Coastal fan destabilization and forest management

FSP project Y051324
Final report for the 2004/05 project year.

Thomas Millard[1], David Wilford[2] and Marian Oden[3]

Note: This document is preliminary to a technical report which will be published in 2005/06. Users of this report should use the technical report once it becomes available.

1) Research Geomorphologist, Coast Forest Region
2) Research Hydrologist, Northern Forest Region
3) Consultant, Oden Geoscience

Abstract

Alluvial and colluvial fans were studied to determine geomorphic disturbance type, methods of predicting disturbance type and power, and how forest operations can destabilize fans. Fifty-five fans in the southern Coast Mountains, northern Vancouver Island, and south-western Vancouver Island were field traversed and additional watershed data was collected using GIS. Thirty-nine fans had harvesting or roads, although in some cases the harvesting was very little. Forest operations on the study fans occurred from 1957 to 2004. Forty-five fans showed evidence of old debris flows (>50 years old), 5 showed evidence of old debris floods, and 9 showed evidence of old water floods. Only 13 fans had recent (<50 years old) debris flows, 7 had recent debris floods, and 29 had water floods. Best predictors of geomorphic disturbance type are apex slope gradient, the Relative relief ratio, and the Melton Ratio. Forest operations caused destabilization at 22 sites, and included avulsions, channel incision, bank erosion and channel widening.

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. Fans may be easily destabilized by forest harvesting and roads due to their dynamic nature, with consequent significant environmental impacts and safety hazards. The presence of mature forests may strongly influence how channel processes affect fan stability.

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

There is limited knowledge about the effect of forest practices on fans. Most fan research has occurred on 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 debris flows in the upstream catchment (Bovis and Jacob, 1999; Jackson et al, 1987). BC forested fan literature is often limited to case studies (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 the type of impacts that have resulted from forestry operations. Wilford classifies fans on the basis of the geomorphic processes occurring on the fan – debris flows, debris floods, and normal fluvial floods, and the ability an event to affect forest structure on the fan. He also identifies watershed attributes that can predict the type of process that are likely to occur on fans. Forest management on fans needs to consider the geomorphic processes likely to occur, because debris flows can have peak discharges 40 times greater than anticipated peak streamflows (water floods), and debris floods can have peak discharges up to three times the anticipated peak streamflow (Hungr et al. 2001; Jakob and Jordan 2001)..

As with many geomorphic processes, the results of studies in one area may not be applicable to other areas. There are very significant differences between coastal fans and the fans that Wilford studied in west-central BC. Tree size and species, precipitation regimes, terrain, and geology may all affect fan processes differently between the two regions. Therefore, in order to better manage coastal fans and support the FRPA, additional work is needed.

This project has the following objectives:

1. To characterise coastal fans using Wilford's (2003) classification and to determine coastal fan sensitivity to destabilization.

2. To assess the extent and character of forestry-related fan destabilization in coastal BC and to determine the factors causing the disturbance.
3. To develop a method for ranking hazard and risk on fans appropriate for forest management.

2.0 Forested fan assessment in British Columbia

The GAP assessed fan destabilization potential using two criteria. The first criteria, a fan destabilization index, used a combination of the number of channels on a fan, and the depth of channel incision. Increasing numbers of channels indicated a greater chance of destabilization, and increasing channel incision indicated a lesser chance of destabilization. The second criteria used the frequency of debris flow deposits to assess destabilization potential. As with much of the initial GAP, the assessment procedure was based on expert opinion, but was based on limited data.

As noted earlier, Wilford's (2003) work in west-central BC is the only systematic study of BC fans and forestry to date. Wilford classifies fans by the dominant type of "hydrogeomorphic" process, and uses watershed attributes to predict the type of process that will be occurring on any particular fan (Table 1). As noted previously, the class limits for these watershed attributes, or even the significance of each variable, may not be equivalent in coastal BC compared to west-central BC.

Table 1. Class limits for the hydrogeomorphic processes.

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

Wilford defines three power levels of geomorphic events:

1. Low power events do not have sufficient power to uproot or break trees. Deposition of sediment occurs around trees.
2. High power, site level events that create small swaths through the forest on a fan that are not visible on aerial photographs. The width of these swaths is less <20 m.
3. High power, stand level events that create large swaths, >20 m wide, that are visible on aerial photographs.

Wilford investigated several watershed attributes that could be used to predict the process type likely to occur on a fan. Some of the attributes that Wilford found significant, such as the Melton ratio (Relief/Area$^{0.5}$: Melton, 1957), have been shown to be significant in a number of studies, and are likely to be significant in this study as well. However class limits for some of the attributes such as watershed area are almost certainly different for coastal fans due to the very different precipitation regimes. Without testing these attributes, the direct application of Wilford's results to coastal fans is tenuous.

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. Preliminary air photo work identified numerous fans in each area, with a variety of fans, logged and unlogged. 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 working and identifying changes in the young, thick forests that have regenerated on fans after logging.

