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Coastal fan destabilization and forest management

by

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Cover photo: Alluvial fan in a Vancouver Island forest, with an 8m-wide channel ending in a 15m-wide splay of cobbles and fine sediment.

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ABSTRACT

Alluvial and colluvial fans were studied to determine hydrogeomorphic disturbance type, methods of predicting disturbance type and power, and how forest operations can affect fan processes. Fifty-five fans in the southern Coast Mountains and Vancouver Island were field traversed, and watershed data was collected using a geographic information system. Evidence of old debris flows (>50 years old) was observed on 41 fans; five showed evidence of old debris floods, and nine showed evidence of old water floods. Only 13 fans had evidence of recent (<50 years old) debris flows, seven had recent debris floods, and 29 had recent water floods. The best predictors of geomorphic disturbance type are the fan apex slope gradient, and the Watershed Relative Relief and Melton ratios. Thirty-nine fans had harvesting or roads, although in some cases the harvesting was minimal. Forest operations on the study fans occurred from 1957 to 2004. Forest operations caused destabilization on 15 fans, including avulsions, channel incision, bank erosion and channel widening. Zoning a fan into active, potentially active, and inactive zones is considered an important step toward effective forest management on fans.

KEY WORDS

Alluvial fans, colluvial fans, debris flows, debris floods, fan destabilization, hydrogeomorphic processes, forestry.

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1.0 INTRODUCTION

Alluvial and colluvial fans are located at the bottom of confined channels, and are built from sediment and woody debris deposition in unconfined, lower gradient areas. Debris flows, debris floods, and fluvial (water) floods can all affect a fan surface. These geomorphic processes (or more specifically, hydrogeomorphic processes) can occur within a forestry timeframe (i.e., a period of 100 years), which is more frequent than most people consider (Innes 1983; Jakob and Jordan 2001; Wilford 2003). It has been demonstrated that conventional forest management practices on fans has exacerbated the impacts of naturally occurring geomorphic events: channel avulsions down roads, broadcasting of sediment further across a fan surface, and channel entrenchment (Wilford et al. 2003). These forest management related effects are referred to as "fan destabilization".

Fan stability assessment is required as part of the Gully Assessment Procedure (GAP, Anon 2001), a cited guidebook in the *British Columbia Forest Practices Code*. The new *Forest Planning and Practices Regulations* (Section 54) of the *Forest and Range Practices Act* (FRPA) requires that forestry activities do not cause fan destabilization that causes a material adverse effect in coastal British Columbia (the Coast). Recent work by Wilford (2003) in west-central BC has provided new fan assessment procedures, but there has been almost no research investigation on the Coast, and only limited testing of Wilford's results. Forest managers on the Coast require significant, new science-based knowledge to meet their FRPA obligations.

There is limited knowledge about the effect of forest practices on fans. Most fan research has occurred on arid or semi-arid fans (Bull, 1964; Ryder, 1971), although there is some international recognition of the role of forests on fans (Irasawa et al., 1991). Discussion of fans is often related to deposition of debris flows that originate in the upstream catchment (Bovis and Jacob, 1999; Jackson et al, 1987). Literature on forested fans in BC is often limited to case studies (e.g., Kellerhals and Church, 1990). With the exception of Wilford's studies (2003) in west-central BC, very little systematic work has been done in BC studying geomorphic processes on forested fans and their interactions with forestry operations.

As with many geomorphic processes, the results of studies in one area may not be applicable to other areas. There are likely significant differences between coastal fans and the fans that Wilford studied in west-central BC. Tree species and size, precipitation regimes, terrain, and geology may all affect watershed and fan processes differently between the two regions. Therefore, to provide information in support of FRPA, this research project was initiated on the Coast to:

1. Characterise coastal fans using Wilford's (2003) classification, and to determine coastal fan sensitivity to destabilization.
2. Assess the extent and character of forestry-related fan destabilization, and to determine the factors causing the disturbance.
3. Develop a method for evaluating hazards on fans appropriate for forest management.

2.0 FORESTED FAN ASSESSMENT IN BRITISH COLUMBIA

The Gully Assessment Procedure (GAP) assesses fan destabilization potential using two criteria. The first criterion, a fan destabilization index, uses a combination of the number of channels on a fan, and the depth of channel incision. Increasing numbers of channels indicates a greater chance of destabilization, and increasing channel incision indicates a lesser chance of destabilization. The second criterion uses the frequency of debris flow deposits to assess destabilization potential.

Wilford (2003) classifies fans by the most powerful type of geomorphic process that occurs on a fan: debris flow > debris flood > water flood. Four power levels are also defined on the basis of the extent of forest disturbance:

1. *No power* describes situations where no evidence can be found

of geomorphic processes having occurred in the past 250 years (approximately).

2. *Low power* events do not have sufficient power to uproot or break trees. Deposition of sediment occurs around trees. These events are not observable on 1:20,000 aerial photographs.
3. *High power, site level* events create narrow swaths through the forest on a fan. The width of these swaths is <20 m, and they are generally not visible on 1:20,000 aerial photographs.
4. *High power, stand level* events create swaths >20 m wide through the forest, visible on 1:20,000 aerial photographs.

Basic watershed morphometrics and attributes were tested in west-central British Columbia to determine whether they are significantly associated with fan type (Wilford et al. 2004). Table 1 shows the watershed attributes found most useful for predicting the disturbance type. Some of the attributes that Wilford et al. found significant, such as the Melton ratio (defined as Watershed Relief/Watershed Area$^{0.5}$, Melton 1957), have been shown to be significant in other studies (Jackson et al 1987, Bovis and Jakob 1999), and are likely to be significant in this study area as well. However class limits for some of the attributes such as watershed area or watershed length are likely to be different for coastal fans due to the very different precipitation regimes.

3.0 STUDY DESIGN AND METHODS

To evaluate fans from a broad range of coastal conditions, four areas were selected for study: the Nahatlatch Valley near Boston Bar, the Elaho Valley near Squamish, the Walbran and McClure Lake area of southwestern Vancouver Island, and the Woss area of northern Vancouver Island (Figure 1). Preliminary aerial photograph interpretation identified numerous fans in each area, with a variety of fan types and logging history. Once field work began, most fans within an area were assessed. The major reason for excluding a fan was difficult access. In some cases, fans that had been logged about 20-30 years ago were excluded due to the difficulty of identifying geomorphic features on fans where young, thick forests have regenerated after logging.

For each fan, data on fan attributes, watershed attributes, forest practices, and forest practices effects were collected, using a combination of map work, air photo interpretation, and field work.

Fan attribute data collected included:

- **Fan surface slope gradients** at locations from the apex to the toe.
- **Number and location of active channels:** Active channels exhibit areas of fresh sediment that has no accumulation of leaf litter or vegetation established on it. The channel may or may not have water in it at the time of the field work.
- **Channel gradient, width, bankfull depth, and depth of incision** from the bottom of the channel to the fan surface (or the top of any levées present). Gradient was measured using a clinometer. Distance measurements used tape measures or for longer distances a laser rangefinder.
- **Disturbance type:** debris flow, debris flood, or water flood. Fans were classified by the most powerful type of events; if a fan had evidence of debris flows, it was classified as a debris flow fan even if there was evidence of debris floods or water floods. Similarly, if a fan had evidence for both debris floods and water floods, it was classified as a debris flood fan. Debris flow deposits were identified based on the presence of bouldery lobes or levées, the presence of large boulders (usually with a b-axis >1 m, and sometimes much larger), and massive, poorly sorted, matrix-supported deposits. Sheet deposits of massive, generally clast-supported sediment, with no evidence of levées, were identified as debris flood deposits. Water flood deposits were identified on the basis of typical fluvial forms such as bars, sedimentary structures such as laminations, cross-bedding or cut and fill structures, imbrication, and generally clast-supported deposits (VanDine, 1985; Smith 1986; Costa, 1988; Wells and Harvey, 1987; Hungr et al., 2001).
- **Disturbance power** based on forest cover disturbance (no power, low power, high power site level, high power stand level).
- **Age of events**, using aerial photograph interpretation or dendroecological techniques (Wilford et al. 2005a) classified as either "recent" (less than approximately 50 years), or "old" (greater than 50 years).
- **Process features:** sediment splays, woody debris jams, levées, lobes, avulsions.
- **The frequency of geomorphic events**, determined by dating scars on trees or cohorts of trees that occupy a fresh

Table 1. Class limits for the hydrogeomorphic processes (From Wilford et al. 2004). (WS length is watershed length, measured in a straight line from the fan apex to the most distant point along the watershed boundary).

Hydrogeomorphic Process	Watershed Attribute	Class Limits
Water floods	Melton ratio	< 0.30
Debris Floods	Melton ratio and watershed length	Melton: 0.30 to 0.6 When Melton > 0.6, WS Length ≥2.7 km
Debris Flows	Melton ratio and watershed length	Melton > 0.6 and WS Length < 2.7 km

surface created by a high power geomorphic event (Wilford et al. 2005a). Forest stands in coastal BC may become established as early as the summer after an event occurs, particularly for a species such as red alder (Alnus rubra).

- **The presence or absence of paraglacial, or relict, surfaces** that are above the modern surface of the fan (Ryder 1971a, 1971b).
- **Data on harvest history, road location, and road construction**, as well as process features (sediment splays, woody debris jams, levées, avulsions, incisions, debris flow, or debris flood events) that were caused by, or interacted with, forest operations.

We defined the location of sediment splays, debris flow deposits, and avulsions by their location relative to the fan apex, the intersection point, and the fan toe. The intersection point is the location at which the channel merges with the contemporary fan surface, that is, the channel becomes unconfined. The fan toe marks the lowest edge of fan sediments. Identifying the edge of fan sediments is not always possible on forested fans, and in some cases the fan toe is truncated by the valley bottom stream or lake. We defined the location of the fan toe using one of three criteria:

1. Where all channel features ended and fan gradient was <0.5° (or 1%);
2. Where a fan channel met the valley bottom river;
3. The lake edge.

