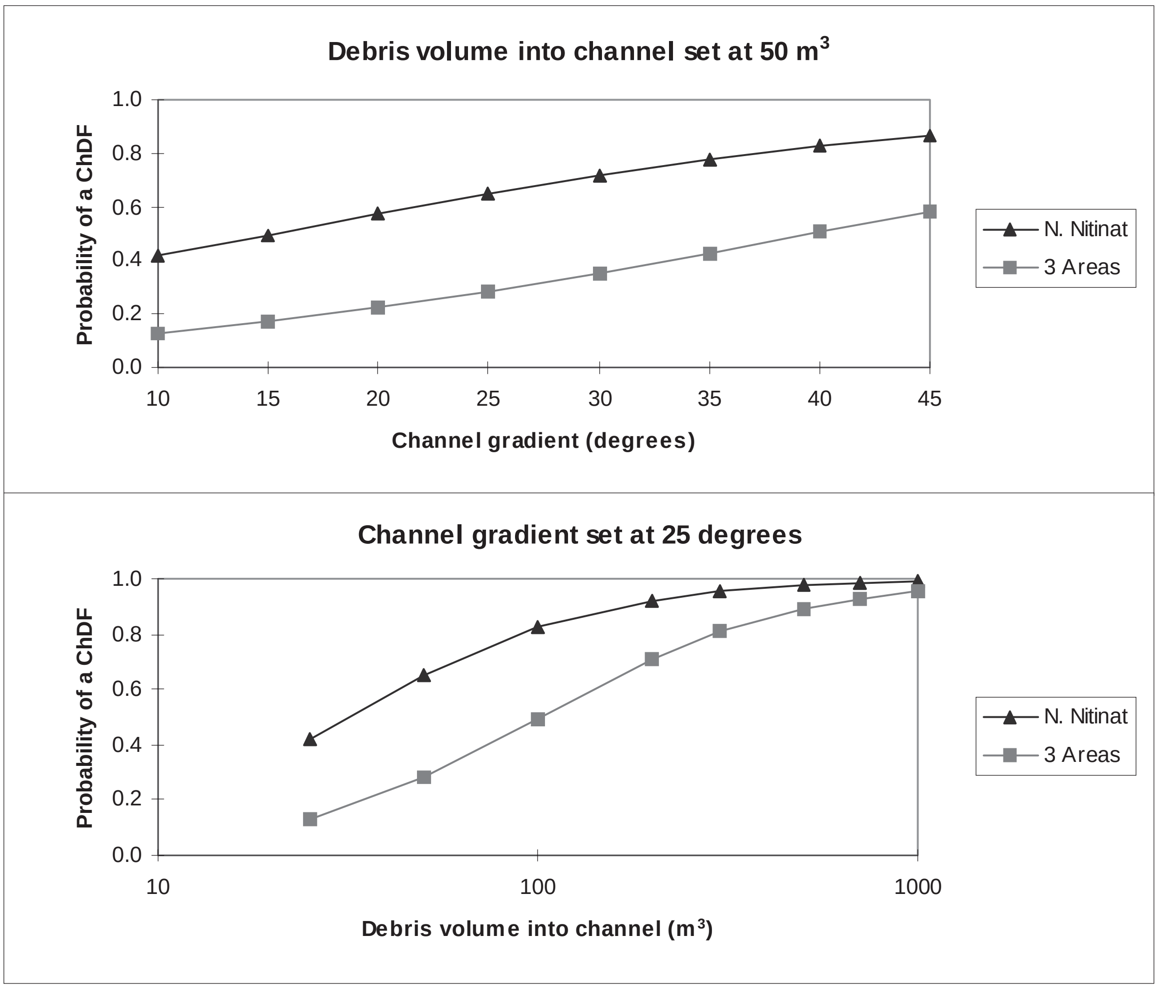
4.2.6 SIDEWALL BEST MODEL

The complete data set for sidewalls has 227 slope failures, with 37 of these slope failures events being ChDF. Logistic regression should be avoided when there is a large difference in sample sizes between the two outcomes. To better balance the number of NochDF and ChDF, the data set for sidewall analysis was limited to slope failures with initial failure volumes greater than 25 m^3 – the minimum size that resulted in a ChDF. In addition, NochDF events with a gully wall slope distance greater than 60 m were excluded, as this was the largest gully wall slope distance with a ChDF. This resulted in 80 NochDF compared with 37 ChDF. The analysis used geographic area, terrain type, soil drainage, channel gradient, angle of entry, gully wall slope angle,

Table 16 Results of Sidewall Best Model

	p-value	Parameter estimate
Whole model test	0.0001	
Hosmer-Lemeshow test	0.37	
Intercept	0.0001	-6.98
Geographic area	0.034	
Geographic area: North Nitinat		0.78
Geographic area: South Nitinat, Squamish, QCI		-0.78
Channel gradient	0.030	0.064
log channel volume	0.0000	3.08

Figure 19 Sidewall Best Model



gully wall slope distance, log channel volume, and surficial depth.