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

Fan attribute data collected included:

- Slope gradients (field work)
- Number of active channels (field work)
- Channel gradient, width, bankfull depth and depth of incision from the bottom of the channel to the fan surface or top of any levees present (field work)
- Disturbance type: debris flow, debris flood, or water flood. (VanDine, 1985; Smith 1986; Costa, 1988; Wells and Harvey, 1987; Hungr et al., 2001; field work). Fans were classified by the most powerful type of events: if a fan had 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.
- Disturbance power (established through air photo interpretation and field work)
- Age of events, classified as either "recent", less than approximately 50 years, or "old", greater than 50 years.
- Process features (field work: sediment splays, woody debris jams, levees, lobes, avulsions). Splays are broad unconfined deposits of sediment outside of defined channel areas.
- Bedrock geology of the watershed (map information)
- Presence of landslides in the watershed (air photo interpretation)

Watershed attributes shown in Table 2 were collected using GIS derived data.

Table 2. GIS-derived 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		Melton's Ruggedness Index = Relief/(Area)$^{0.5}$
WS shape	km^{-1}	Watershed Shape = Area / Length^2
Relief ratio		Relief / Watershed 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 = Channels / 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˚
B3040100 m	%	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˚

Data on the harvest history, road location, and road construction were collected, as well as process features (sediment splays, woody debris jams, levees, avulsions, incisions, debris flow, or debris flood events) that could be associated with specific forest management practices.

The fans are classified using the dominant old disturbance type. Old disturbance type is chosen since limiting the fans to events <50 years ("recent events") does not adequately reflect the potential for debris flows. One-way analysis of variance (ANOVA) is used to identify watershed and fan attributes that have significantly different means when fans are classified by old disturbance type. If differences are detected, Bonferroni multiple comparisons determine which groups have different means (Milliken and Johnson 1992).

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

All statistical tests use a significance level of 0.05.

Forest practices effects were evaluated to determine 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. Geomorphic interpretation formed the basis for this portion of the project.

4.0 Study locations

Nahatlatch Valley

The Nahatlatch Valley is an west-east trending valley that drains 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. The valley is a deep glacial trough. Valley bottom elevations are about 300– 400 m, and ridge-tops are at 1500–1700 m above sea level (asl). The Nahatlatch River meanders across the 600–1000 m wide flat 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 fans are located adjacent to Nahatlatch Lake, and are more specifically fan deltas (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 30-year climatic normals, 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 2008 mm, of which 94% is rainfall, and with a maximum daily rainfall of 173 mm.

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.

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.

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. The valley bottom elevation is about 300 m, with very steep valley sidewalls rising to over 2000 m asl. The valley bottom is about 500–800 m wide. Bedrock is primarily granodiortite, with some quartz monzonite and granitoid gneiss (Roddick and Woodsworth, 1977).

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 1229 mm of precipitation annually, with 67% as rain. 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 2367 mm of 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 of 2003. Over a three day period, 548 mm of rain fell, with additional snow melt. The Elaho River has a short gauging history, but other nearby rivers had floods with return periods of over 100 years, and perhaps as much as 200 years (A. Chapman, pers.comm., 2005).

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.

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 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. 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 are from about 200–400 m, and ridge top elevations are generally from 1000–1500m asl.

Much of Vancouver Island is underlain with Karmutsen Formation and Island Intrusions. The Karmutsen Formation is basaltic lava, pillow lava, and tuff. The Inland Intrusives are granodiorite, quartzdiorite, granite, and quartz monzonite. Bedrock in the Woss Lake area is primarily Karmutsen Formation, with Island Intrusions 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 underlie the area to the north and east of Claude Elliot Lake. The study site near Nimpkish Lake is underlain by Bonanza Formation, which is 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 3337 mm of precipitation annually, 99% of it as rain. 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 1591 mm of precipitation, 96% of it rain. The largest one-day rainfall recorded is 116 mm.

Lower elevations, and all the fans in the Woss area are within the CWHxm2 or CWHvm1 biogeoclimatic zones. 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 900–1100 m. Two of the McClure Lake study sites are fan deltas, and one study site within the Walbran Valley is partially a fan delta.

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 3700 mm of precipitation annually, with 98% as rain. The maximum daily rainfall recorded is 257 mm. Port

Renfrew, approximately 25 km to the SW, receives 3671 mm of precipitation annually, with 98% of it being rain. Its maximum daily rainfall is 293 mm.

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

5.0 Results

Table 3 summarizes the fans investigated in this study. Almost three-quarters of the fans had some amount of harvesting or with roads. In the Nahatlatch Valley, most logged fans were selectively harvested in the 1950s-60s, with smaller trees or cohorts of smaller trees left standing. Almost all other fans were clearcut, although sometimes only a portion of the fan was clearcut. 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.

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**

5.1 Process type, frequency and watershed/fan attributes

Table 4 shows the old process type and power, and Table 5 shows the recent process type and power. Although three-quarters of the fans show 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 effects outside of the 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.

Table 4 Summary of old geomorphic process type

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

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

Table 5 Summary of recent geomorphic process type

Location	No power[1]	Debris flow		Debris flood			Water flood		
		Site	Stand	Low	Site	Stand	Low	Site	Stand
Nahatlatch	3	1			1		8		1
Elaho			2			1	1		
Woss	3	1	3	1		2	2	8	2
McClure/Walbran		4	2	2			5	1	1
Total	**6**	**6**	**7**	**3**	**1**	**3**	**16**	**9**	**4**

1) No power indicates that no debris flow, debris flood or water flood events that affected areas outside of the bankfull channel have occurred.