Two ratios are defined that normalize the location of process features on a fan:

$$\text{Apex ratio} = \frac{(\text{Distance from the fan apex to the process feature})}{(\text{Distance from the fan apex to fan toe})}$$

$$\text{Intersection ratio} = \frac{(\text{Distance from fan intersection point to process feature})}{(\text{Distance from fan intersection point to fan toe})}$$

Watershed attributes included:

- Bedrock geology and surficial materials of the watershed
- Presence of landslides in the watershed
- Following Wilford (2003), a set of geographic information system (GIS) generated attributes (Table 2). GIS data was collected at a scale of 1:20,000.

The fans were classified using the dominant "old" disturbance type. "Old" disturbance type was chosen since limiting the fans to events <50 years ("recent events") may not adequately reflect the potential for debris flows from sediment-limited watersheds (Bovis and Jakob 1999). To determine whether "old" disturbance type can be identified using watershed or fan attributes we used one-way analysis of variance (ANOVA) tests. If significant differences in attribute means were detected, Bonferroni multiple comparison tests were used to determine which groups have different means (Milliken and Johnson 1992). Strongly skewed variables were log-transformed before the ANOVA and Bonferroni tests.

Logistic regression analysis was used to identify multivariate models that are useful predictors of old disturbance type.

All statistical tests used a significance level of 0.05.

Forest practices effects were evaluated to determine the relationship between the type of fan and forest practices that may result in fan destabilization. Due to the complexities of fan type, geomorphic process history since logging, and forest practices, we did not do a rigorous statistical analysis for this aspect of the project.

4.0 STUDY LOCATIONS

Fans from a broad range of locations within the Southern Coast Mountains and Vancouver Island were surveyed (Figure 1). This provided a range of geology, physiography, and biogeoclimatic zone.

Nahatlatch Valley

The Nahatlatch Valley is a west-east trending valley that drains from the west into the Fraser River. The valley is located on the west side of the Fraser Canyon a few kilometres north of Boston Bar, within the easternmost portion Pacific Ranges of the Coast Mountains (Holland, 1976). Bedrock in the study area is granodiorite and quartz diorite of the Scuzzy Pluton (Monger, 1969).

The study sites are all located in the middle portion of the valley, from Nahatlatch Lake to the junction of Mehatl Creek and Nahatlatch River (Figure 2). The valley is a deep glacial trough. Valley bottom elevations are about 300–400 m, and ridge-tops are at 1,500–1,700 m above sea level (asl). The Nahatlatch River meanders across the 600–1000 m wide valley bottom. Fans are located along both the south and north sides of the valley where steep side drainages enter the main valley. Some of the channels discharge into Nahatlatch Lake, and the landform is more specifically defined as a fan delta (Prior and Bornhold 1988).

Slopes above the valley bottom typically have veneers of till and colluvium (Ryder, 1981), and many of the steep slopes have exposed bedrock. Snow avalanche tracks are common on the upper slopes, with these tracks occasionally reaching the lower valley slopes and the upper portions of some fans.

Lytton, in the Fraser Canyon approximately 30 km north of the mouth of the Nahatlatch River, receives 432 mm of precipitation annually (Environment Canada 2005), with almost 80% of this as rainfall. The majority of precipitation, both rain and snow, occurs in the fall and winter months. The maximum daily rainfall recorded for Lytton is 60 mm. Hope, about 65 km south of the mouth of the Nahatlatch River at the bottom end of the Fraser Canyon, has a more coastal climate. Annual precipitation is 2,008 mm, of which 94% is rainfall, with a maximum daily rainfall of 173 mm. It is likely that the Nahatlatch Valley has a climate intermediate between Lytton and Hope. Like Hope, the valley is subject to occasional high-intensity short-term rainfall events.

Table 2. Watershed attributes.

Attribute	Unit	Description
WS Area	km^2	Planimetric area of the watershed
WS Relief	km	Maximum elevation – minimum elevation
WS Length	km	Straight-line, planimetric distance between the fan apex and the furthest point on the watershed divide
Melton Ratio		Melton's Ruggedness Index = WS Relief / (WS Area)$^{0.5}$
WS shape		Watershed Shape = Area / Length^2
Relief ratio		Relief / WS Length
ER ratio		Elevation-Relief Ratio (approximation to the hypsometric integral) = (meanRel – minRel) / (maxRel – minRel)
Channel Length	km	Total length of stream channels in the watershed
Drainage density	km/km^2	Drainage density = Channel lengths / Area
G30P	%	Percent of watershed with slopes >30°
G35P	%	Percent of watershed with slopes >35°
G40P	%	Percent of watershed with slopes >40°
G3040P	%	Percent of watershed with slopes >30° and <40°
L4P	%	Percent of watershed with slopes <4°
G3025m	%	Percent of watershed within 25 m of streams with slopes >30°
G3050m	%	Percent of watershed within 50 m of streams with slopes >30°
G30100m	%	Percent of watershed within 100 m of streams with slopes >30°
G3525m	%	Percent of watershed within 25 m of streams with slopes >35°
G3550m	%	Percent of watershed within 50 m of streams with slopes >35°
G35100m	%	Percent of watershed within 100 m of streams with slopes >35°
G4025m	%	Percent of watershed within 25 m of streams with slopes >40°
G4050m	%	Percent of watershed within 50 m of streams with slopes >40°
G40100m	%	Percent of watershed within 100 m of streams with slopes >40°
B304025m	%	Percent of watershed within 25 m of streams with slopes >30° and <40°
B304050m	%	Percent of watershed within 50 m of streams with slopes >30° and <40°
B3040100m	%	Percent of watershed within 100 m of streams with slopes >30° and <40°
L425m	%	Percent of watershed within 25 m of streams with slopes <4°
L450m	%	Percent of watershed within 50 m of streams with slopes <4°
L4100m	%	Percent of watershed within 100 m of streams with slopes <4°

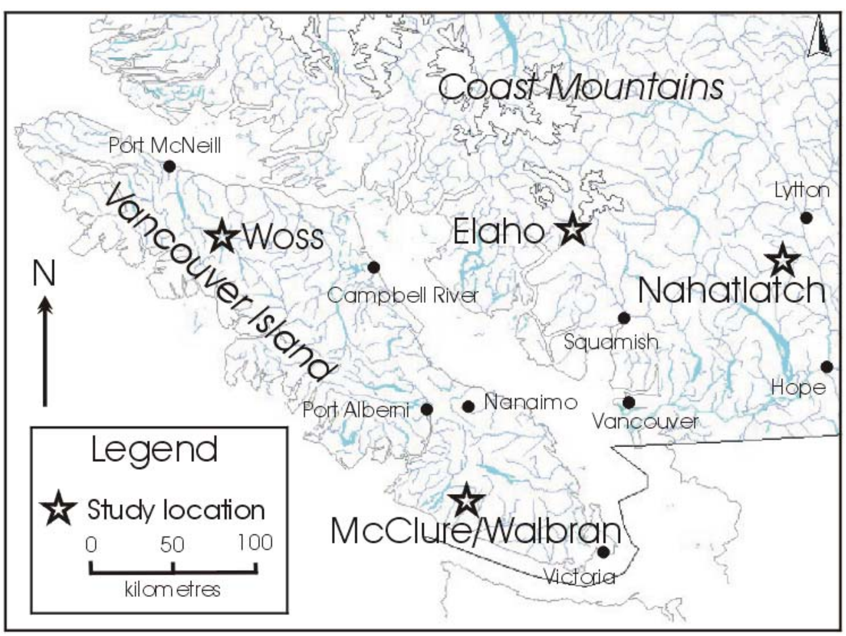


Figure 1. Location map for study sites.

Most of the valley bottom and lower slopes are in the CWHds1 biogeoclimatic zone. Some lower south-facing slopes are in the IDFww, and north-facing slopes are in the CWHms1. Higher elevations are in ESSFmw and the highest elevations are in ATi (Nuszdorfer and Boetger 1994).

Fires are a significant factor within the valley. A large burn occurred in 1938 on the north-facing valley slope, and some of the south-facing slopes burned in 1958. Both burns affected portions of some of the study watersheds (Ministry of Forests 2000).

Logging of the valley bottom and lower elevation slopes upstream of Nahatlatch Lake commenced in the late 1950s and ended by the mid 1970s in the study area portion of the valley. The valley bottom is now a provincial park.

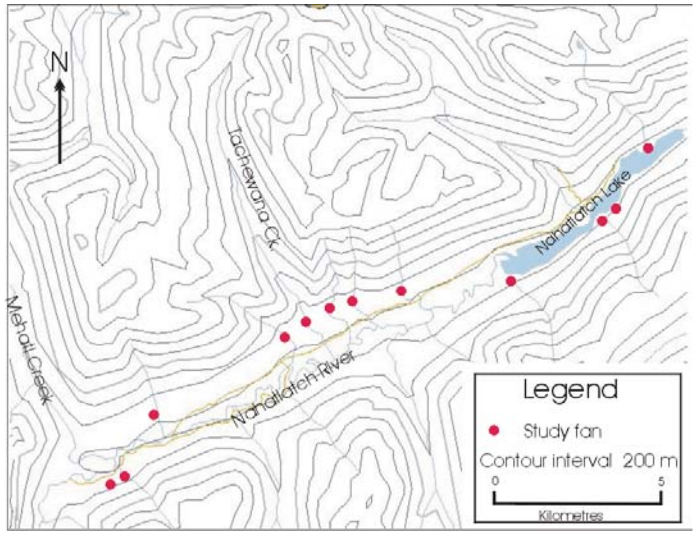


Figure 2. Nahatlatch Valley sample sites.

Elaho Valley

The Elaho Valley, approximately 40 km WNW of Whistler, is another deep glacial trough located within the Pacific Ranges of the Coast Mountains. The Elaho River flows north to south in the study portion of the valley (Figure 3). The valley bottom elevation is about 300 m, with very steep valley sidewalls rising to over 2,000 m asl. The valley bottom is 500–800 m wide. Bedrock is primarily granodiortite, with some quartz monzonite and granitoid gneiss (Roddick and Woodsworth 1977).

