Forestry on Fans: Identifying Hydrogeomorphic Hazards

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ABSTRACT

For forest managers, fans pose a serious problem in mountainous areas due to periodic debris flows, hyperconcentrated flows, and peak flows. These hydrogeomorphic events challenge roads and drainage structures, impact plantations, and pose safety risks. In addition, natural events can be aggravated by forestry activities on fans, impacting aquatic resources, improvements, private property, and drinking water. This paper presents first-year results from a research project that is developing a hazard classification for forestry on fans and documenting past forest management experiences on fans. The study area is in the Prince Rupert Forest Region of British Columbia. The hazard classification will be based on a combination of site features on fans and watershed attributes. Central to the site features are forest stand attributes that, in combination with dendrochronology, are used to determine the power and frequency of hydrogeomorphic events. Other site features include geomorphic and sedimentologic signatures. Watershed attributes include morphometrics, extent of unstable terrain, channel characteristics, and snow avalanches. The documentation of past forest management experience highlights the need to recognize fans early in the planning process, recognize evidence of hydrogeomorphic processes, modify current road construction prescriptions, and expand the recognition of riparian forests from their current fish focus to include their hydrogeomorphic role. Alluvial and colluvial fans are the products of unstable terrain and can be subject to contemporary hydrogeomorphic processes. Recognition of these hazards is a key to sustainable forest management in mountainous areas.

INTRODUCTION

Fans are gently sloping landforms in mountainous areas that present an enticing opportunity for a range of land uses from forestry to housing developments. However, floods, hyperconcentrated flows, and debris flows—the processes that form fans—frequently challenge development. Natural events have been aggravated by forestry activities, exacerbating impacts to fish habitat, private property, improvements, and drinking water.

The current lack of a hazard classification for forestry on fans has led to a failure to recognize the presence of hydrogeomorphic processes and, consequently, impacts to roads, drainage structures, plantations, and safety issues. Operational forestry staff are sometimes surprised when they encounter challenges on fans, particularly in situations where the area has been mapped for terrain stability hazards using the current standards adopted in British Columbia (B.C. Ministry of Forests 1999). This is because the current hazard maps focus primarily on identifying initiation zones, rather than runout zones, which are frequently fans.

A fan is a landform, the surface of which forms a segment of a cone that radiates downslope from the point where a stream emerges from the confines of a mountain channel (Bull 1977; Ritter et al. 1995). Fans are composed of sediments that originate in a source area watershed and are transported by fluvial processes or debris flows, or a combination of the two. Alluvial fans are characteristically < 4° (Jackson et al. 1987). Debris flow fans are steeper—to 15° using the British Columbia terrain system (Howes and Kenk 1988) or 20° using the international system (Bull 1977). Steeper fans are usually referred to as cones.

The origin of many fans in British Columbia is linked to glacial episodes unrelated to modern conditions (Ryder 1971a, 1971b; Ritter et al. 1993). However, there is a spectrum of fans ranging from actively growing, and dissected, to those in a steady-state, dynamic equilibrium (as described in other environments by Denny 1965, 1967; Hunt and Mabey 1966; Hooke 1968; Beaty 1970). The contemporary activity may be superficial given the overall thickness of a fan; however, such activity can have significant implications for forests, roads, drainage structures, and plantations.

This paper describes a research project that is using site and watershed features to develop a hazard classification for forestry activities on fans. Literature explicitly regarding fans is heavily biased to arid regions and very limited information exists regarding the hydrogeomorphic role of forests on fans. We are using knowledge from a range of related subject areas because there is a considerable body of literature on debris flows (Costa and Wieczorek 1987), floods (Baker et al. 1988), and dendrochronology and forest stand development (Oliver and Larson 1996).

Fieldwork began in the spring of 2000 in the Prince Rupert Forest Region, British Columbia. While the hazard classification has not yet been finalized, extension of initial results to operational activities has clearly demonstrated that there is both an interest and an opportunity to improve the nature of forestry activities on fans.

A BRIEF DESCRIPTION OF THE STUDY AREA

The study area is in west-central British Columbia, within the Prince Rupert Forest Region (Figure 1). Study fans lay across a broad geographic area, between 53°46′ and 55°43′ N and 126° and 129°10′ W.

The western fans are within the Coastal Western Hemlock (CWH) biogeoclimatic zone and their watersheds have Mountain Hemlock (MH) and Alpine Tundra (AT) at higher elevations (Banner et al. 1993). The central fans are within the Interior Cedar–Hemlock (ICH) biogeoclimatic zone and their watersheds have Engelmann Spruce–Subalpine Fir (ESSF) and Alpine Tundra (AT) at higher elevations. The eastern fans are within the Sub-Boreal Spruce biogeoclimatic zone and their watersheds have ESSF and AT at higher elevations. Some of the eastern fans are totally within the ESSF. Major tree species found on fans are presented in Table 1.