One-way ANOVA identified the watershed and fan attributes in Table 6 as significant predictors of old geomorphic process type. Ranked Bonferroni adjusted multiple comparisons determined which groups have different means. Old process type was chosen since limiting the response of a basin to a period of 50 years (“recent process”) is not a sufficient time period to accurately reflect the possibility of debris flows occurring. All attributes with a significance level ≤ 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, but do not reflect overall watershed processes. Using watershed attributes to predict fan process is not appropriate for this type of watershed.

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

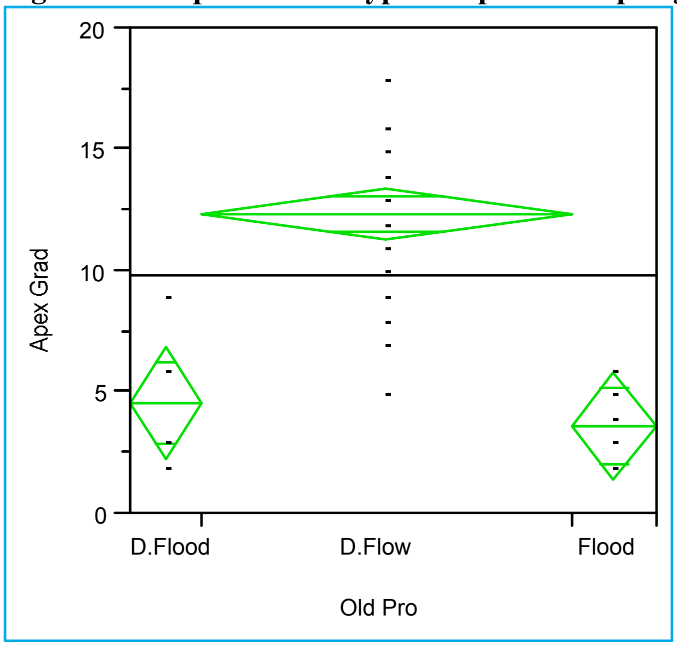
Attribute	**Pr > F**	**R^2 Adj.**	**Bonferroni identified groups (α =0.05)**
Apex gradient	<0.0001	0.59	Debris flow ≠ (Debris flood, Water flood) (≠ indicates Debris flow is significantly different to both Debris flood and Water flood)
WS area	<0.0001	0.49	Debris flow ≠ (Debris flood, Water flood)
WS Length	<0.0001	0.42	Debris flow ≠ (Debris flood, Water flood)
Melton Ratio	<0.0001	0.48	Debris flow ≠ (Debris flood, Water flood)
Relif Ratio	<0.0001	0.63	Debris flow ≠ (Debris flood, Water flood)
WS Shape	<0.0001	0.27	Debris flow ≠ (Debris flood, Water flood)
Channel Length	<0.0001	0.37	Debris flow ≠ (Debris flood, Water flood)
L4P	0.002	0.07	Debris flow ≠ Flood
G30-25m	0.046	0.08	Debris flow ≠ Flood
G30-50m	0.019	0.10	Debris flow ≠ 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	0.0005	0.08	Debris flow ≠ Water flood

For all attributes in Table 6, the ranked Bonferroni test identifies 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 (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 are apex gradient and the relief ratio. Watershed area, length, and the Melton ratio are also useful predictors.

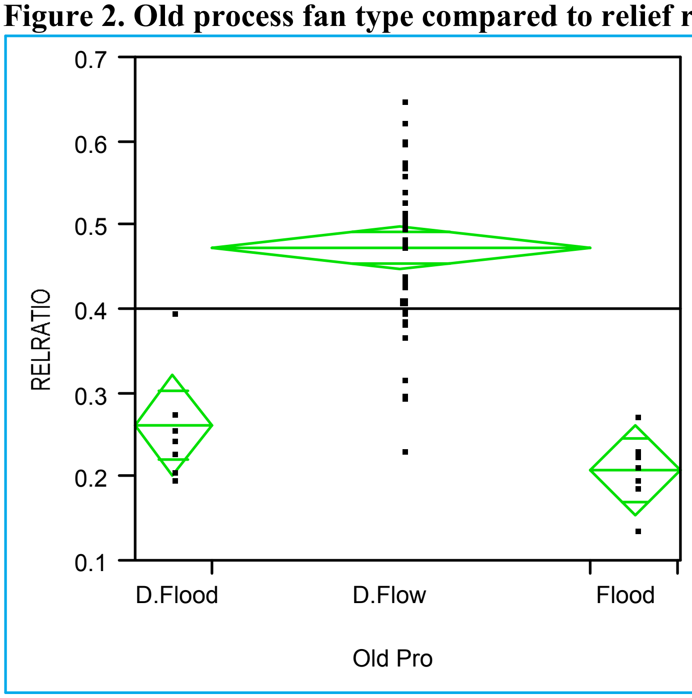
Figure 1 shows the distribution of apex gradients by fan type. The middle horizontal line in the diamonds in Figures 1–5 show the group mean, and the points of the diamond show the 95% confidence interval. Point locations may represent multiple samples. Debris flow fans almost always have steeper apex gradients than either debris flood or water flood fans. Seven debris flow fans had apex gradients of ≤8˚. Five of these fans we noted our classification of the old process as “uncertain” due to limited debris flow evidence. The debris flood fan with an apex gradient of 9˚ appeared borderline between debris flood and debris flow. It may be that fans with apex gradients of about 8˚ have events which are transitional between debris flows and debris floods.