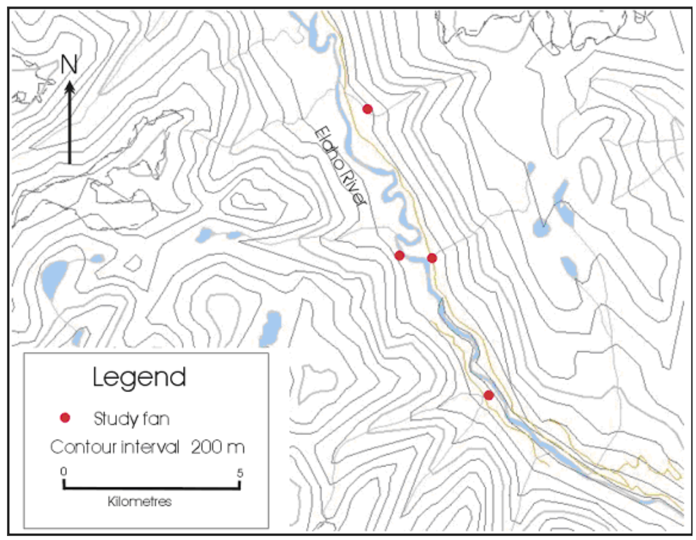


Figure 3. Elaho Valley sample sites.

The Pemberton Icefield is to the east of the study sites, and most of the study fans have glaciers in the headwaters of their basins. Exposed bedrock, till, and colluvium are common on higher slopes. Snow avalanches are frequent on many slopes.

Whistler, at an elevation of 658 m, receives an average of 1,229 mm of precipitation annually, with 67% as rain (Environment Canada 2005). The maximum recorded daily rainfall is 97 mm. Squamish, approximately 60 km SSE of the Elaho Valley, and at an elevation of 46 m, receives 2,367 mm of annual precipitation, 90% of it rain. The maximum daily rainfall at Squamish is 129 mm. Fall and winter months receive the majority of the precipitation.

The largest flood event measured for the Elaho River occurred in October 2003. Over a three-day period, 548 mm of rain fell, with additional snow melt. The Elaho River has a short gauging history, but the October 2003 event in nearby rivers resulted in floods with return periods of over 100 years, and perhaps as much as 200 years (A. Chapman, pers.comm. 2005)[1].

The valley bottom is in the CWHds1 biogeoclimatic zone, with mid-slopes in the CWHms1, and higher slopes in the MHmm2. Ridge-top areas are in ATc zone or are occupied by glacial ice (Nuszdorfer and Boetger, 1994). Logging in the valley began in the 1970s and continues to date.

Woss study area

The town of Woss is located on northern Vancouver Island within the Vancouver Island Ranges (Holland, 1976). Fan study sites are located within a 25 km radius of Woss: along Woss Lake, about 7 km south of Woss; near Schoen Lake, about 24 km ESE of Woss; near Claude Elliot Lake, about 12 km NNE of Woss, and one fan located near Nimpkish Lake, about 25 km WNW of Woss (Figure 4). The Woss Lake study sites are fan deltas, two of the Schoen Lake study sites are fan deltas, and two of the Claude Elliot study sites are fan deltas. Valley bottom elevations range from 200–400 m, and ridge top elevations are generally from 1,000–1,500m asl.

Bedrock in the Woss Lake area is primarily Karmutsen Formation (basaltic lava, pillow lava, and tuff), with Island Intrusions (granodiorite, quartzdiorite, granite, and quartz monzonite) at the north end of the lake. The Schoen Lake area is primarily Karmutsen Formation, with some metasediments of the Vancouver Formation. In the Claude Elliot Lake area and to the south, the Island Intrusions are present, while Karmutsen Formation underlies the area to the north and east of Claude Elliot Lake. The study site near Nimpkish Lake is underlain by Bonanza Formation, which is

[1] Allan Chapman, Forecast Hydrologist, BC Ministry of Environment.

basaltic to rhyolitic lava, tuff, breccia, and minor argillite and greywacke (Muller, 1977).

Port Alice, located about 65 km NW of Woss, is on a fjord on the west side of Vancouver Island, and receives 3,337 mm of precipitation annually, 99% of it as rain (Environment Canada 2005). Fall and winter months have the greatest precipitation, and the one-day maximum rainfall recorded is 234 mm. Alert Bay, 50 km NNE of Woss, and east of Vancouver Island, receives 1,591 mm of precipitation, 96% of it rain. The largest one-day rainfall recorded is 116 mm. Precipitation amount in the Woss area is likely to be intermediate between Port Alice and Alert Bay, with more of the precipitation falling as snow.

Lower elevations, and all the fans in the Woss area, are within the CWHxm2 or CWHvm1 biogeoclimatic zones (Nuszdorfer and Boetger, 1994). Higher elevations are within the MHmm1 zone, and there are small amounts of ATc at the highest elevations. The Woss area has a long history of logging, with some of the study fans being logged in the 1960s.

Walbran Creek and McClure Lake area

This area is located in the southwest portion of Vancouver Island, between Nitinat Lake and Port Renfrew. The area is part of the Vancouver Island Mountains. Valley bottom elevations are about 200–300m and ridge top elevations are about 900–1,100 m. Two of the McClure Lake study sites are fan deltas, and one study site within the Walbran Valley is partially a fan delta (Figure 5).

Island Intrusions are the dominant bedrock type in the area. Some Bonanza Formation may underlie portions of some of the study fan watersheds (Muller, 1977).

The Nitinat River Hatchery is approximately 15 km NW of McClure Lake and although about 25 km inland, is only at an elevation of 15 m. It receives 3,700 mm of precipitation annually, with 98% as rain (Environment Canada 2005). The maximum daily rainfall recorded is 257 mm. Port Renfrew, approximately 25 km to the SW, receives 3,671 mm of precipitation annually, with 98% of it rain. Its maximum daily rainfall is 293 mm.

Logging within the McClure Lake area commenced in the late 1960s and is ongoing.

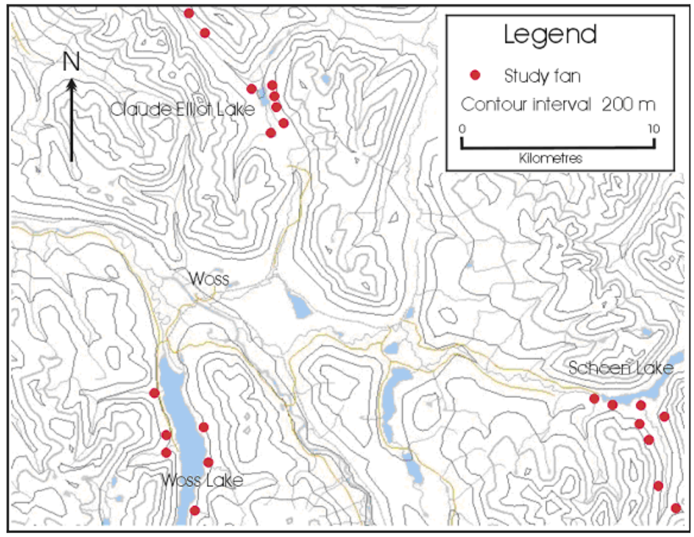


Figure 4. Woss study sites.

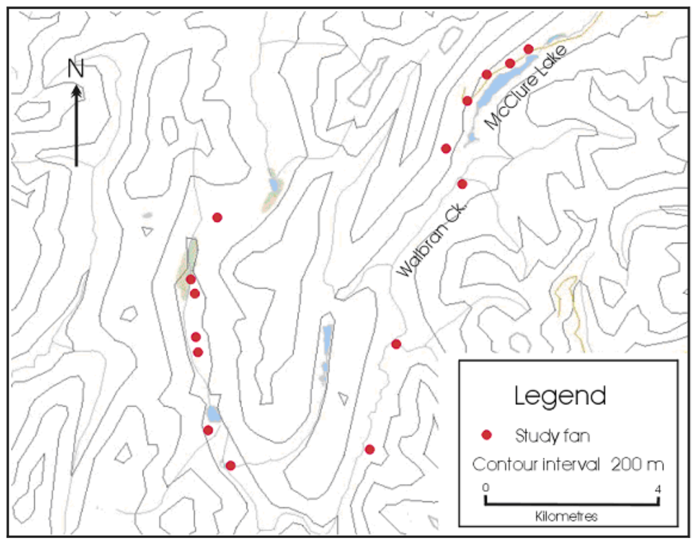


Figure 5. Walbran Creek and McClure Lake sample sites.

5.0 RESULTS

5.1 PROCESS INDICATORS AND EXAMPLES

Photographs presented in Appendix A (Figures 21-40) illustrate geomorphic process indicators, fan features, and forest operations effects.

Table 3 summarizes the fans investigated in this study. Almost three-quarters of the fans had roads or some amount of harvesting. Less than half of the fans had logging within the watershed area above the fan, and in six cases the total watershed area logged was very small. In the Nahatlatch Valley, most logged fans were selectively harvested in the period 1950-1965, with smaller trees or cohorts of smaller trees left standing. Forest cover on almost all other fans was clearcut, although in some cases only a portion of the fan was clearcut.

Many fans had paraglacial surfaces that are relict and no longer active. Of the 55 fans studied, 28 had relict surfaces. On these fans the modern channel had entrenched into the old surface as much as 20 m, with the inactive surfaces often constituting a much larger area than the contemporary fan surface.

5.2 PROCESS TYPE, FREQUENCY, AND WATERSHED/FAN ATTRIBUTES

Tables 4a and 4b show the old process type and power, and Tables 5a and 5b show the recent process type and power. Although three-quarters of the fans showed evidence of old debris flows, only six fans (11%) had recent debris flow events. In addition, six fans were classified as "no power" for recent events; in other words, they showed no sign of contemporary geomorphic effects outside of the stream channel. In many cases, debris flow fans appear to have been stable for several centuries, with old-growth forest stands growing on debris flow deposits.