The study area lies within the Western and Interior Systems of the

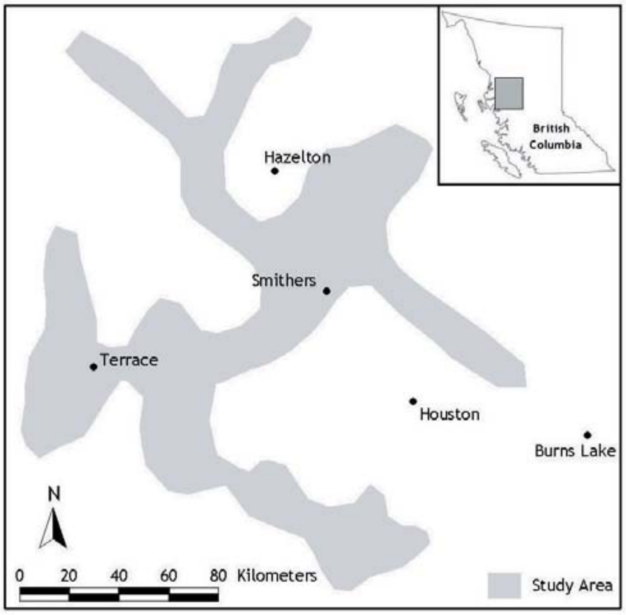

FIGURE 1 *Location map of the study area.*

TABLE 1 *Major tree species on the study area fans. Hybridization between the spruce are common in the study area (Coates et al. 1994).*

Common name	**Latin name**
White spruce	*Picea glauca*
Engelmann spruce	*Picea engelmannii*
Sitka spruce	*Picea sitchensis*
Western hemlock	*Tsuga heterophylla*
Western redcedar	*Thuja plicata*
Lodgepole pine	*Pinus contorta* var. *latifolia*
Amabilis fir	*Abies amabilis*
Subalpine fir	*Abies lasiocarpa*
Paper birch	*Betula papyrifera*
Cottonwood	*Populus balsamifera* ssp. *trichocarpa*
Aspen	*Populus tremuloides*
Red alder	*Alnus rubra*
Mountain alder	*Alnus incana*

Canadian Cordillera (Holland 1964). The Kitimat Ranges are within the Coast Mountains of the Western System. They are granitic mountains, characteristically round-topped and domed because they were overridden by glacial ice. The Interior System includes the Skeena Mountains, Nass Basin, Hazelton Mountains, and Nechako Plateau. This system is underlain chiefly by volcanic and sedimentary rocks and overall is less rocky and rugged than the Western System.

Long-term climatic stations in the study area are limited to valley-bottom locations. Extrapolation of records to study watersheds can be problematic due to mountainous terrain. However, this information can provide an indication of extreme events even though the absolute amounts of precipitation may be uncertain. Septer and Schwab (1995) compiled a record of floods for the Prince Rupert Forest Region. The records include data from the long-term stations plus newspaper reports and records from the Hudson Bay Company.

The Water Survey of Canada operates a series of stream gauging stations in the study area. However, most gauged watersheds are very large compared with the study watersheds, making unit runoff calculations and even event dating problematic. However, the hydrometric data are useful in describing the principal runoff regimes. Characteristically, the western and central portions of the study area experience biannual peak flows. Spring snowmelt provides the highest volume of runoff, and in some years the highest peak flows. Fall rain or rain-on-snow events can produce significant peak flows as well as erosion events (debris avalanches and debris flows). The same biannual peak flows occur in the eastern portion of the study area; however, in general, the spring snowmelt peaks are significantly larger than the fall peak flows.

METHODS

For this project, we are defining "contemporary" as within the last 300–500 years. The reason for this time frame is its relevance to forestry and our principal dating mechanism, dendrochronology. The term "hydrogeomorphology" refers to a combination of hydrologic and geomorphic processes, namely debris flows, hyperconcentrated flows, floods, channel avulsions, and snow avalanches.

One objective is to describe 60 fans and their watersheds: 30 that are forested and 30 that have been harvested or roaded. In each case, the fans will range from stable to actively influenced by hydrogeomorphic processes. Field descriptions of fans include forest stands, biogeoclimatic zones, hydrogeomorphic processes (Table 2), dendrochronology, stream channels, and topographic cross-sections. On those fans with forestry activities, field descriptions are supplemented with a history compiled through discussions with operational staff and pre-logging air photos and forest cover maps.

Reconnaissance overviews of watersheds are undertaken by helicopter to describe stream channels, sediment sources, and snow avalanche activity. On the ground, three aspects of hydrogeomorphic events are described: frequency, power, and extent of disturbance. Frequency is established using dendrochronology (dating of scars, abrupt changes in radial growth, physiological features, and tree establishment). Four time classes were defined that are relevant for forestry (Table 3). The selection was based on B.C. Forest Practices Code requirements (free growing, road drainage structures), forest rotations, and the spectrum of forestry plans (from development plans to Land and Resource Management Plans).

The power of events is assessed based on the impact to a forest stand (Table 4). The classes have direct implications for forestry investments. For example, low-power events may have impacts on newly established regeneration but should have limited impacts on sapling-sized regeneration. Moderate-power events may remove trees that are younger than 50 years old, and thin older stands. Moderate-power events may have some effect on roads and drainage structures. High-power events will remove trees and drainage structures and cause significant damage to roads.