Figure 1. Old process fan type compared to apex gradient



Fan type is compared to relief ratio in Figure 2. Again, debris flood fans are intermediate between debris flow fans and water flood fans. Debris flow fans rarely have a relief ratio <0.3. Although the debris flow fans that had lower apex gradients were often borderline with debris flood processes, the debris flow fans with 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 lower sections of considerable size where debris flows could initiate.

Figure 2. Old process fan type compared to relief ratio



Figures 3 and 4 compare old process fan type with watershed area and watershed length. Although debris flow watersheds are generally smaller and shorter than debris flood or water flood fans, there is a greater degree of overlap for these watershed attributes and fan type.

Figure 3 Old process fan type compared to watershed area

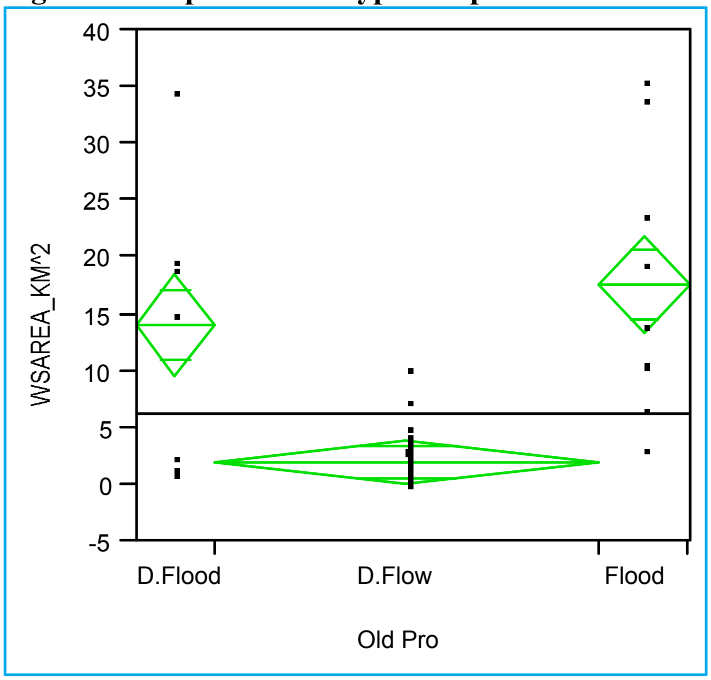
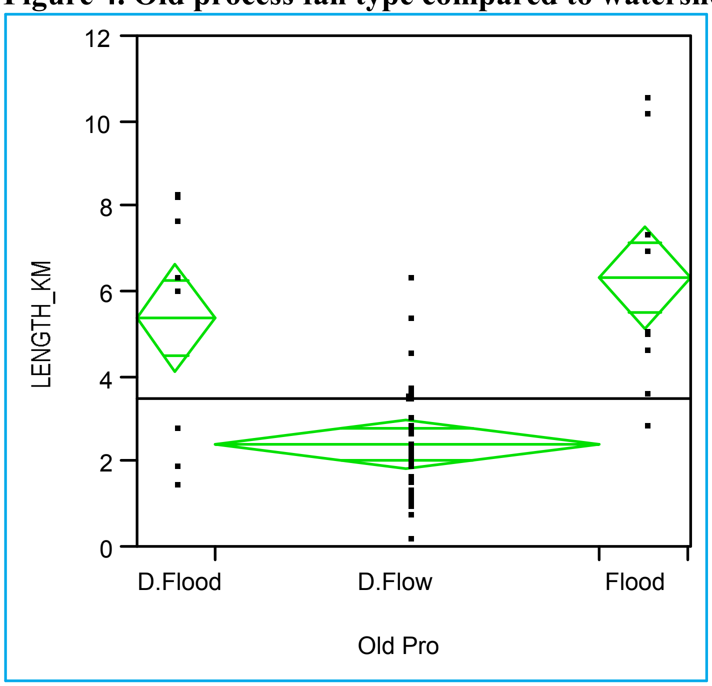
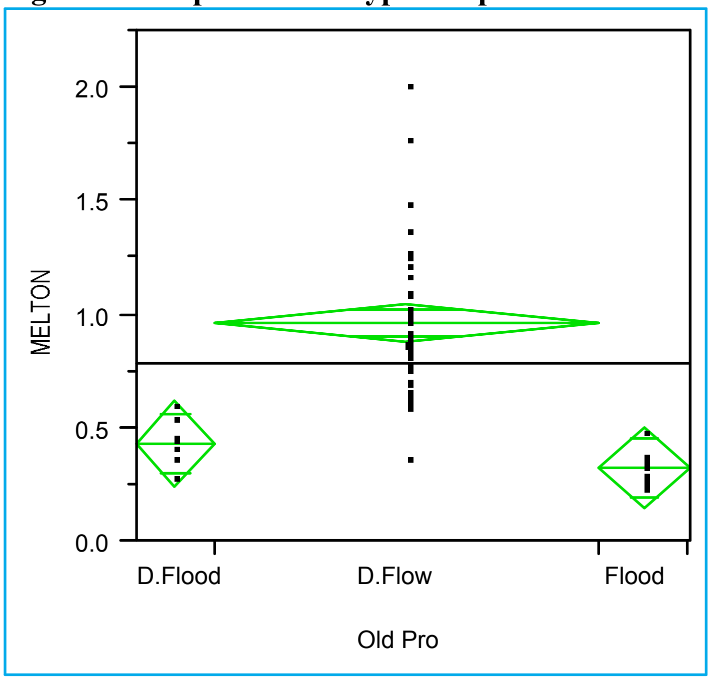