The analysis resulted in three variables significant to 0.05: geographic area, channel gradient, and the log transform of debris volume into the channel. A separate analysis excluded the North Nitinat data and indicated the remaining three areas were not significantly different, and therefore the model was run again using the two-class geographic area variable. Table 16 shows the statistical results. Figure 19 shows the effect of geographic area, channel gradient, and volume of debris delivered to the channel.

4.2.7 SIDEWALL PREDICTIVE MODEL

Variables included in the Sidewall Predictive Model logistic regression analysis were geographic area, terrain type, soil drainage class, channel gradient, gully wall slope angle, gully wall slope distance, and surficial depth.

Table 17 Results for the Sidewall Predictive Model

	p-value	Parameter estimate
Whole model test	0.0001	
Hosmer-Lemeshow test	0.03	
Intercept	0.57	-0.17
Geographic area	0.0002	
Geographic area: North Nitinat		1.13
Geographic area: South Nitinat, Squamish, QCI		-1.13
Terrain type	0.004	
Terrain type: shallow		-0.67
Terrain type: deep		0.67
Channel gradient	0.11	0.033

The analysis resulted in geographic area, channel gradient and terrain type significant to 0.05. There was no significant difference between South Nitinat, Squamish, and Queen Charlotte Islands, so these areas were combined into a single variable. The parameter estimates for terrain type were all unstable and so the two class variable of terrain was used in another run (terrain types 1, 2, 3, and 4 combined into one class, and terrain types 5, 6, and 7 combined into another class). When geographic area was reclassified and the model run once again, channel gradient became not significant. Table 17 shows the statistical results for the Sidewall Predictive Model which used geographic area, terrain class, and channel gradient. The Hosmer-Lemeshow test shows the model did not fit the data well. Because the model did not fit the data, the effects are not shown.

When all the models were considered together, several trends were evident. The Best Models all showed the volume of debris delivered to the channel had a large effect on debris flow probability. Both the Gully Best Model and the Gully Predictive Model showed location had a large effect on debris flow outcome, with headwall slope failures much more likely to have resulted in debris flows than sidewall slope failures. All the models showed the North Nitinat area was significantly different from the three other areas, but that the South Nitinat, Squamish, and the Queen Charlotte Islands areas were not significantly different. Terrain type, divided into shallow and deep types, was significant in the Gully Prediction Model and the Sidewall Prediction Model (although the Sidewall Prediction Model did not fit the data well). Surficial material depth was significant in the Headwall Prediction Model. Thus the depth of surficial material had a significant effect. Gully wall slope distance was shown as significant in the Gully Best Model and the Headwall Predictive Model. However the effect of gully wall slope distance was directly proportional in the Gully Best Model, and inversely proportional in the Headwall Predictive Model. This suggested that gully wall slope distance was not a useful variable.

5.0 DISCUSSION

This study identifies gully location and the debris volume delivered to the channel as highly significant for debris flow initiation in gullies. Slope failures in gully headwall locations are much more likely to initiate debris flows than slope failures from sidewalls (Tables 11 and 13, Figures 14 and 16). The initial failure volume required to initiate a headwall debris flow is about half the volume of an event required to initiate a sidewall debris flow (Table 9), and the headwall slope angle can be considerably less than the sidewall slope angle required to initiate a debris flow (Figures 10 and 11).

Although headwall slope failures are much more likely to result in a debris flow, the greater number of slope failures in sidewall locations result in an almost equal number of sidewall debris flows as headwall debris flows. Some sidewalls are themselves gullied, resulting in near-headwall conditions. In most gully systems, there is more sidewall area than headwall area, and headwalls are often located above cutblock locations. Consequently, although headwall slope failures are more likely to result in a debris flow, there are more opportunities for sidewall slope failures and subsequent debris flows. Sidewall locations must not be dismissed as insignificant for debris flow hazard.

A major difference between headwall slope failures and sidewall slope failures is the angle of entry. The median headwall slope failure angle of entry is 0°, whereas the median sidewall slope failure angle of entry is 74°. In both headwall and sidewall locations, the angle of entry for ChDF is significantly less than the angle of entry for NochDF. To a large extent the variables location and angle of entry are interchangeable.