One-way ANOVA identified the watershed and fan attributes in Table 6 as significant predictors of old geomorphic process type. Ranked Bonferroni adjusted multiple comparison tests determined which groups have different means. Skewed distributions were transformed to achieve normal or near normal distributions. "Old" process type was chosen since limiting the response of a basin to a period of 50 years ("recent process") does not provide a sufficient time period to accurately reflect the possibility of debris flows occurring. All attributes with a significance level $\leq$0.05 are reported.

One sample was excluded from this analysis. Fan WT-7, in the Walbran Valley, was identified as a debris flow fan. However, the watershed has a large, low-gradient upper portion, and then a short, steep, incised lower portion immediately above the fan apex. Debris flows appear to initiate immediately above the fan apex and do not reflect overall watershed processes. Using the watershed attributes selected for this study to predict fan process is not appropriate for this type of watershed.

Table 3. Summary of fans studied.

Study area	Number of fans studied	Number of fans with harvesting on the fan	Number of fans with roads	Number of fans with harvesting or roads	Number of fans with watershed harvesting
Nahatlatch	14	8	9	9	1
Elaho	4	4	4	4	0
Woss	22	11	15	16	11
McClure/Walbran	15	8	8	10	11
Total	**55**	**31**	**36**	**39**	**23**

Table 4a. Summary of old geomorphic process type (number of cases).

Location	Debris flow[1]	Debris flood			Water flood			Total
	Stand	Low	Site	Stand	Low	Site	Stand	
Nahatlatch	13						1	**14**
Elaho	3			1				**4**
Woss	14			2	1	2	3	**22**
McClure/Walbran	11		2		1		1	**15**
Total	**41**	**0**	**2**	**3**	**2**	**2**	**5**	**55**

1) In cases where debris flow deposits are too old to determine power, stand level power is assumed.

Table 4b. Summary of old geomorphic process type (per cent).

Location	Debris flow[1]	Debris flood			Water flood			Total
	Stand	Low	Site	Stand	Low	Site	Stand	%
Nahatlatch	24						2	**26**
Elaho	5			2				**7**
Woss	25			4	2	4	5	**40**
McClure/Walbran	20		4		2		2	**28**
Total (%)	**75**	**0**	**4**	**5**	**4**	**4**	**9**	**100**

1) In cases where debris flow deposits are too old to determine power, stand level power is assumed.

For all attributes in Table 6, the ranked Bonferroni tests identify debris flows as distinct from water floods, but debris floods are never identified as distinct from water floods. Debris flows are distinct from debris floods for most attributes, but in some attributes (e.g., L4P, G30-25m, G30-50m, L4-100 m) there is no significant difference between debris flow fans and debris flood fans. Sample size is small for both debris flood and water flood fans, and this may limit the ability to identify significant differences.

The best univariate predictors of old fan process, defined as having the greatest adjusted R^2, are apex gradient, the relief ratio, the Melton ratio, and watershed area. Watershed length, watershed shape, and channel length are also useful predictors.

Figure 6 shows the distribution of apex gradients by fan type. Point locations in Figures 6–11 may represent multiple samples (i.e., some parameters are the same for some fans and their watersheds). Debris flow fans almost always have steeper apex

Table 5a. Summary of recent geomorphic process type (number of cases).

Location	No power	Debris flow		Debris flood			Water flood			Total
		Site	Stand	Low	Site	Stand	Low	Site	Stand	
Nahatlatch	3	1			1		8		1	**14**
Elaho			2			1	1			**4**
Woss	3	1	3	1		2	2	8	2	**22**
McClure/Wal.		4	2	2			5	1	1	**15**
Total	**6**	**6**	**7**	**3**	**1**	**3**	**16**	**9**	**4**	**55**

Table 5b. Summary of recent geomorphic process type (per cent).

Location	No power	Debris flow		Debris flood			Water flood			Total
		Site	Stand	Low	Site	Stand	Low	Site	Stand	
Nahatlatch	5	2			2		15		2	**25**
Elaho			4			2	2			**7**
Woss	5	2	5	2		2	4	15	4	**40**
McClure/Wal.		7	4	4			9	2	2	**27**
Total	**11**	**11**	**13**	**5**	**2**	**5**	**29**	**16**	**7**	**100**

Table 6. Significant fan and watershed attributes when comparing old process type.

Attribute	**Pr > F**	**R^2 Adj.**	**Bonferroni identified groups (á =0.05)**
Apex gradient	<0.0001	0.59	debris flow ≠ (debris flood, water flood)[2]
WS area[1]	<0.0001	0.52	debris flow ≠ (debris flood, water flood)
WS length[1]	<0.0001	0.33	debris flow ≠ (debris flood, water flood)
Melton ratio[1]	<0.0001	0.57	debris flow ≠ (debris flood, water flood)
Relief ratio	<0.0001	0.63	debris flow ≠ (debris flood, water flood)
WS shape[1]	<0.0001	0.27	debris flow ≠ (debris flood, water flood)
Channel length[1]	<0.0001	0.38	debris flow ≠ (debris flood, water flood)
L4P[1]	0.002	0.18	debris flow ≠ water flood
G30-25m	0.046	0.08	debris flow ≠ water flood
G30-50m	0.019	0.10	debris flow ≠ water flood
B3040-25m	0.0006	0.17	debris flow ≠ (debris flood, water flood)
B3040-50m	0.0005	0.17	debris flow ≠ (debris flood, water flood)
B3040-100m	0.0022	0.13	debris flow ≠ (debris flood, water flood)
L4-100m[1]	0.0007	0.22	debris flow ≠ water flood

1) Variable transformed using Log_{10} (variable +1).
2) "debris flow ≠ (debris flood, water flood)" indicates the attribute identifies debris flow fans as significantly different to both debris flood and water flood fans, but that the attribute does not identify a significant difference between debris flood and water flood fans. "Debris flow ≠ water flood" indicates debris flow fans are significantly different from water flood fans, but not significantly different from debris flood fans.

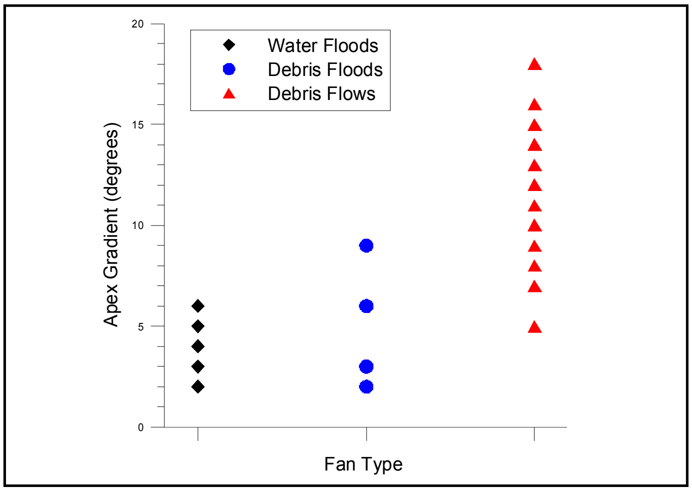


Figure 6. Old process fan type compared with apex gradient.

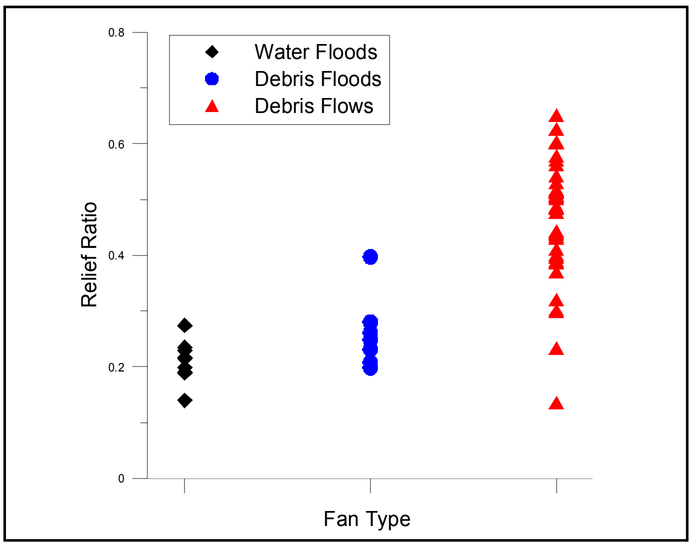


Figure 7. Old process fan type compared with relief ratio.

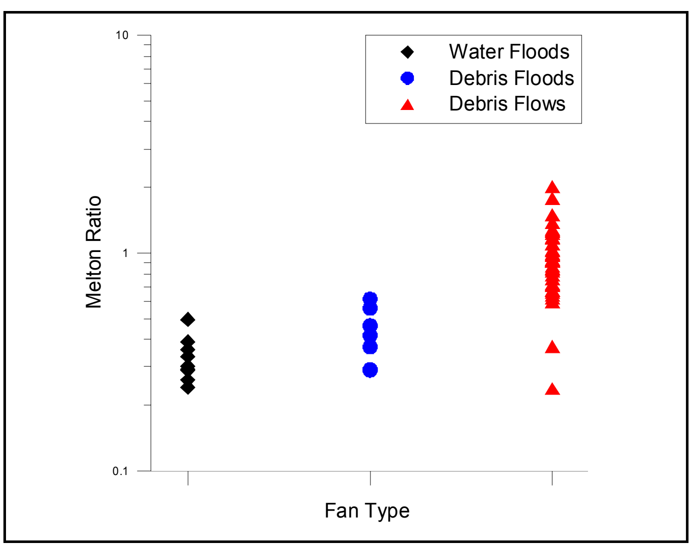


Figure 8. Old process fan type compared with Melton ratio.

gradients than either debris flood or water flood fans. Seven debris flow fans had apex gradients of ≤8°. The "old" process classification on five of these fans was noted as "uncertain" due to limited evidence. The debris flood fan with an apex gradient of 9° was difficult to classify because sediment deposits appeared borderline between debris flood and debris flow.