Figure 4. Old process fan type compared to watershed length



The Melton ratio (Figure 5) 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 broad watershed areas above a steeply incised channel immediately above 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.

Figure 5. Old process fan type compared to Melton ratio



5.1.2 Multivariate analysis of fan type and watershed or fan attributes

All of the Bonferroni tests show a significant difference between water flood and debris flow fans, and all show no significant difference between debris flood and water flood fans. Most Bonferroni tests show that debris flows 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
- 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 Relief Ratio, and 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.

5.2 Location of process features on fans

To determine whether avulsions, debris flow deposits, or splays have predictable locations within a fan, we evaluate where these features are located in relation to the fan apex or the intersection point. The intersection point is the location where fan-head entrenchment (channel confinement) ends. We define two fan ratios:

1. Apex ratio = (distance from the apex to the feature)/(distance from the apex to the toe of the fan)
2. Intersection ratio = (distance from the intersection point to the feature)/(distance from the intersection point to the toe of the fan). In some cases there is no fan-head entrenchment, and therefore the intersection ratio becomes equivalent to the apex ratio.

The toe of the fan was defined by one of three features:

1. Where a fan channel met the valley bottom river
2. Where all channel features ended and fan gradient was generally <1°
3. The lake edge.

Figures 6 through 8 are distribution histograms of process features for the range of apex ratios. The data presented here reflects locations of active or recent processes since the field work focussed on these locations. All process features can occur in any fan location, but there are some patterns. Figure 6 shows that debris flow deposits most frequently occur in the upper 60% of the fan (as measured by distance from apex). In contrast, most splay deposits occur in the lower 60% of the fan (Figure 8). Channel avulsions occur frequently in all locations on the fan, although somewhat less frequently near the fan toe.

Figures 9 through 11 are similar frequency distribution histograms using the intersection ratio. A few debris flow deposits, avulsions, and splays are located above the intersection point (shown in Figures 9 to 11 as negative values). The aulsion locations relative to the intersection point show a consistent decline in frequency as distance below the intersection point increases. Splays are most frequent on the lower portions of fans.

The decreasing avulsion frequency, and the increasing splay frequency towards the toe of the fan suggests that channel processes in the higher portions of the fan have sufficient energy that new channels can be created, while on lower portions of the fan there is insufficient stream energy to create new channels, and therefore splays occur instead.

The Intersection ratios show somewhat more consistent pattern than the apex ratio, likely a result of the limited possibility for avulsions and splays, and to some degree debris flow deposits, to occur within the entrenched fan head area.

Figure 6.

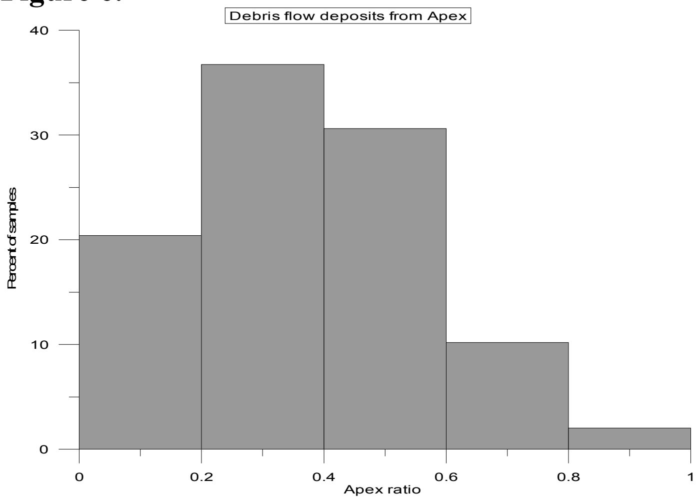


Figure 7.