The extent of impact from events is determined through dendrochronological observations, establishment of younger cohorts, and other physical observations (e.g., tree burial, sediment storage behind logs [log steps], fine sediments on vegetation, levees, and boulder/gravel splays).

TABLE 2 *Classification and characteristics of flow processes and deposits (after VanDine 1985; Smith 1986; Pierson and Costa 1987; Wells and Harvey 1987; Costa 1988)*

Characteristics	**Water flood**	**Hyperconcentrated flow**	**Debris flow**
1. Flow			
Flow type	Fully turbulent	Partly turbulent (at all times, however, high *sediment load dampens* small eddies) to laminar	Laminar at time of deposition but may be turbulent on steep slopes
Mean velocity	To 90 km/hr	0.6 m/min to 115 km/hr	To 115 km/hr
Sediment concentration	1–40% by weight 0.4–20% by volume	40–70% by weight 20–47% by volume	70–90% by weight 47–77% by volume
Sediment support mechanism	Turbulence, electrostatic forces	Turbulence, grain dispersive pressure, buoyancy	Matrix strength (cohesion and structural support), grain dispers. press., buoyancy
Sediment concentration profile	Non-uniform (solids and water are separate components of flow)	Non-uniform to uniform (solids and water are separate components of flow)	Uniform (solids and water move as a single viscoplastic body)
Bulk density	1.01–1.33 g/cc	1.33–1.80 g/cc	1.80–2.30 g/cc
Shear strength	0–100 dyne/cm^2	100–400 dyne/cm^2	> 400 dyne/cm^2
Fluid type	Newtonian	Newtonian to Non-Newtonian	Non-Newtonian Viscoplastic (coulomb-viscous and Bingham-plastic models)
Viscosity	0.01–20 poise	20– 200 poise	>> 200 poise
Fall velocity (% of clear water)	100–33	33–0	0
2. Deposits			
Mode of deposition	Grain-by-grain, dominated by traction processes	Rapid grain-by-grain aggradation from both suspension and traction	*En masse*
Stratification	Massive or horizontal stratification (with cross-stratification)	None or horizontal stratification	None
Grading	Variable: as a result of sequential processes rather than a single process	Frequently distribution normal graded (coarse on bottom, fine on top)	None; reverse; reverse to normal, coarse-tail normal
Sediment characteristics and texture	Clast-supported with an open framework or distinctly finer grained matrix of infiltrated sand; rounded clasts; wide range of particle sizes; sorting from front to tail; *b*max - < 100 mm to > 200 mm	Clast-supported, with predominantly coarse sand, moderate to poorly sorted, *b*max typically < 180 mm	Matrix-supported; rarely clast-supported; very poor to extremely poor sorting; extreme range of particle sizes; *b*max 60–230 mm, may contain megaclasts – 400 mm
Clast long-axis (A) orientation; imbrication	Always perpendicular to flow; usually well imbricated	Large cobble to boulder – usually perpendicular to flow; pebbles to small cobbles – usually parallel to flow; weak imbrication and collapse packing	Variable, based on location within flow; parallel to flow is most prominent; weak to no imbrication
Landforms and deposits	Bars, fans, sheets, splays, channels have large width-to-depth ratio	Similar to water flood	Marginal levees, term. lobes, trapezoidal to U-shaped channel

TABLE 3 *Time classes relevant for forestry*

Time period (years)	Category
0–50	Significant
50–100	Important
100–200	Moderate
200+	Low

TABLE 4 *Power of hydrogeomorphic events based on impact to forest stands*

Power	Forest stand description	Forest stand type
Nil	No effect on forest stands.	FS-1
Low	Original stand remains, although it may have been killed by the event. A younger cohort may be established on the sediments from the event.	FS-2
Moderate	Original stand has been thinned by an event with a younger cohort established on the sediments. Trees from the original stand may be found in debris piles.	FS-3
High	Original stand is removed by an event. A younger cohort is established on the sediments. Trees from the original stand may be found in debris piles.	FS-4

Watershed morphometrics are determined by GIS analysis. The basic attributes include watershed area, relief, basin length, length of stream channels, and area of potentially failing slopes. The attributes were selected due to their influence on the processes influencing fans, namely peak streamflow generation and erosion.

The Melton Index is calculated by dividing relief by the square root of the watershed area (Melton 1965). This index has been found to be reliable for differentiating watersheds with alluvial or debris flow fans (Jackson et al. 1987). Characteristically, watersheds with an index of $< 0.25–0.30$ have alluvial fans, while debris flow fans are associated with higher indices.

Basin shape (Rf) is determined by dividing watershed area by the square of watershed length. The theory is that equidimensional (round) watersheds ($Rf = 0.7854$) have a shorter time of concentration and thus high peak flows than elongated watersheds (e.g., $Rf = 0.07958$) (Strahler 1964). Similarly, drainage density has been associated with peak flows: the higher the density, the higher the peak flows (Patton and Baker 1976). Basin magnitude, the number of first-order streams, is also linked to hydrologic response (Shreve 1966, 1967).