Fan type is compared to the Relief ratio in Figure 7. Again, debris flood fans are intermediate between debris flow fans and water flood fans. Debris flow fans rarely have a relief ratio <0.3, whereas almost all debris flood and water flood fans have a relief ratio <0.3. Although fans with apex gradients of about 8° often showed characteristics of both debris flows and debris flood processes, some fans with a relief ratio <0.3 show clear evidence of debris flows. These watersheds were either hanging valleys or valleys with the headwaters on a plateau. In either case they had steep incised lower reaches with the potential to initiate debris flows that could reach the fan.

The Melton ratio (Figure 8) separates debris flow fans from debris flood or water flood fans fairly effectively. Only two debris flow fans have a Melton ratio <0.6, and both of these watersheds have gently sloping upper watershed areas above a steeply incised gully located immediately upstream of the fan. The maximum Melton ratio for debris flood fans is 0.6. All but one of the water flood fans have a Melton ratio <0.40. However, there is a large degree of overlap in the Melton ratios of debris flood fans and water flood fans.

Figures 9, 10, and 11 compare "old" process fan type with watershed area, watershed length, and watershed shape (WS Area/ WS Length^2). Although debris flow watersheds are generally smaller (Figure 9) and shorter (Figure 10) than debris flood or water flood fans, there is a greater degree of overlap for these watershed attributes and fan types than for the attributes shown in Figures 6 through 8. Similarly, although water flood and debris flood fans tend to have higher watershed shape values than debris flow fans (Figure 11), there is a large degree of overlap between fan types.

5.2.1 MULTIVARIATE ANALYSIS OF FAN TYPE AND WATERSHED OR FAN ATTRIBUTES

All of the Bonferroni comparison tests listed in Table 6 identified a significant difference between water flood and debris flow fans, and all showed no significant difference between debris flood and water flood fans. Most Bonferroni comparison tests identified that debris flow fans are significantly different from debris flood fans. Therefore we combined debris flood and water flood fans for multivariate analysis. Logistic regression models tested all combinations of non-correlated variables, using a response variable of debris flow fan or non-debris flow fan.

Many of the significant attributes are correlated. By definition, the following attributes are correlated:

- Watershed area with watershed length, Melton ratio and watershed shape;
- Watershed length with Melton ratio and relief ratio;

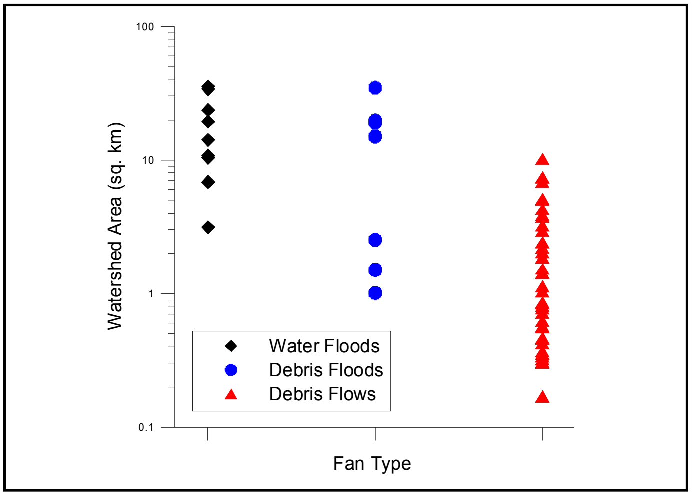


Figure 9. Old process fan type compared with watershed area.

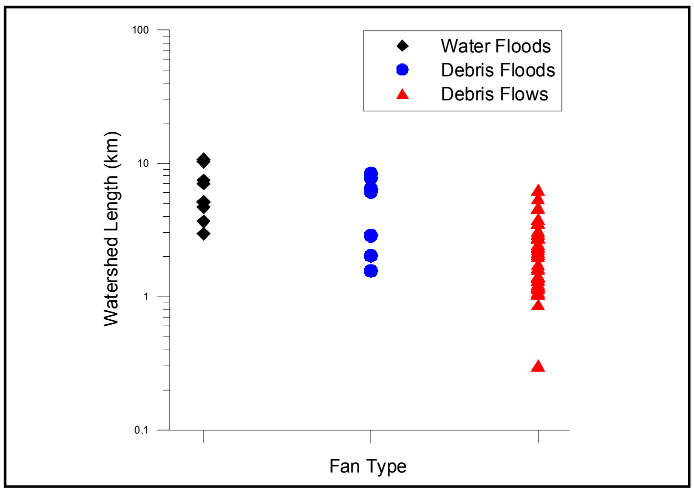


Figure 10. Old process fan type compared with watershed length.

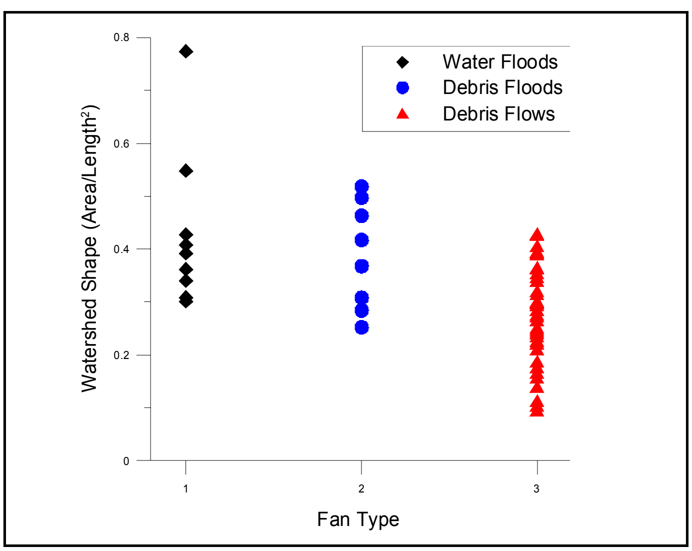


Figure 11. Old process fan type compared with watershed shape.

- Melton ratio with relief ratio;
- All attributes measuring percentages of watershed area in specific slope classes.

In addition, the following attributes are correlated using a criterion of $r = 0.50$:

- Apex gradient with watershed area, watershed length, Melton ratio, relief ratio, channel length, and B3040-100m;
- Watershed length with channel length;
- Melton ratio with watershed shape and channel length;
- Relief ratio with watershed shape, channel length, L4P, G30-25m, G30-50m, B3040-25m.

A total of ten multivariate models have significant results (at p = 0.05), but none yield results that are better predictors than the best univariate predictors (apex elevation, relief ratio, and Melton ratio). Since the univariate results are better predictors of "old" process, we present no multivariate results.

Wilford et al. (2004) found that a combination of watershed length and Melton ratio provided the best predictive ability for fan process, with debris flow fans having a Melton ratio of >0.6 and a watershed length of <2.7 km, and water flood fans having a Melton ratio <0.3 (Table 1 contains the class criteria from Wilford et al.). Figure 12 shows the data for this study plotted using the combination of Melton ratio and watershed length, and the class boundaries determined by Wilford et al. The plot shows that coastal BC fans are similarly classified by Melton ratio, with almost all debris flow fans having a Melton ratio >0.6, debris flood fans generally having a Melton ratio

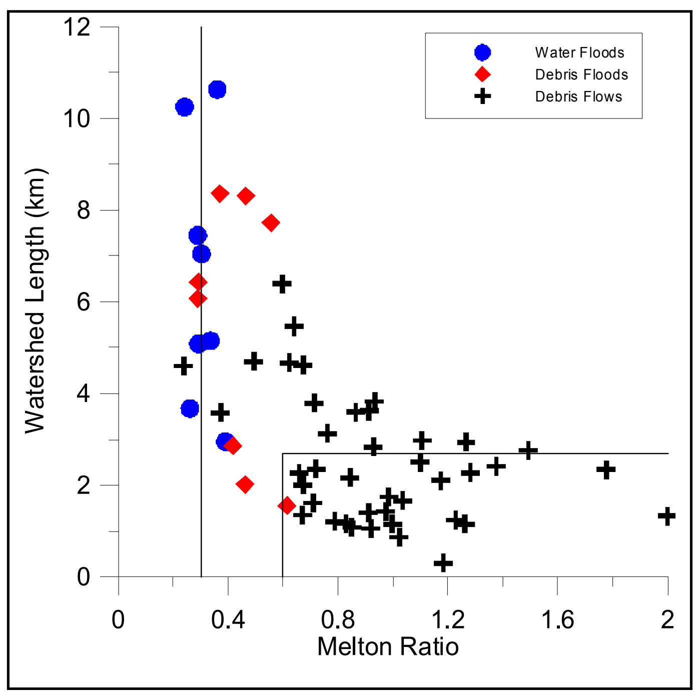


Figure 12. Differentiating fan process using the Melton ratio and watershed length (as proposed by Wilford et al., 2004).

between 0.3 and 0.6, and water flood fans generally having a Melton ratio of <0.3.

5.3 LOCATION OF PROCESS FEATURES ON FANS

To determine whether avulsions, debris flow deposits, or splays occur at predictable locations on a fan surface, we evaluated where these features are located in relation to the fan apex or the intersection point. On some fans there is no fan-head entrenchment, and therefore the intersection ratio becomes equivalent to the apex ratio. Features affected by forest operations were excluded from this analysis.

Figures 13 through 15 are distribution histograms of process features for the range of apex ratios. The data presented here reflects locations of active or recent geomorphic process evidence. We observed that all process features can occur on any location on a fan surface, but some patterns are apparent. Figure 13 shows that debris flow deposits most frequently occurred on the upper 60% of the fan (as measured by distance from apex). In contrast, most splay deposits occurred on the lower 60% of the fan (Figure 15). Channel avulsions occurred frequently on all locations on a fan, although somewhat less frequently near the fan toe (Figure 14).