However, the logistic regression analysis showed location is a more significant variable than angle of entry, and this may be because other factors are associated with location than just angle of entry. Channel gradients are steeper in headwall than sidewall locations. Half of the headwall slope failures have moderately well or poorly drained soils compared with less than one-third of the sidewall slope failures. These factors may also help to explain why headwalls are more likely to initiate debris flows than sidewalls. Once the data is split into headwall and sidewall data sets, logistic regression shows angle of entry is not a significant factor. Thus knowing, or being able to estimate, angle of entry is not likely to result in a better assessment of debris flow likelihood than simply knowing gully location. The most important result of this portion of the analysis is that location is an easily identified feature of gullies and is an important factor in determining debris flow likelihood.

The second highly significant variable for the initiation of debris flows is the volume of debris delivered to the channel. All the Best Models, which use volume of debris delivered to the channel, show it has a marked effect on debris flow outcome. To a large degree this variable is correlated with the initial failure volume and the initial failure area; however, these variables are not as good predictors in determining debris flow outcome. In about 90% of debris flows, the amount of debris that enters the channel is at least 80% of the initial failure volume. Clearly, whether a slope failure delivers most of the initial failure volume to the channel is critical to the development of a debris flow. Several variables – gully wall slope angle, gully wall slope distance, channel gradient, and angle of entry were tested to determine whether these variables had an effect on the percentage of debris delivered to the channel. No effect from any of these variables was found.

There is limited indication of how to identify gully walls likely to have large initial failures. Figure 2 shows that gully sidewalls with deeper surficial materials (terrain types 5, 6, and 7) can have large initial failure volumes, while veneer terrain types (terrain types 1, 2, 3, and 4) have few slope failures with an initial volume greater than 100 m^3. Each of the Predictive Models show slope failures in deep terrain types or with deeper surficial materials are more likely to result in a debris flow. All other factors being equal, deeper surficial materials should be treated more cautiously. However, surficial material veneers can still generate debris flows. The minimum depth of a slope failure to initiate a debris flow is 0.2 m, but above this minimum depth there is little predictive ability.

Channel gradient is significant in the Gully Models and the Sidewall Best Model. However, channel gradient is not significant in either of the Headwall Models. The minimum channel gradient for headwall slope failures is 20°, with about three-quarters of the slope failures having channel gradients greater than 27° (Figure 6). The logistic regression models may not be able to determine a channel gradient effect in headwalls simply because most of the slope failures occurred with steep channel gradients. In contrast, about half the sidewall slope failures occur with a channel gradient less than 20°, and less than one-quarter have a channel gradient greater than 27°. The greater range of sidewall channel gradients may result in significant effects being detectable.

The sidewall data shows that there are no ChDF that initiate or continue on channel gradients of less than 11°. Almost all sidewall slope failures that initiate a debris flow on channel gradients less than 20° have a debris volume delivered to the channel greater than 50 m^3, indicating that larger events are required to initiate debris flows on low channel gradients. There is no clear threshold effect of channel gradient, but the logistic models allows evaluation of the probability of a debris flow for a given channel gradient. In general, an increase of channel gradient from 10° to 45° results in a 10-40% increase in the probability of a debris flow.

The data from this study shows that debris flows may initiate, or continue, on a broad range of channel gradients, with occasional debris flows initiating in channels with a minimum channel gradient of 11°. This is considerably less than the 25° noted by VanDine (1996) as usually the minimum channel gradient required to initiate debris flows, but just above 10°, noted by VanDine as the channel gradient at which deposition usually begins. Since this study examined slope failures that initiated a channelized debris flow, or that continued as a debris flow, the range of events which this study investigates may be broader than the type of debris flow initiation that VanDine refers to.

All the models, with the exception of the Headwall Best Model, show geographic area to be a significant factor. In each analysis, the best division of geographic area separates the North Nitinat area from the other three areas. Since the South Nitinat, Squamish, and Queen Charlotte Islands areas are shown to behave in a similar fashion, it appears that the parameters that determine debris flow initiation in Coastal British Columbia are fairly consistent throughout the region. Therefore the results of this study are likely to be broadly applicable within Coastal British Columbia.

However, the slope failures from the North Nitinat area are significantly different from slope failures in the other locations. Within the North Nitinat area there are zones of highly sheared and fractured granodiorite or diorite, and this may affect debris flow initiation (T. Rollerson, pers. comm). Of the debris flows that have bedrock visible in the failure plane, the bedrock in 11 was noted as moderately fractured or sheared, compared with the bedrock in three debris flows noted as massive or slightly fractured. This may be the most likely explanation as to the difference in the North Nitinat area. In addition, the North Nitinat area has a greater proportion of large slope failures. Terrain types do not seem to vary greatly between geographic areas, nor does channel gradient.