The hypsometric integral is the area under a curve representing the percentage of a watershed below a given elevation (Strahler 1952). A low integral is found in watersheds with most of the area at lower relative elevations. The higher the integral, the more area is found at higher relative elevations. While the integral is related to long-term erosional development of the watershed, it also may be used as an attribute for peak flow generation (e.g., the extent of watershed in the high-elevation snowmelt zone).

Relief ratio is relief divided by basin length. This ratio has the potential to be linked to both runoff and erosion (Schumm 1956).

Terrain stability maps were not available for study watersheds, so area between 30 and 40° was chosen as an approximation of the extent of unstable soils (Jim Schwab, B.C. Ministry of Forests, pers. comm., 2000). The forest cover maps produced by the B.C. Ministry of Forests have a designation for actively failing soils (ES1). This value is being explored; however, it applies only to forested areas of a watershed and may therefore underestimate the total extent of erosion-prone sites. Bedrock geology will be used as a watershed attribute; however, we were not able to access the GIS data for this paper. Our intent is to use a system such as Selby's (1980) to characterize bedrock erodability.

INITIAL RESULTS

Field- and map-based data have been collected on 16 unlogged and 14 logged fans to date. The analysis is currently under way; however, a series of trends is apparent, and preliminary interpretations can be made.

Morphology of Fans

The range of fan morphology in the study area reflects historic and contemporary hydrogeomorphic activity. Low-gradient fans formed by alluvial deposition characteristically have larger watersheds (> 12 km^2). Steeper-gradient fans formed by debris flows have smaller (< 12 km^2) watersheds. Contemporary activity does not always reflect the mode of fan origin.

Evidence of paraglacial fans range from remnants along the main valley sides to major portions of the original deposits. The contemporary fan surfaces are generally 6–10 m below these deposits. Erosion of the original deposits is most likely due to a decline in sediment delivery from the watershed.

Contemporary fan activity ranges from entrenchment to actively growing. Very few fans were found to be in a “steady state equilibrium.” Entrenchment is occurring on alluvial and debris flow fans. It appears as though debris flow scour rather than fluvial action is causing the entrenchment on most debris flow fans. Of note, ancient debris flow levees are having a similar effect on the morphology of some fans, as has been reported for entrenched fans. This takes the form of fan elongation, with the transport of coarser sediments further down the fan.

Forest Stands as Indicators of Hydrogeomorphic Activity

Forest stands are a generally reliable information source for the frequency, power, and extent of hydrogeomorphic events. However, there appear to be several limitations. It is generally difficult to take wedges from trees with scars that are older than approximately 50 years (felling is necessary and we have not done this). Growth responses from an event can range from abrupt negative to abrupt positive growth, including no response even on buried trees. A negative growth response (consisting of an abrupt reduction in ring widths) is the result of deep burial and changes in soil water conditions. A positive growth response (an abrupt increase in ring widths) can be related to the removal of competition or an improvement in soil water conditions. Positive growth responses were found on some buried trees. Approximately 30 dendrochronology samples were taken per fan.

All conifer and deciduous species in the study area were observed to develop adventitious roots after burial by sediments. The critical burial depth that causes mortality has not been determined. Buried trees are apparent due to their lack of “butt flare” (Figure 2). The time taken to regain butt flare appears to be at least 50 years.

We are classifying the power of hydrogeomorphic events by the effect on forest stands (Table 4). Four classes are used, ranging from no effect to

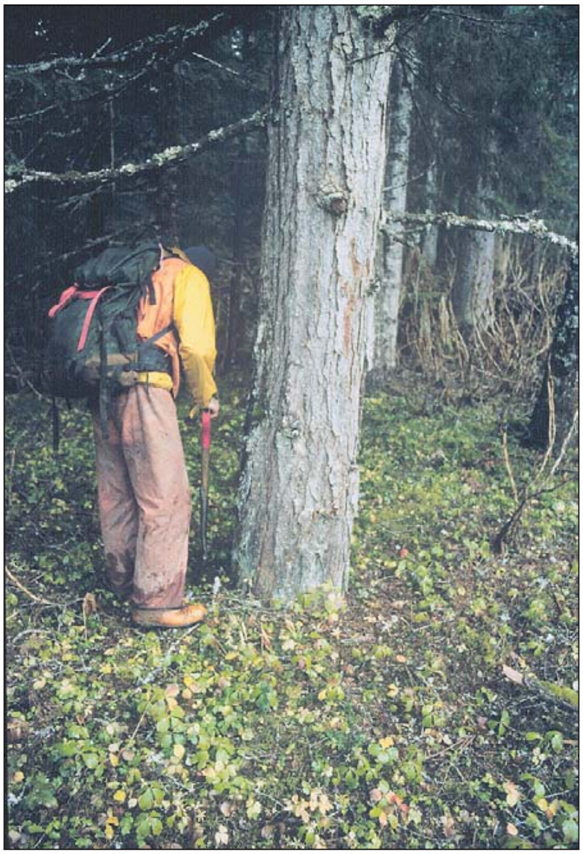

FIGURE 2 *Sediments have buried the butt of this tree. Lack of the characteristic "butt flare" is an indication of active sediment deposition.*

complete removal of the original stand. Of the 30 fans explored, no fans were identified as having FS-1 stands (no effect from hydrogeomorphic events). Only two fans were found with FS-2 stands representing the most powerful events. No fans were described with only FS-3 stands representing the most powerful events. Most fans have FS-4 stands (high power). These fans also have FS-2 and FS-3 stands (low to moderate power) at the margins of the FS-4 stands.