Figures 16 through 18 are similar frequency distribution histograms using the intersection ratio, but patterns showing debris flow deposits, and avulsion and splay locations are more apparent. Debris flow deposits, avulsions, and splays located above the intersection point were rare (shown in Figures 16 to 18 as negative values). Most debris flow deposits were located midway between the intersection point and the toe of the fan. Avulsions were most frequent immediately downstream of the intersection point and declined in frequency as distance below the intersection point increased (Figure 17). Splays were most frequent on the lower portions of fan surfaces (Figure 18).

We evaluated channel width, depth, and incision to determine channel configurations likely to result in avulsions. Figure 19 plots avulsion and non-avulsion locations compared to channel width and bankfull channel depth. Figure 20 plots avulsion and non-avulsion locations compared to channel width and channel incision. Neither channel depth or channel incision appears to have a strong effect on the location of avulsions, with the exception of an upper limit of channel incision. The maximum depth of channel incision at which an avulsion occurred was three metres. Only five avulsions, of a total of 114 observed, occurred when channel incision was greater than 2 m, and four of these avulsions occurred on fans with recent debris flows.

5.4 HARVESTING AND ROAD EFFECTS

A total of 39 fans had forest operations (harvesting or roads). Table 7 is a summary of harvesting and road effects on fan processes and features. Identifying specific effects and their causes can be difficult, particularly for fans logged decades prior to this project. We generally relied on interpretation of historical aerial photographs to identify effects that occurred prior to about 1980. Bank erosion generally refers to field evidence of localized erosion. Channel widening refers to channels that were measurably wider using aerial photographs.

Of the fifteen fans that had negative forestry-fan process interactions, ten were negatively affected by forestry operations, and on seven of these fans the extent of change was beyond the range of natural variability, meeting the definition of fan destabilization. Seven fans had forestry infrastructure that was impacted by natural fan processes.

Most of the logging-related fan destabilization effects are a result of roads, skid trails, or channel crossing structures. Roads and crossing structures caused over 80% of the forest management-related avulsions, with half of these associated with climbing roads (i.e., the road gains elevation toward the stream crossing). In some cases multiple channels were intercepted by a ditch, with all of the water delivered to one crossing structure. In at least one case this concentrated discharge was associated with channel incision below the road. Avulsions associated with climbing roads caused some of the greatest impacts to fans.

Several fans had logging to the channel banks. In these cases, it

Figure 13. Debris flow deposits from the apex.

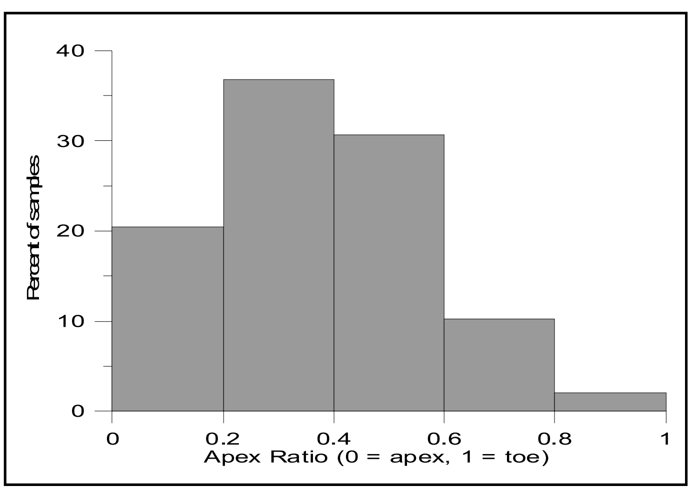


Figure 14. Avulsion location from the apex.

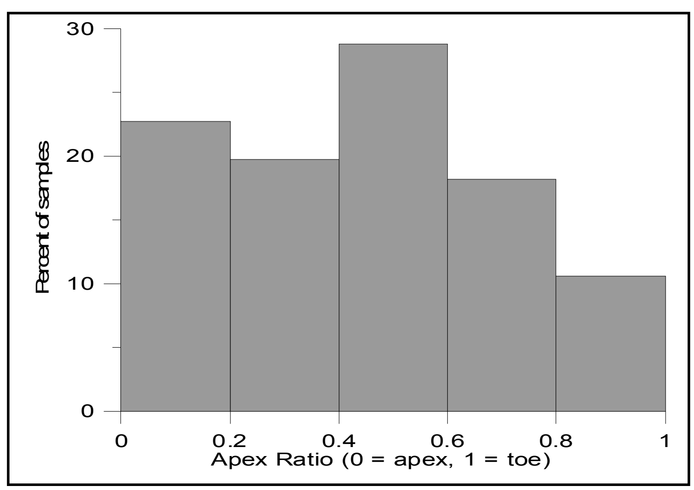


Figure 15. Splay deposits from the apex.

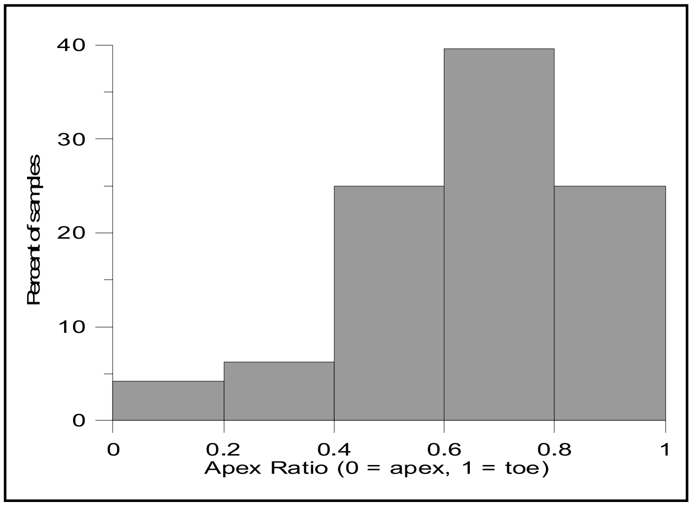


Figure 16. Debris flow deposits from the intersection point.

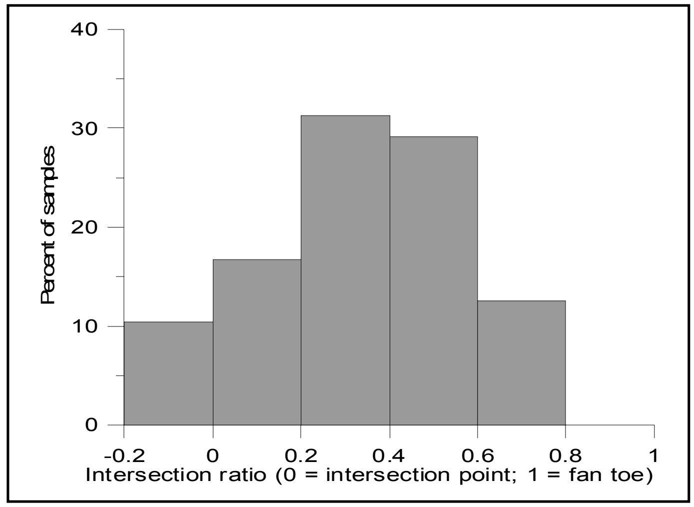


Figure 17. Avulsion location from the intersection point.

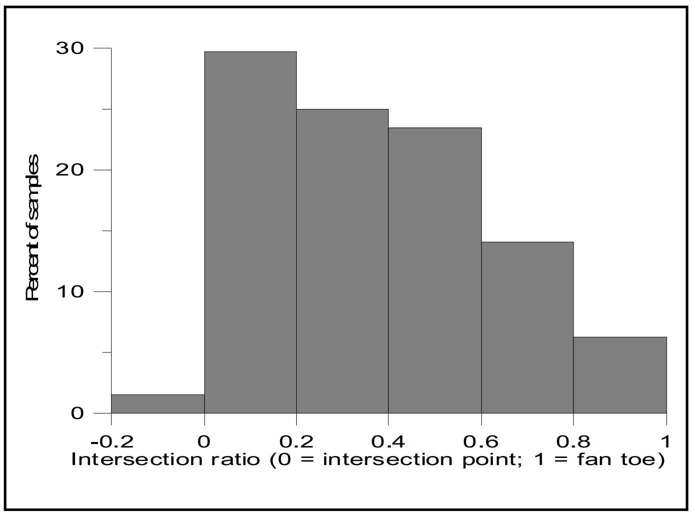


Figure 18. Splay locations from the intersection point.

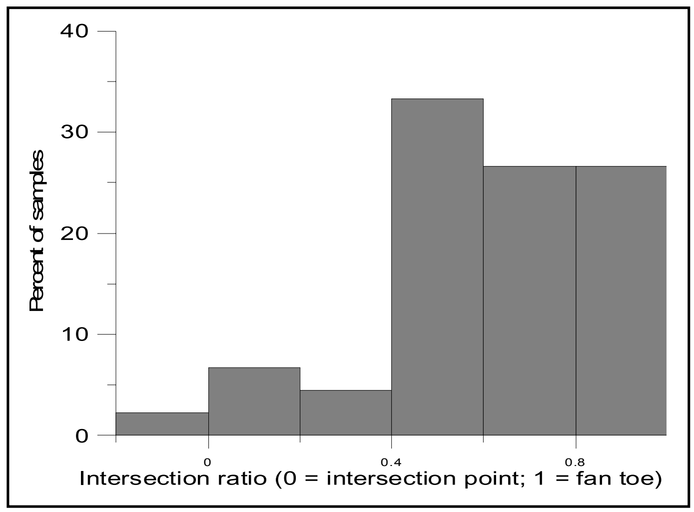


Figure 19. Channel width, channel depth, and the presence or absence of avulsion.