Whatever the cause of the difference, this result shows that local areas within Coastal British Columbia may differ from the norm. Investigators should satisfy themselves that their area does not have unusual debris flow initiation characteristics.

Gully wall parameters are useful for defining minimum and maximum criteria for debris flow initiation. No debris flows initiate from headwall locations if the gully wall slope angle is less than 26° in till, and 32° in colluvial sediments. Sidewall locations do not initiate debris flows if the gully wall slope angle is less than 35° for till and 39° for colluvium, except for one colluvial ChDF that has a sidewall slope angle of 34° (Figure 11). Few slope failures and no debris flows were recorded on gully wall slopes greater than 55°, most likely because slopes this steep are primarily rock and do not produce large failures. In addition, the minimum gully sidewall slope distance to initiate a debris flow is 7 m.

6.0 CONCLUSION AND RECOMMENDATIONS

This study investigates gully debris flow initiation potential in four geographic areas of Coastal British Columbia. Two hundred and eighty-six slope failures were investigated, of which 75 were debris flows. Two types of analysis were done, the first to identify any factor which may affect the initiation of channelized debris flow, and the second to identify factors which can be used in pre-logging assessments to identify debris flow prone gully locations. Both single and multivariate analyses were used to identify factors in debris flow initiation.

This study has important findings for gully management in Coastal British Columbia. While previous studies have shown some similar results (Rood, 1990; Bovis and Dagg, 1992), this is the most complete study to date to characterize debris flow initiation in Coastal British Columbia gullies. The study confirms the importance of headwall locations, and also indicates that headwalls are not only more likely to initiate a debris flow once a slope failure has occurred, but that slope failures are more likely to occur on lower gradient slopes within headwalls. Angle of entry is closely associated with gully location, and can be a substitute variable for location. Channel gradient is confirmed as a factor for sidewall debris flow initiation, and the probability of initiation relative to channel gradient is now better defined. Analysis shows that gully wall slope angle and gully wall slope distance are useful for defining minimum criteria for slope failures which result in debris flows.

In addition to location (headwall or sidewall), the volume of debris delivered to the channel and the initial failure volume are the most important factors in determining whether a slope failure will result in a debris flow. Deep terrain types have larger sidewall failures, and deep terrain types are more likely to initiate debris flows than shallow terrain types. However, other than terrain type, there is little indication whether a slope failure will be large or small, or how much of the initial failure will reach the channel. Future studies should examine factors affecting initial failure size and the debris volume delivered to the channel in more detail.

For both headwall and sidewall locations, a set of minimum criteria can be stated for debris flow initiation in this study. Below these criteria, debris flows did not occur. Above these criteria, debris flows occurred, but not all slope failures resulted in debris flows.

For headwalls, minimum debris flow initiation criteria are:

- Initial slope failure area of at least 30 m^2;
- Initial slope failure volume of at least 10 m^3;
- Debris volume delivered to the channel of at least 10 m^3;
- Gully wall slope angle of at least 26° for till slopes;
- Gully wall slope angle of at least 32° for colluvial slopes.

For sidewalls, minimum debris flow initiation criteria are:

- Initial slope failure area of at least 50 m^2;
- Initial slope failure volume of at least 25 m^3;
- Debris volume delivered to the channel of at least 25 m^3;
- Gully wall slope angle of at least 35° for till slopes;
- Gully wall slope angle of at least 39° for colluvial slopes (with one exception);
- A gully wall slope distance of at least 7 m.

Above these minimum criteria, the likelihood of debris flow initiation increases with the following factors:

- For both headwalls and sidewalls, an increase in volume of debris delivered to the channel;
- For both headwalls and sidewalls, an increase in initial slope failure size;
- For both headwalls and sidewalls, an increase in the depth of surficial material;
- For sidewalls, an increase in channel gradient.

The results of this study show that debris flow initiation is a complex process. As with most geomorphic processes, a significant degree of uncertainty exists, as demonstrated in the logistic regression output. Although the results of this study better define the factors which result in debris flow initiation, there are limitations to this type of study. Study results use data from four areas of Coastal British Columbia and show that there is significant variation in debris flow initiation rates between some of these areas. Although the results are likely to be applicable throughout most of Coastal British Columbia, caution must be used when applying these results. Terrain scientists should examine local slope failures and debris flows before applying these results to a specific location.