We have observed that the extent of disturbance from hydrogeomorphic events on most fans is limited to swaths of 10–20 m wide, primarily along stream channels that range from 2 to 6 m wide. Such narrow zones of disturbance are very difficult to detect on air photographs, particularly where the forest cover is moderately open due to devil's club (*Oplopanax horridus*) ecosystem associations. The fans with the widest zones of disturbance are alluvial fans (≥ 180 m).

Hydrogeomorphic Role of Forests on Fans

Forests and woody debris influence the transport and storage of sediments, and erosion on a fan surface. It is common to observe lateral and terminal confinement of sediments from hydrogeomorphic events due to stems and large woody debris. In some cases, the volume of stored sediments can be significant (Figure 3). In other cases, the amount stored per event may be small, but incrementally may lead to the development of fine-textured levees and an elevation of the stream channel above the general fan surface. In cases where an avulsion occurs, the stream energy is frequently dissipated across

FIGURE 3 *Woody debris held by standing trees can lead to significant sediment storage. In situations like this, it is prudent to prescribe reserves to maintain the hydrogeomorphic role of trees.*

the fan surface by woody "obstructions." In many situations, it appears as though subsequent hydrogeomorphic events lead to the re-establishment of the original stream channel.

The hydrogeomorphic role of forests on our study fans ranges laterally out from the stream channel from zero to several hundred metres. The paths taken by events are usually along old channels, although downed woody debris can play a significant role in redirecting events.

Streams on Fans

Streams are a common feature on fans, and the stream is often at the highest location of the fan cross-section. This appears to be due to levees and the hydrogeomorphic role of forests.

Streams on fans can range from entrenched (by up to 5 m) to unconfined (very low banks). Frequently, channel dimensions are determined by hydrogeomorphic events rather than by fluvial action. Channel substrate can range from fluvial sediments to large colluvial lag sediments. Large woody debris (LWD), both as individual pieces and log jams, can act as hydraulic structures, limiting down-cutting of the channel. LWD can also cause avulsions on several fans. Large woody debris can increase lateral channel erosion; however, this fluvial activity was observed to be generally minor compared with the hydrogeomorphic process influencing the channel. Structures formed by clasts range from none in channels with a history of recent events, to strong in channels that have not experienced disturbance for a long period of time.

Even on debris flow fans, streams on fans are a major source of operational forestry challenges. Generally, the problems arise because drainage structures are sized to allow water flow and are insufficient for bedload and woody debris. Multiple channels on fans also lead to problems because, in any given event, all water and debris may be transported down one rather than all channels. As a result, drainage structures are usually significantly undersized to handle the resulting flows.

Watershed Attributes

Fans are directly influenced by the supply of water, sediment, and woody debris from their watersheds. We are exploring a series of watershed morphometrics and attributes that are related to water and sediments to determine which factors are sensitive to hydrogeomorphic processes. Table 5 presents a subset of our data.

The Melton Index is characteristically greater than 0.25–0.3 in debris flow–dominated watersheds (Jackson et al. 1987). However, in Mill Creek, there is no evidence of contemporary debris flows on the fan, although the index is 0.879. The presence of snow avalanches that are influencing the whole channel within this watershed may have a strong influence on the lack of debris flows.

Roads on Fans

Forest roads are an integral component of forestry activities and represent the highest risk for fan destabilization. We found a series of design, construction, and maintenance issues repeated on destabilized fans (summarized in Table 6).

Inappropriate road locations and drainage structures on fans can be expensive. On one study fan, more than $600 000 was spent to relocate a road and install an adequate bridge. The original road and undersized bridge led to an avulsion, and subsequent attempts to control the stream and add a jump span to the original structure proved unsuccessful. Commonly, eroded roads are abandoned and no attempts at fan restoration are made due to the prohibitive costs and technical challenges. In most cases, inappropriate roads and drainage structures exacerbate impacts from hydrogeomorphic events.

Logging on Fans

Logging on fans involves the removal of tree stems and generally an increase in the amount of small and large woody debris as well as the disruption of downed large woody debris. Ground disturbance can be continuous as a result of skid trails or discontinuous as a result of winter harvesting or cable yarding. The B.C. Forest Practices Code requires riparian reserves on fish-bearing streams or streams that are directly tributary to fish streams. The streams on many fans do not have fish; as a result, riparian reserves are not always left.

The two main logging-related effects on fan stability are due to the removal of forests that play an active hydrogeomorphic role and skid trails that intercept broadcast flows.