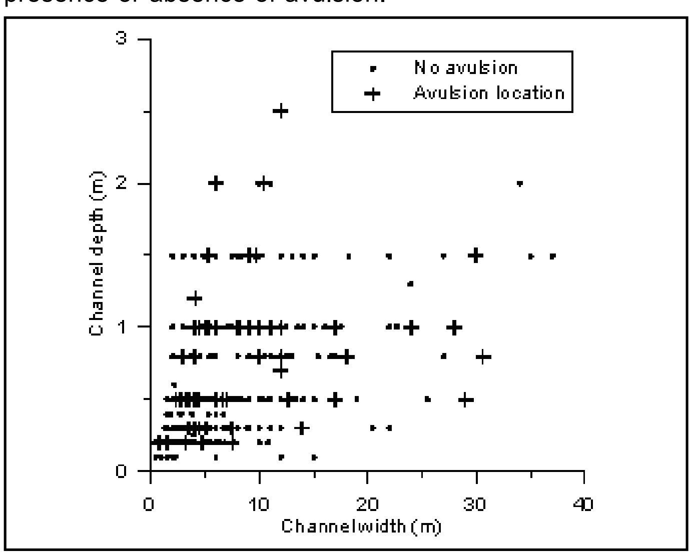
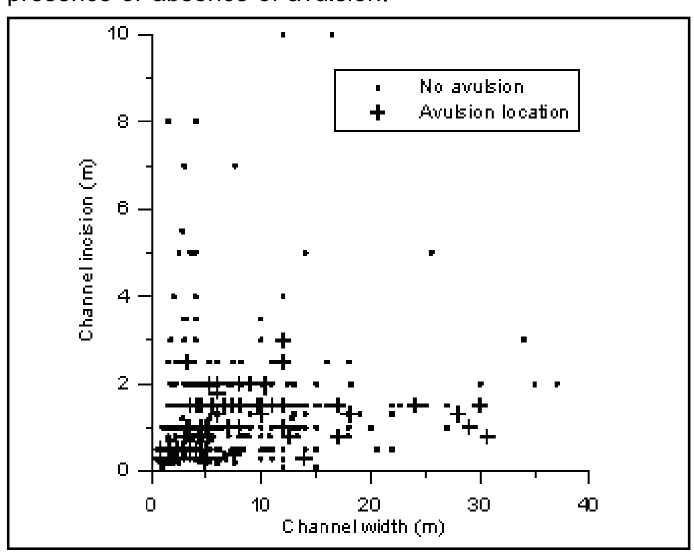


Figure 20. Channel width, channel incision, and the presence or absence of avulsion.



is probable that some degree of bank erosion, avulsion, or splaying occurred, but in most cases we could not positively identify it. Many of the fans were logged prior to 1970, and detecting any changes that may have occurred as a result of forest operations decades ago is difficult. The 11 fans that were logged after 1985 presented a better opportunity for determining causal relationships. On these 11 fans, four fans had little or no logging near the channel, and logging debris jams resulted in an avulsion on one fan and bank erosion on another fan logged after 1985. Three fans had post-logging debris flow or debris flood events that originated in the watershed. These events overwhelmed any lesser channel changes that may have resulted from logging to the channel banks, but it is possible the extent of impact was greater due to the absence of a mature forest. Two other fans had no identifiable fan destabilization effects from logging.

Many of the fan destabilization effects observed result from logging practices that are no longer employed. In two cases, fans and their channels were destabilized to an extreme extent, with the channels moved to accommodate industrial activities on the fan. These actions occurred in the 1950–1970 period.

The "sediment deposited on road" and the "bridge/crossing structure lost" categories are observations of fan process impacts to road structures, and generally indicate costs to the licensee rather than environmental effects. In some of these cases the fans crossed have frequent geomorphic processes, and the structures lost are intended to be sacrificial, or sediment deposited on roads is viewed as a maintenance issue. In other cases the cost to the licensee could be reduced through better road and drainage structure design.

6.0 DISCUSSION AND CONCLUSION

This study examines a sample of alluvial and colluvial fans in coastal British Columbia, the geomorphic processes on these fans, and how forest operations interact with these processes. Fans are a common feature in coastal BC, and forestry operations are known to have caused both environmental and operational problems. Recent work in north-central BC by Wilford (2003) classified fans using the type of geomorphic process and its power, defined by the ability to create forest disturbance on the fan surface. The objectives of this study were to classify coastal BC fans using Wilford's (2003) classification of fan disturbance type and power level, to determine the extent of forestry-related fan disturbance, and to develop methods of evaluating hazard on fans.

Determining geomorphic process type and power is important for managing forestry operations on fans. We found field work to be the most reliable method of identifying fan process where deposition features can be identified with greater certainty. Site features such as large boulders, bouldery lobes and levees, and matrix-supported deposits are reliable indicators of past debris flows. Features that indicate water flood deposits include imbricated clasts, bar structure, and clast-supported sediments. Debris flood deposits are more difficult to identify. Massive deposits of generally clast-supported sediments, but with little or no water flood features, generally indicate debris flood deposits.

Prediction of geomorphic process type in coastal BC fans can often be done remotely, using either aerial photograph interpretation or watershed attribute analysis. Wilford (2003) found that a combination of Melton ratio and watershed length produced an effective separation of geomorphic process. This

Table 7. Summary of cause and effects from harvesting or roads.

Effect	Cause (and number of cases)
Avulsion	Climbing road (5, includes cat/skidder tracks) Undersized bridge (2 but one uncertain) Using road to concentrate drainage to one road crossing (3) Windthrow at edge of cutblock (1) Logging debris jam (1)
Channel incision	Flow concentration from road diversion (2, but one uncertain) Harvesting (1 uncertain)
Bank erosion	Logging debris jam (2) Landing encroaching into channel (1) Undersized culvert (1)
Channel widening	Undersized bridge (1)
Extreme channel modification	Gravel pit (1) Landing constructed in channel area (1)
Sediment deposited on road	Undersized drainage structure (5) Avulsion initiated above the road (4) Debris flow deposit (1)
Bridge/crossing structure lost	Debris flow (1) Debris flood (2) Water flood (1)

study found that the most useful watershed attributes for identifying geomorphic process is the Relief ratio and the Melton ratio. However, watershed length does not appear to be an effective criterion for the coastal fans.

Although process identification on most fans results in near-certain classification, on some fans the features can be vague and definitive process identification is challenging. Two reasons exist for the inability to definitively identify process.

First, as noted by Hungr et al. (2001), debris flow, debris flood, and water flood flows are a continuum, and therefore fan features are sometimes intermediate in characteristic. Five fans in this study with apex gradients of about 8° have sediment deposits features intermediate between debris flood and debris flow. Fans with apex gradients of about 8º may have events that are intermediate between debris flows and debris floods.

Second, the age of deposits or features may result in indeterminate process identification. On several fans we interpreted the presence of debris flow deposits, but the expression of these deposits was subdued from an accumulation of organic material. Many debris flow fans appear to have not experienced debris flow activity for many centuries, and possibly millennia. In the Nahatlatch Valley, most of the watersheds have very little surficial material, and the granitic bedrock in the Nahatlatch Valley likely produces limited amounts of contemporary sediment. These watersheds could be classified as sediment supply limited (Bovis and Jakob, 1999), with very infrequent debris flow activity. On these and similar fans, using the "old" fan process classification does not accurately reflect contemporary hazards. Conversely, limiting the period of assessment to the "recent" period (defined in this study as approximately 50 years), does not adequately identify the likelihood of occasional events such as debris flows that may still occur on a fan.

The interaction between geomorphic processes and forests produces forest stands and scarred trees that indicate process type, power, and frequency. Detailed fieldwork to date geomorphic-event caused scars on trees, or to date cohorts of trees growing on single-event deposits, can provide information about the power and frequency of the geomorphic events that occurred within the last century or sometimes even longer time periods (Wilford et al. 2005a).

Most fans show a progressive decline in geomorphic power from the apex to the toe of the fan. High energy events lose power as fan gradients decrease and channel confinement declines. Upper portions of a fan may be subject to debris flows, while lower portions of a fan may only be subject to debris floods or water floods. Fans often display a decreasing frequency of avulsions and an increasing frequency of splays toward the toe of the fan (Figures 13-18). This suggests that channel processes in the upper portions of fans have sufficient energy to create new channels, while on lower portions of the fan there is insufficient stream energy to erode new channels, and therefore splays (deposition) occur. On several fans, the lower portions had almost no channel or even splay deposits, indicating a complete lack of geomorphic power near the toe of the fan.

6.1 EVALUATION OF FAN DESTABILIZATION HAZARD AND FOREST MANAGEMENT ON FANS

Evaluation of fan destabilization hazard needs to consider the type and power of geomorphic disturbance events, where these events are likely to occur on a fan, and how forestry operations may affect or interact with these events. As discussed earlier, field assessment is the most reliable method of identifying the geomorphic processes that occur on a fan. Fan surfaces can be broadly grouped into three zones to identify where these events are likely to occur:

- One or more active geomorphic process zones, termed the hydrogeomorphic riparian zone in Wilford et al. (2005b). This zone contains one or more active channels, and may contain recent sediment deposits located outside of the channels. Depending on the fan, the sediment deposits may be from debris flows, debris floods, or water floods. Forests interact with and likely limit the spatial extent of active geomorphic processes. Areas with active interaction between forests and geomorphic processes warrant retention of forests, while stable channel locations with little or no interaction between forests and geomorphic processes indicates some harvesting may be possible. Road crossing designs of this zone need to account for the type, power, and frequency of geomorphic process that occur on the fan.
- Inactive, but potentially active, fan surfaces adjacent to active zones. Avulsions or debris flows may initiate new activity within these areas. Harvesting may be possible in these areas but may affect the direction and spatial extent of any event. Roads may strongly affect avulsions or other geomorphic events.
- Relict surfaces that are no longer active. Of the 55 fans studied, 28 had relict surfaces. This is substantially more than found by Wilford et al (2005c), who found 13 of 65 fans had elevated and inactive surfaces. These surfaces are often low-hazard sites for both roads and harvesting, as they are isolated from most geomorphic processes.