This study provides terrain scientists with methods to evaluate the likelihood of debris flow initiation in gullies. These methods should not be relied on exclusively – other methods may yield better results. Evidence of previous debris flow initiation in a gully reach is strong evidence that further debris flows may occur. In addition, although this study identifies criteria for gully wall slope failure occurrence, it did not examine gullies which did not have slope failures – an important aspect of determining slope failure likelihood.

The objectives of this study were to identify factors associated with debris flow initiation and to develop methods to predict debris flow initiation. This study characterizes many of the factors which affect debris flow initiation and provides criteria to assess debris flow likelihood. The objectives of this study must be put into the context of better forest management. More accurate assessment of debris flow hazards is one step towards better gully management; however it must be kept in mind that gullies may have several hazards that need to be considered before development should occur.

7.0 REFERENCES

Anonymous. 1995a. Gully Assessment Procedure Guidebook. (Forest Practices Code of BC) Province of British Columbia, Victoria, BC.

Anonymous. 1995b. JMP Statistical and graphics guide. SAS Institute. Cary, NC. pp 213-235.

Benda, L.E. and T.W. Cundy. 1990. Predicting deposition of debris flows in mountain channels. Canadian Geotechnical Journal 27: 409-417.

Bergerud, W.A. 1996. Introduction to Regression Models: with worked forestry examples. Biom. Info. Hand. 7. Res. Br., BC Min. For., Victoria, BC. Work. Paper 26/1996.

Bovis, M.J. and B.R. Dagg. 1992. Debris flow triggering by impulsive loading: mechanical modeling and case studies. Canadian Geotechnical Journal, 29: 345-352.

Brayshaw, D.D. 1997. Factors affecting post-logging debris flow initiation in steep forested gullies of the southwestern Canadian Cordillera, Fraser Valley Region. Unpublished Masters thesis. Department of Geography, UBC.

Dietrich, W.E. and T. Dunne. 1978. Sediment budget for a small catchment in mountainous terrain. Zeitschrift fur Geomorpologie, Supp. 29, pp 191-206.

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

Holland, S.S. 1976. Landforms of British Columbia. Bulletin 48, BC Department of Mines and Petroleum Resources. Victoria, BC.

Hosmer, D.W. and S Lemeshow. 1989. Applied logistic regression. John Wiley and Sons, New York. pp 465-466.

Howes, D. 1987. A method for predicting terrain susceptible to landslides following forest harvesting: a case study from the southern coast mountains, British Columbia. Proc. International Association Hydrological Sciences Symposium XIX. University of BC Vancouver, BC.

Muller, J.E. 1977. Geology of Vancouver Island. Geological Survey of Canada Open File 463.

Nuszdorfer, F. C. and Boetger, R., compilers and editors. 1994a. Biogeoclimatic Units of Vancouver Forest Region, Mapsheet 5 of 6, Southern Vancouver Islands and Sunshine Coast. Victoria: Province of British Columbia, Ministry of Forests, Research Branch.

Nuszdorfer, F. C. and Boetger, R., compilers and editors. 1994b. Biogeoclimatic Units of Vancouver Forest Region, Mapsheet 6 of 6, Fraser Valley - Lillooet River. Victoria: Province of British Columbia, Ministry of Forests, Research Branch.

Nuszdorfer, F. C. and Boetger, R., compilers and editors. 1994c. Biogeoclimatic Units of Vancouver Forest Region, Mapsheet 1 of 6. Queen Charlotte Islands. Victoria: Province of British Columbia, Ministry of Forests, Research Branch.

Rollerson, T.P. 1984. Terrain stability study - TFL 44. Land Use Planning Advisory Team. Woodlands Services, MacMillan Bloedel Ltd. Nanaimo, BC.

Rollerson, T.P. 1992. Relationships between landscape attributes and landslide frequencies after logging: Skidegate Plateau, Queen Charlotte Islands. BC Ministry of Forests, Land Management Report No. 76.

Rollerson, T.P, B. Thomson, and T.H. Millard. 1997. Identification of Coastal British Columbia terrain susceptible to debris flows. First International Symposium on Debris Flows, August 1997, San Francisco, California. United States Geological Society/ American Society of Civil Engineers.

Rood, K.M. 1990. Site Characteristics and landsliding in forested and clearcut terrain, Queen Charlotte Islands, BC. BC Ministry of Forests, Land Management Report No. 64.

VanDine, D.F. 1996. Debris flow control structures for forest engineering. Research Branch, Ministry of Forests, Victoria, BC Working Paper 22/1996.