DISCUSSION

Forests have been described as "silent witnesses" to hydrogeomorphic processes (Schweingruber 1996). At the stand level, the evidence is in structure, composition, and age-class distribution. At the tree level, the evidence is in scars and abrupt changes in growth. Forests can provide information on the frequency, power, and areal extent of hydrogeomorphic events. For these reasons, forest stands were chosen as the leading indicator for a hazard classification of hydrogeomorphic activity on fans. A key to the utility of trees as a leading indicator is that forestry staff are familiar with trees and readily learn to see the signs.

The original concept in this project was that a whole fan would be hazard-classified based on the highest Forest Stand Type. However, with the sampling to date it is apparent that classifying zones on fans is more appropriate. A major reason for this is the limited extent of disturbance from hydrogeomorphic events on most fans. Significant portions of many fans in our study present no apparent hydrogeomorphic hazards for forestry

TABLE 5 *Some watershed attributes associated with fans that have Forest Stand Types 1, 2, and 4 (abbreviations for biogeoclimatic zones are in the section describing the study area)*

Attribute	**Carrigan**	**Shedin**	**Mill**	**Compass**	**Wan**	**Legate**	**Tsez-akwa**	**Kits**
Biogeoclimatic zones (fan/watershed)	ICH/ ESSF	ICH/ ESSF, AT	ICH/ ESSF	ICH/ ESSF, AT	ESSF/ AT	CWH/ MH, AT	SBS/ ESSF, AT	ICH/ ESSF, AT
Forest Stand Type on fan	FS-2	FS-2	FS-2	FS-4	FS-4	FS-4	FS-4	FS-4
Hydrogeomorphic process	Hyper. flow	Debris flow to apex	Flood	Hyper. flow	Debris flow	Debris flow	Flood	Debris flow
Frequency class (years)	100	0–50	0–50	0–50	0–50	0–50	50–100	0–50
W/S area (km^2)	1.560	4.824	1.408	18.220	1.286	1.318	99.266	0.493
Melton Ruggedness Index	0.382	0.464	0.879	0.345	0.655	1.076	0.159	0.785
Hypsometric integral	0.654	0.497	0.542	0.424	0.504	0.520	0.372	0.539
W/S shape	0.557	0.165	0.302	0.294	0.361	0.221	0.291	0.387
Relief ratio	0.285	0.188	0.483	0.187	0.394	0.505	0.086	0.488
Drainage density km/km^2	2.517	2.573	2.613	2.654	2.325	4.019	1.795	6.170
% W/S 30–40°	14.3	0.9	59.5	21.2	31.6	39.6	4.2	40.9
% W/S ESA1	0	0	53	14	3	29	4	30
Snow avalanche	Nil	Nil	Whole channel	Valley sides	Whole channel	Whole channel	Valley sides	Valley sides

TABLE 6 *Some common road problems and solutions*

Some common road problems	**Solutions**
Roads climb to stream crossings	Roads drop to stream crossings/cross at apex
Roads built at slope break in stream/fan	Cross streams in uniform slope reaches
Ditches	No ditch lines/limit road width
Lack of cross-drainage	Use rolling grade in old channels/frequent cross-drains
Drainage structures affect channel hydraulics	Structures with rectangular cross-section
Excavation into stream channel–channel destabilization	Place rip-rap to maintain channel stability if excavation is required
Inadequate drainage structures–multiple channel situations	Design all structures in multiple channel situations to handle all the flow or to be “fail safe”
Roads not deactivated	Deactivate roads and structures ASAP/build with deactivation in mind
Breached streambanks	Do not breach banks/reconstruct with deactivation
Skid trails on fans channel water	Limit skid trails, deactivate and replace LWD

activities. Given the limited areal disturbance even on fans experiencing powerful events, air photo identification of disturbances can be difficult to impossible. Fieldwork is required to identify the nature and extent of hydrogeomorphic disturbances on most fans.

Our observations indicate that forests can play an important hydrogeomorphic role on fans. Irasawa et al. (1991) found that forested fans subject to debris flows had steeper slope gradients due to the storage of sediments on the upper fan surface. This storage role appears to be occurring with a tendency for the stream channel to remain in its original location. Trees and woody debris act as major roughness elements during the early stages of an avulsion. In general, a stream has difficulty in establishing a new single-thread channel. As a result, deposition occurs on the forested fan surface and it is common for the stream to return to its original channel (Sato 1991). In addition, large woody debris and debris jams in the stream channel act as hydraulic structures, storing sediments and limiting channel down-cutting (Keller and Swanson 1979). As a consequence, the cross-sections of fans characteristically have the stream channel at the highest location. However, once a "successful" avulsion occurs, it is unlikely that the stream will return to its original location. This situation was observed on several logged or roaded fans, particularly where no, or narrow, riparian reserves were retained.

The B.C. Forest Practices Code specifies widths of riparian zones for streams that have fish or streams that are directly tributary to fish streams. The reserve widths are primarily based on the average height of trees adjacent to streams (e.g., 30 m). Our observations indicate that both the rationale for reserves and their widths should be revisited, given the important hydrogeomorphic role played by forests on many fans.