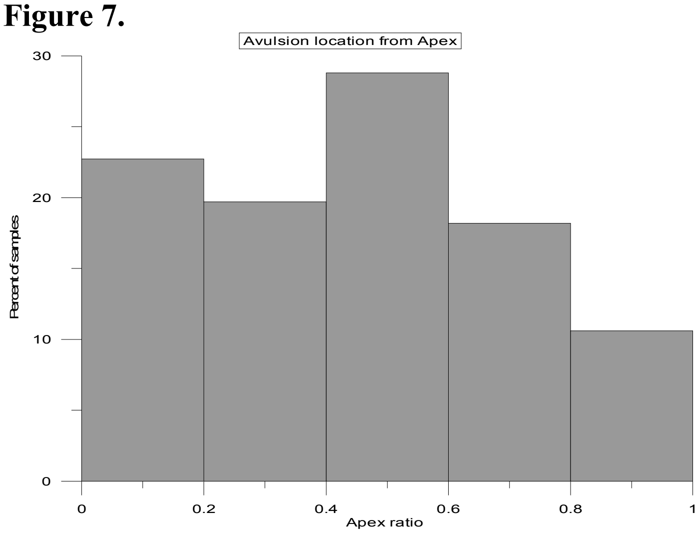


Figure 8

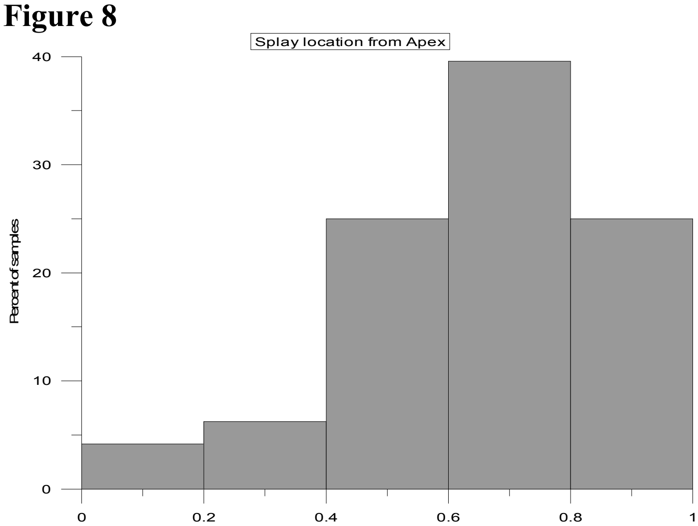


Figure 9

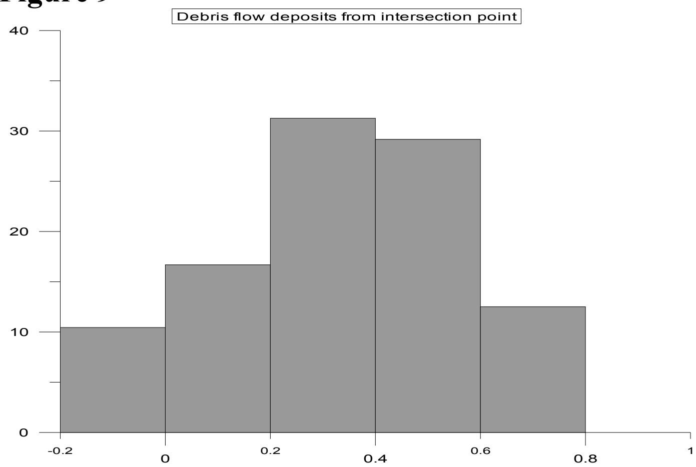


Figure 10

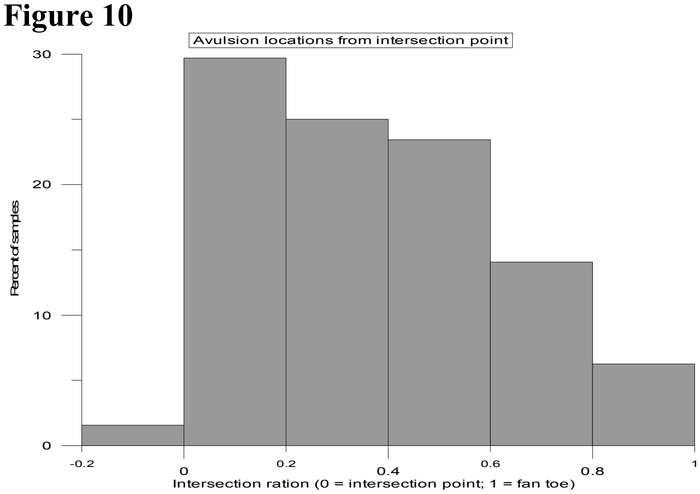
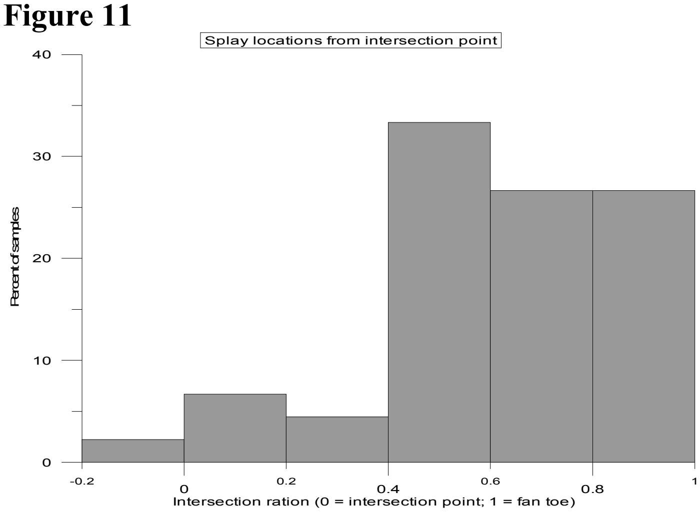