On many fans, the upper portion of the fan or the lowest portions of the fan present the best opportunities for road locations. Confined channels that frequently occur in the upper portions of a fan are often good areas for road crossings. The decline in geomorphic power from the top of the fan to the lower portion of the fan often means that the lower parts of the fan can be good road locations. However as power is lost in channel and debris flow processes, so too is channel confinement and therefore there are often broad areas of splays or small channels with shifting locations. As a result, long sections of road crossings low on fans may be subject to low power events. These events could increase maintenance requirements, and the road may require rip-rap to limit erosion damage.

Fan surfaces adjacent to an entrenched channel should not be considered inactive until confirmed by field work. Confined channels on lower portions of a fan may not be confined above, so upstream avulsions may still affect the road, even though the channel is confined at the road crossing.

Additional discussion of forest management on fans is contained in Wilford et al. (2005b). Observations made during the course of this project indicate that the hazard recognition features and management recommendations presented in that publication are valid for the Coast. However, this analysis found that the predictive models presented in that publication do not apply to the study area.

Forest management on fans requires careful consideration of the type of geomorphic processes that are likely to occur on a fan, as well as their power, frequency, and spatial extent. We observed many fans that had some degree of impact from forest operations, but in general the most damaging of these impacts were associated with old logging practices. We also observed many fans that had not been impacted by forest management activities, demonstrating that forest management on fans can be successfully done. Recognition of fans and application of research results to forest management will help to ensure that fan destabilization does not occur as a result of forest operations.

APPENDIX A: PHOTOS ILLUSTRATING GEOMORPHIC PROCESS INDICATORS, FAN FEATURES, AND FOREST OPERATIONS EFFECTS

Figure 21. Looking upstream in the Nahatlatch Valley, a typical U-shaped glacial trough with steep sides and flat valley bottom (fans are located where side drainages enter the main valley).

Figure 22. A paraglacial fan surface in the Nahatlatch Valley (this surface is 3-20 m above the contemporary channel).

Figure 23. Coarse debris flow lobe deposits (this deposit is at least 50 years old).

Figure 24. Large debris flow boulder in the centre of an active channel.

Figure 25. Mid to lower portion of a fan with recent debris flood deposits in a broad splay among trees; a debris flow deposited on the upper portion of the fan about 50 years ago.

Figure 26. Broad water flood deposits on the lower portion of a fan.

Figure 27. Imbrication of cobbles – an indication of water floods.

Figure 28. Lower portion a fan with braiding channels and splays that strongly interact with the forest – storing sediments and likely limiting the extent of new channels.

Figure 29. A 6m-wide channel that ends abruptly in a splay. Sediment is composed of cobbles and finer sediment. Beyond this point no channel is evident, although some sand and silt deposits are present.

Figure 30. An 8m-wide channel that ends in a 15m-wide splay of cobbles and finer sediment. No defined channel is present past this point and the fan surface is completely vegetated.

Figure 31. Two ages of red alder cohorts are present along this channel (the 1-2 m high alders in the right-center of the photograph date from about 1994, and the mature alders in the background date from about 1920).

Figure 32. Looking downstream at a large 3m-high woody debris jam. An active avulsion is located on the left of the photo, and dispersed flow occurs around the right side. Note the person located to the right of the jam for scale.

Figure 33. A gap in mature timber caused by a recent debris flow; two cohorts of red alder trees at centre date from about 1986 and 1994.

Figure 34. Large tree showing >1 m of deposited sediment and then later excavation on one side.

Figure 35. The downside face of a woody debris jam at the apex of a fan.

Figure 36. The same jam as in photo at left, but from above, looking downstream; the majority of flow is to the right, but the jam creates a partial avulsion to the left during high flows.

Figure 37. A buried tree trunk indicating deposition of sediment around the tree; the tree later died and rotted, leaving a 1.2m-deep “tree hole”.

Figure 38. Buried trees on recent broad splay deposits (note the lack of butt flare on the trees).

Figure 39. Deep knickpoint erosion along a climbing road that was caused by an avulsion that followed the road alignment.

Figure 40. Road crossing of channel with naturally high sediment load (a wider box culvert would allow for better passage of sediment).

REFERENCES

Anon. 2001. Gully Assessment Procedure. Fourth Ed. Forest Practices Guidebook. BC Min. of Forests and BC Environment. 60 pp.

Bovis, M.J. and M. Jakob. 1999. The role of debris supply conditions in predicting debris flow activity. Earth Surf. Processes and Landforms. 24:1039-1054.

Bull, W.B. 1964. Geomorphology of segmented alluvial fans western Fresno county, California. US Geol. Survey Prof. Paper 437-A. pp. 1-71

Costa, J.E. 1988. Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker, V.R, Kochel, R.C., and Patton, P.C. (eds.). Flood Geomorphology. John Wiley. New York. pp. 113-122.

Environment Canada, 2005. 30-year Climatic Normals Website. http://climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html

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

Hungr, O., Evans, S.G., Bovis, M.J., and Hutchinson, J.N. 2001. A review of the classification of landslides of the flow type. Environmental and Engineering Geoscience. 7(3): 221-238.

Irasawa, M., Ishikawa, Y., Fukumoto, A., and Mizuyama, T. 1991. Control of debris flows by forested zones. In: Proceedings of the Japan-U.S. Workshop on Snow Avalanche, Landslide, Debris Flow Prediction and Control. Sept. 30 – Oct. 2, 1991. Tsukuba, Japan. Science and Tech. Agency of Japanese Gov. pp.543-550.

Jackson, L.E., Kostaschuk, R.A., and MacDonald, G.M. 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. In: Costa, J.E. and Wieczorek, G.F. (eds.). Debris flows/avalanches: Process, Recognition, and Mitigation. Reviews in Eng. Geol. Vol. VII. Geol. Soc. Am. pp. 115-124.

Jakob, M and Jordan, P. 2001. Design flood estimates in mountain streams – the need for a geomorphic approach. Can. J. Civ. Eng. 28:425-239.

Kellerhals, R. and M. Church. 1990. Hazard management on fans. Rachochi, A. and Church, M. (eds.) Alluvial Fans: a field approach. John Wiley and Sons. New York. pp. 335-354.

Melton, M.A. 1957. An analysis of the relation among elements of climate, surface properties and geomorphology. Office of Nav. Res. Dept. Geol. Columbia Univ., NY. Tech. Rep. 11, 102pp.

Milliken. G.A. and Dallas E Johnson, D.E. (1992) Analysis of Messy Data, Volume 1: Designed Experiments. Van Nostrand Reinhold. New York, New York.

Ministry of Forests. 2000. Forest Cover Map Series 92H.091. Resource Inventory Branch, BC Ministry of Forests. Victoria, BC.

Monger, J.W.H. 1969. Hope map area, west half, British Columbia. Geological Survey of Canada Paper 69-47.

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

Nuszdorfer, F. C. and Boetger, R., compilers and editors. 1994. Biogeoclimatic Units of Vancouver Forest Region. Province of British Columbia, Ministry of Forests, Research Branch.

Prior, D.B, and Bornhold, B.D. Submarine morphology and processes of fjord dan deltas and related high-gradient systems: modern examples from British Columbia. In Memec, W, and R.J. Steel, (eds.)Fan Deltas: Sedimentology and Tectonic Setting. Blackie and Son.

Roddick, J.A., and G.J. Woodsworth. 1977. Geology of the Pemberton Map Area. Geological Survey of Canada, Open File 482 map.

Ryder, J. 1971a The stratigraphy and morphology of paraglacial aulluvial fans in south-central BC. Can. J. Earth Sci. 8: 279-298.

Ryder, J.M. 1971b. Some aspects of the morphometry of paraglacial alluvial fans in south-central British Columbia. Can. J. Earth Sci. 8: 1252-1264.

Ryder, J. 1981. Terrain inventory and Quaternary geology, Lytton, British Columbia. Geological Survey of Canada Paper 79-25. 20 pp and map.

Smith, G.A. 1986. Coarse-grained nonmarine volcaniclastic sediment: terminology and depositional process. Geol. Soc. of Amer. Bulletin. 97: 1-10.

Strahler, A.N. 1958. Dimensional analysis applied to fluvially eroded landforms. Geol. Soc. Amer. Bull. 69: 279-99.

Wells, S.G. and Harvey, A.M. 1987. Sedimentologic and geomorphic variations in storm-generated alluvial fans, Howgill Fells, northwest England. Geol. Soc. Amer. Bulletin. 98: 182-198.

Wilford, D.J. 2003. Forest stand characteristics as indicators of hydrogeomorphic activity on fans. PhD. Thesis. Faculty of Forestry. UBC.

Wilford, D.J., Sakals, M.E., and Innes, J.L. 2003. Forestry on fans: a problem analysis. Forestry Chronicle. 79(2).

Wilford, D.J., Sakals, M.E., Innes, J.L., Sidle, R.C., and Bergerud, W.A. 2004 Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. Landslides 1(1): 61-66.

Wilford, D.J; Cherubini, P. and M. Sakals. 2005a. Dendroecology: a guide for using trees to date geomorphic and hydrologic events. BC Ministry of Forests Res. Br. Victoria BC. Land Management Handbook 58. 20p.

Wilford, D.J; M.E. Sakals and J.L. Innes. 2005b.Forest management on fans: hydrogeomorphic hazards and general prescriptions. BC Ministry of Forests Res. Br. Victoria BC. Land Management Handbook 57. 35 p.

Wilford, D.J., Sakals, M.E., Innes, J.L., and Sidle, R.C. 2005c. Fans with forests: contemporary hydrogeomorphic processes on fans with forests in west central British Columbia, Canada. In: Harvey, A.M., A.E. Mather, and M. Stokes (eds.). Alluvial Fans: Geomorphology, Sedimentology, Dynamics. Geological Society, London. Special Publications 251: 24-40.

VanDine, D.F. 1985. Debris flows and debris torrents in the southern Canadian Cordillera. Can. Geotechnical J. 22: 44-68.