First, many fans have streams that do not have fish and thus there is no legislated requirement for reserves. We have consistently observed that the removal of hydrogeomorphically active forests has dramatic effects on streams and fan surfaces. In particular, we noted channel avulsions, channel entrenchment, channel widening, dewatering, and sediment deposition across fan surfaces. The nature and extent of these disturbances are considerably greater than would be expected in a forested situation. The resulting impacts are to forest growing sites, roads, stream ecology, and aesthetics.

Second, basing reserve width on average tree height is not appropriate because the zone of hydrogeomorphically active forests on fans is not a function of tree height. Rather, the zone is determined by the trajectories of hydrogeomorphic events, topographic differences that are sometimes subtle, and stochastically through the presence of large woody debris. It is appropriate to combine these features with dendrochronology and stand information to tailor reserves and management zones for individual fans.

A management zone is generally specified next to a riparian reserve. Given that future hydrogeomorphic events may extend further than contemporary evidence suggests, it is prudent to leave high stumps and large woody debris in the management zone to act as future sediment traps. Of note, we inspected stumps on a fan with a reserve and found evidence of recent and historic debris flow scars (dating back over 400 years). In this case, more attention should have been paid to the reserve layout. In addition, there was no management zone to protect the reserve from windthrow that was already occurring 2 years post-harvesting.

Logging activities on a fan can influence fan stability. In particular, we observed that skid trails can intercept and concentrate overland flows. The trails become new stream channels and experience considerable erosion as a result unless there are rolling dips, cross-ditches, or woody debris placement.

When dealing with fans there is perhaps a tendency to focus on dramatic erosional events such as major floods or debris flows that occur irregularly. However, streams on fans pose a hazard for forestry activities due to annual or biannual high flow periods (spring snowmelt and fall rain or rain-on-snow). Bedload and debris movement can challenge drainage structures seasonally, and if undersized or not adequately maintained, can lead to significant erosion of roads. In addition, we observed that where channel excavations for drainage structures are not buttressed with rip-rap, sediments from channel erosion can quickly overwhelm drainage structures.

Fans are a product of, and influenced by, the water and sediment being delivered from their watershed. For this reason, we are exploring the significance of watershed morphometrics and features. At this point, the analysis is still under way; however, we have made several initial conclusions. It appears as though snow avalanches may condition a stream channel such that the dominant sediment transport mechanism is bedload movement rather than debris flows. Characteristically, snow avalanche channels have limited riparian forests and very few accumulations of woody debris. As a result, sediment storage tends to be continuous along a channel rather than in discrete accumulations that are prone to debris flow mobilization. It also appears that most of the study fans are of paraglacial origin, and that contemporary hydrogeomorphic activity on some fans has shifted from debris flows to hyperconcentrated flows and floods. Thus, floods may be the contemporary hydrogeomorphic process on a fan with a gradient of $> 4°$ and a watershed with a Melton Index > 0.25.

One sage forester has commented that from a roads perspective, fans can be classed into three categories: no problem, nuisance, and problem (D. Keating, pers. comm., 2000). We found very few roads on fans that were "no problem." Most roads on fans have cost a considerable amount of money to maintain in a safe condition. Most of the problems we observed can be avoided or addressed in road design, construction techniques, maintenance, and deactivation (Table 6). However, it is crucial to identify fan landforms early in the planning process. This is generally not happening and, as a result, many situations develop into expensive "nuisances and problems."

Information about the frequency, power, and extent of impact from hydrogeomorphic events is central to developing appropriate forestry prescriptions. However, this information provides only part of the hazard assessment. Previous events or processes may have set the stage for imminent future challenges on a fan. For example, bedload aggradation may predispose a stream to an avulsion. Identifying these situations is necessary, given the long-term implications of many forestry activities.

CONCLUSIONS

Identifying hydrogeomorphic hazards for forestry on fans is central to sustainable forest management. However, even "safe" fans can be destabilized with inappropriate prescriptions for riparian zones, stream crossings, road locations, cross-drainage, and deactivation. Using the analogy of unstable slopes, all fans should be considered as class IV terrain unless proven otherwise. Special attention must be paid to all forestry activities.

As with terrain stability recognition, most operational forestry staff require office and field training in the recognition of fans and the signs of hydrogeomorphic activity. Until the landforms and hazards are identified operationally, forestry activities on fans will continue to be problematic.

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LITERATURE CITED

Baker, V.R., R.C. Kochel, and P.C. Patton (editors). Flood geomorphology. John Wiley, New York, N.Y.

Banner, A., W. MacKenzie, S. Haeussler, S. Thomson, J. Pojar, and R. Trowbridge. 1993. A field guide to site identification and interpretation for the Prince Rupert Forest Region. B.C. Min. For., Smithers, B.C. Land Manage. Handb. 26.

Beaty, C.B. 1970. Age and estimated rate of accumulation of an alluvial fan. White Mountains, California. Am. J. Sci. 268:50–77.