Figure 11



We evaluate channel width, depth, and incision to determine channel configurations likely to result in avulsions. Figure 12 plots avulsion and non-avulsion locations compared to channel width and bankfull channel depth, and Figure 13 plots avulsion and non-avulsion locations compared to channel width and channel incision incision. Neither channel depth or channel incision appear to have a strong effect on the location of avulsions, with the exception of an upper limit of channel incision. Only 13 avulsions occurred when channel incision was ≥2 m, and 8 of these avulsions occurred on fans with recent debris flows. Of the other 5 avulsion sites with channel incision ≥2 m, most occurred on large debris flood or water flood channels.

Figure 12. Channel width, channel depth, and avulsion location

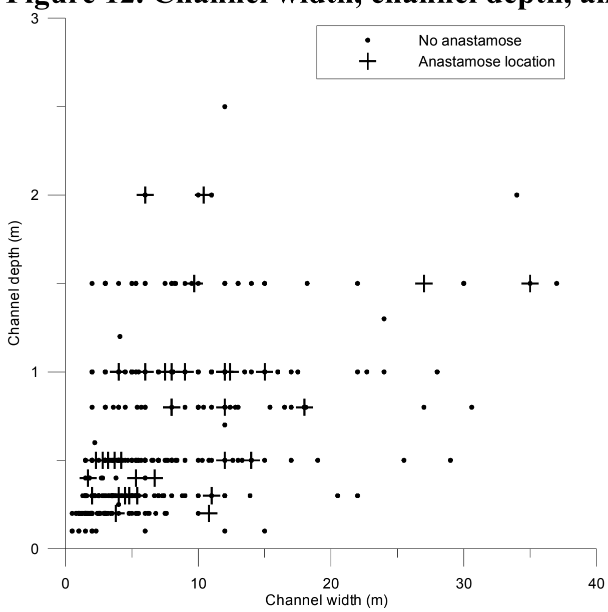
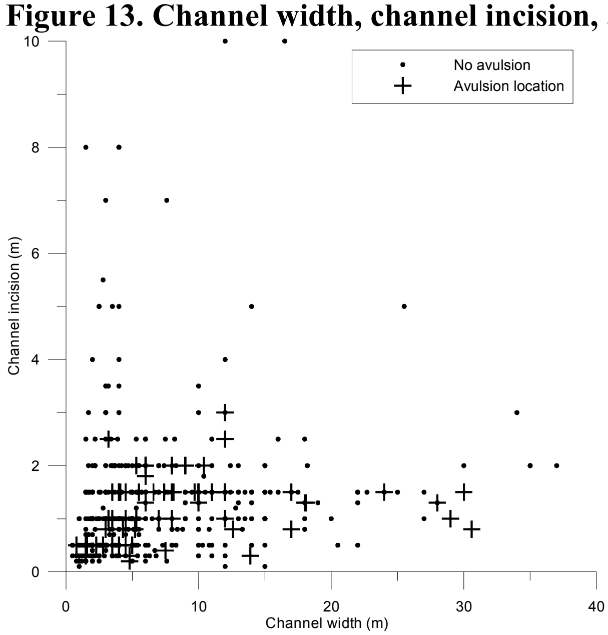


Figure 13. Channel width, channel incision, and avulsion location



5.3 Harvesting and road effects

Table 8 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 a number of decades prior to this project. We generally relied on aerial photograph interpretation to identify effects that occurred prior to about 1980.

Table 8. 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 crossing (3) Windthrow at edge of cutblock (1) 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)

Most of the effects are a result of roads, skid trails, or crossing structures. Roads caused a number of avulsions. In some cases avulsion channels were confined to the ditch and delivered to one crossing structure, but in at least one case this 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 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 decades ago is difficult. The 11 fans that were logged after 1985 are more likely to show these types of effects. Logging debris jams resulted in an avulsion on one fan and bank erosion on another fan logged after 1985. Three fans had debris flow or debris flood events that overwhelmed any lesser channel changes that may have resulted from logging to the channel banks. Four fans had little or no logging near the channel. Two other fans had no identifiable effects from logging.

Many of the changes are a result of old logging practices that are no longer done. In two cases fans and their channels were modified to an extreme extent, with the channel 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 on 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 are very active, 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 design.