British Columbia Ministry of Forests. 1999. Mapping and assessing terrain stability. 2nd ed. Victoria, B.C. Forest Practices Code of B.C. Guidebook.

Bull, W.B. 1977. The alluvial-fan environment. Prog. Phys. Geogr. 1:222–70.

Coates, K.D., S. Haeussler, S. Lindeburgh, R. Pojar, and R.J. Stock. 1994. Ecology and silviculture of interior spruce in British Columbia. B.C. Min. For. and Can. For. Serv., Victoria, B.C. FRDA Rep. 220.

Costa, J.E. 1988. Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. *In* Flood geomorphology. V.R Baker, R.C. Kochel, and P.C. Patton (editors). John Wiley, New York, N.Y. pp. 113–22.

Costa, J.E. and G.F. Wieczorek (editors). 1987. Debris flows/avalanches: process, recognition, and mitigation. Rev. Eng. Geol. Vol. VII. Geol. Soc. Am., Boulder, Colo.

Denny, C.S. 1965. Alluvial fans in the Death Valley region, California and Nevada. U.S. Geol. Survey Prof. Pap. 466.

———. 1967. Fans and pediments. Am. J. Sci. 265:81–105.

Holland, S.S. 1964. Landforms of British Columbia: A physiographic outline. B.C. Dep. Mines and Petroleum Resour., Victoria, B.C. Bull. No. 48.

Hooke, R.L. 1968. Steady-state relationships on arid-region alluvial fans. J. Geol. 75:438–60.

Howes, D.E and E. Kenk. 1988. Terrain classification system for British Columbia. B.C. Min. Environ., Lands and Parks, Victoria, B.C. MOE Man. 10.

Hunt, C.B. and D.R. Mabey. 1966. Stratigraphy and structure. Death Valley, California. U.S. Geol. Surv. Prof. Pap. 494-A.

Irasawa, M., Y. Ishikawa, A. Fukumoto, and T. Mizuyama. 1991. Control of debris flows by forested zones. *In* Proc. 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. 543–50.

Jackson, L.E., R.A. Kostaschuk, and G.M. MacDonald. 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. *In* Debris flows/avalanches: Process, recognition, and mitigation. J.E. Costa and G.F. Wieczorek (editors). Rev. Eng. Geol. Vol. VII. Geol. Soc. Am., pp. 115–24.

Keller, E.A. and F.J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361–80.

Melton, M.A. 1965. The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. J. Geol. 73:1–38.

Oliver, C.D. and B.C. Larson. 1996. Forest stand dynamics. John Wiley, New York, N.Y.

Patton, P.C. and V.R. Baker. 1976. Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. Water Resour. Res. 12:941–52.

Pierson, T.C. and J.E. Costa. 1987. A rheologic classification of subaerial sediment-water flows. *In* Debris flows/avalanches: Process, recognition, and mitigation. J.E. Costa and G.F. Wieczorek (editors). Geol. Soc. Am. Rev. Eng. Geol. Vol. VII, pp. 1–12.

Ritter, J. and 16 others. 1993. Quaternary evolution of Cedar Creek alluvial fan, Montana. Geomorphology 8:287–304.

Ritter, D.F., R.C. Kochel, and J.R. Miller. 1995. Process geomorphology. 3rd ed. Wm. C. Brown Publishers. Dubuque, Iowa.

Ryder, J.M. 1971a. The stratigraphy and morphology of paraglacial alluvial fans in south-central British Columbia. Can. J. Earth Sci. 8:279–98.

———. 1971b. Some aspects of the morphometry of paraglacial alluvial fans in south-central British Columbia. Can. J. Earth Sci. 8:1252–64.

Sato, T. 1991. Flood disaster with drifted logs and sand in Aso Volcano. *In* Proc. 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. 497–506.

Schumm, S.A. 1956. Evolution of drainage systems and slopes in badlands at Perth Amboy, New Jersey. Geol. Soc. Am. Bull. 67:597–646.

Schweingruber, F.H. 1996. Tree rings and environment dendroecology. Paul Haupt Publishers. Berne, Switzerland.

Selby, M.J. 1980. A rock mass strength classification for geomorphic purposes: with tests from Antarctic and New Zealand. Zeit. f. Geomorph. 24:31-51.

Septer, D. and J.W. Schwab. 1995. Rainstorm and flood damage: northwest British Columbia 1891–1991. B.C. Min. For., Victoria, B.C. Land Manage. Handb. 31.

Shreve, R.L. 1966. Statistical law of stream numbers. J. Geol. 74:17–37.

———. 1967. Infinite topographically random channel networks. J. Geol. 75: 178–86.

Smith, G.A. 1986. Coarse-grained nonmarine volcaniclastic sediment: terminology and depositional process. Geol. Soc. Am. Bull. 97:1–10.

Strahler, A.N. 1952. Hypsometric (area-altitude) analysis of erosional topography. Geol. Soc. Amer. Bull. 63:1117–42.

———. 1964. Quantitative geomorphology of drainage basins and channel networks. *In* Handbook of hydrology. V.T. Chow (editor). McGraw-Hill, New York, N.Y. pp. 439–76.

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

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