6.0 Discussion and conclusion

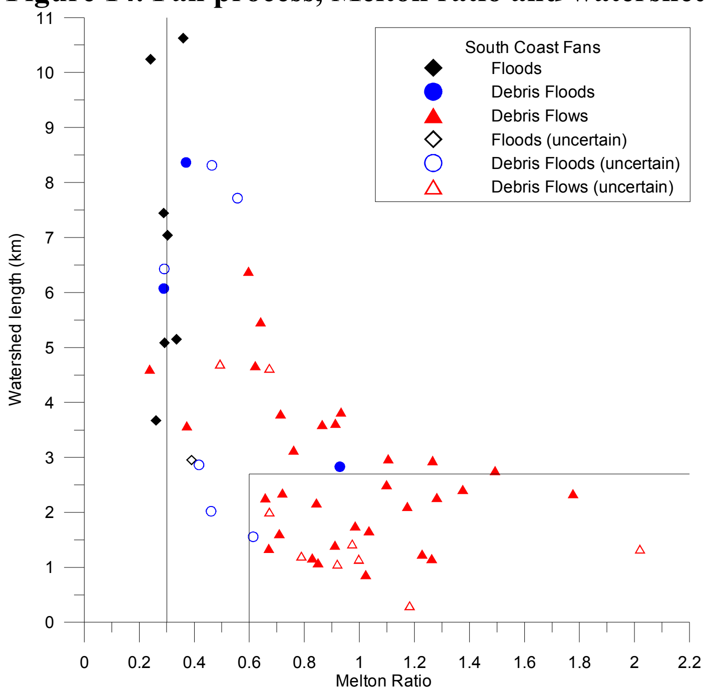
Identification of geomorphic process type on fans is important to understand the potential disturbance extent. Identification of process type in coastal BC fans can often be done remotely, using either aerial photograph interpretation or using watershed attribute analysis, most specifically relief ratio or Melton ratio. However, field work is the most reliable method of identifying fan process where deposition features can be identified with greater certainty. 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. This study noted a number of fans with apex gradients of about 8° that appear to have processes intermediate between debris flood and debris flow. Second, the age of deposits or features may result in indeterminate process identification. On a number of fans we interpreted the presence of debris flow deposits, but the expression of these deposits was subdued from an accumulation of organic material or simply the passage of time. Many old debris flow fans appear to have not experienced debris flow activity for many centuries, and possibly millennia. In the Nahatlatch Valley, many of the watersheds have very little surficial material, and the granitic bedrock in the Nahatlatch Valley likely produces little sediment, so debris flow activity may be extremely rare (Bovis and Jakob, 1999). On these and similar fans, using the old fan process classification may not accurately represent the possibility of debris flows occurring under current conditions.

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 rare events such as debris flows that may still occur on a fan. Detailed fieldwork and dating of geomorphic-event caused scars on trees, or dating of cohorts of trees growing on single-event deposits, may provide information about geomorphic events that occurred within the last few centuries.

Wilford (2003) 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). Figure 14 shows the data for this study plotted using the combination of Melton ratio and watershed length, and the class boundaries determined by Wilford. Fans that are do not have definitive process identification are shown in Figure 12 as "uncertain". The plot shows that coastal BC fans are similarly classified by Melton ratio, with debris flow fans having a Melton ratio >0.6, debris flood fans generally having a Melton ratio between 0.3 and 0.6, and water flood fans generally having a Melton ratio of <0.3. However, the watershed length does not appear to be an effective criteria for the coastal fans.

Figure 14. Fan process, Melton ratio and watershed length



The GAP used channel incision as an index criterion for destabilization. The original criteria indicated that channels with a channel incision of greater than 2 m were unlikely to destabilize. This criteria appears to be slightly low for debris flood or water flood fans, as in five cases an avulsion occur when the channel incision was between 2.0 and 2.5 m on debris flood or water flood fans. Channel incision of <3 m did not confine all debris flows in this study, and in some debris flows channel incision would probably need to be much greater to confine the debris flow.

Fan surfaces can be broadly grouped into three zones:

- One or more active geomorphic process zones, termed the hydrogeomorphic riparian zone in Wilford (2003). This zone contains one or more active channels and may contain recent debris flow deposits or splays. Forests interact with, and limit the spatial extent of, active geomorphic processes. Harvesting should probably be avoided in this zone. Road crossings of this zone need to consider the type and power 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 55 fans, 28 had relict surfaces. These surfaces are often low-hazard sites for both roads and harvesting, as they are isolated from geomorphic processes.

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. Higher 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. On several fans the toe of the fan had almost no channel or even splay deposits. The decline in power often means that the toe of the fan can be a good road location. 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.

Confined channels, such as entrenched fan heads, are often good areas for road crossings. 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.

Forest management on coastal BC fans needs to consider the type and power of the geomorphic events that are likely to occur on the fan. Within a single fan there may be a several different zones of geomorphic process type, power, and activity. Predicting the type and power of events that may occur on a fan is possible using watershed attributes, but the most reliable method is to use a combination of approaches that include air photo interpretation and field work.

Acknowledgements

Funding for this project was provided by the Forest Science Program administered by PricewaterhouseCoopers. Ray Robazza and Colin Campbell of Canadian Forest Products in Woss provided generous assistance for the work around Woss. Parks BC gave permission for the research within the Nahatlatch Park and the Schoen Lake Park. Don Watt, BC Parks host at Nahatlatch Lake, kindly lent us his canoe. Terry Rollerson reviewed a draft of this document.

8.0 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.

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

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).

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