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Recognition of debris flow, debris flood and flood hazard through watershed morphometrics

Abstract Debris flows, debris floods and floods in mountainous areas are responsible for loss of life and damage to infrastructure, making it important to recognize these hazards in the early stage of planning land developments. Detailed terrain information is seldom available and basic watershed morphometrics must be used for hazard identification. An existing model uses watershed area and relief (the Melton ratio) to differentiate watersheds prone to flooding from those subject to debris flows and debris floods. However, the hazards related to debris flows and debris floods are not the same, requiring further differentiation. Here, we demonstrate that a model using watershed length combined with the Melton ratio can be used to differentiate debris-flow and debris-flood prone watersheds. This model was tested on 65 alluvial and colluvial fans in west central British Columbia, Canada, that were examined in the field. The model correctly identified 92% of the debris-flow, 83% of the debris-flood, and 88% of the flood watersheds. With adaptation for different regional conditions, the use of basic watershed morphometrics could assist land managers, scientists, and engineers with the identification of hydrogeomorphic hazards on fans elsewhere.

Keywords Debris flows · Debris floods · Floods · Melton ratio · Hydrogeomorphic processes · British Columbia · Canada

Introduction

Fans are formed by and can be subject to floods, debris floods and debris flows (hydrogeomorphic processes) with resulting damage to infrastructure and loss of life (VanDine 1985). As a result, there is a need to identify hydrogeomorphic hazards early in the planning stages of land development. In cases where this has not been done, it is frequently necessary to design control structures which require identification of specific hazards. Central to hazard recognition is the need to identify the specific hydrogeomorphic process because each process has different associated hazard characteristics. For example, debris flows can have peak discharges 5 to 40 times greater than floods, while debris floods have relative peak discharges of only up to twice those of flood discharges (Hungr et al. 2001).

In the early stages of development planning, hazards from hydrogeomorphic processes can be identified through simple models that use existing data rather than field-derived data. The identification scheme presented here uses topographic information to predict the hydrogeomorphic processes influencing alluvial and colluvial fans. Previously, Jackson et al. (1987) used the Melton ratio (watershed relief divided by the square root of watershed area) (Melton 1957) to differentiate flood and debris flow watersheds in the southern Canadian Rocky Mountains. They found that watersheds prone to flooding had ratios <0.3 while watersheds prone to debris flows had ratios >0.3. Bovis and Jakob (1999) determined that debris flow watersheds had Melton ratios >0.53 in the coastal mountains of southwest British Columbia. It is possible that the lower Melton ratio value identified by Jackson et al. (1987) is due in part to the combining debris floods and debris flows.

This study outlines the use of watershed morphometrics to differentiate hydrogeomorphic processes and tests this model on a series of alluvial and colluvial fans that were examined in the field in west central British Columbia. With adaptation for different regional conditions, the use of basic watershed morphometrics could assist land managers, scientists, and engineers with the identification of hydrogeomorphic hazards on fans elsewhere.

Study area

The study area is in west central British Columbia, Canada, with study fans lying across a broad geographic area, between 53°46′ and 55° 43′ north latitude and 126° 00′ and 129° 10′ west longitude (Fig. 1). The study area lies within the Western and Interior Systems of the Canadian Cordillera (Holland 1964). The Kitimat Ranges are within the Coast Mountains of the Western System, and consist of granitic mountains, characteristically round-topped and domed because they were overridden by large Pleistocene ice sheets. The Interior System includes the Skeena Mountains, Nass Basin, Hazelton Mountains and the Nechako Plateau. This system is underlain chiefly by volcanic and sedimentary rocks and overall is less rocky and rugged than the Western System.

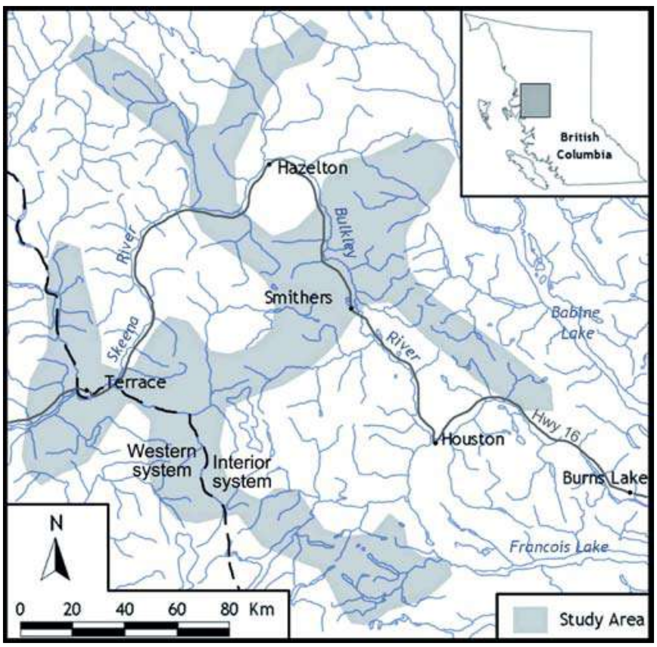

Fig. 1 Location map of the study area

The study area was last glaciated during the Fraser glaciation with ice retreat completed between 10,700 and 9,300 years B.P. (Alley and Young 1978; Clague 1984). The legacy of the glaciation is extensive morainal and glaciofluvial deposits that dominate the landscape, masking much of the underlying bedrock (Runka 1972). Fans are a post-glacial feature in the study area reflecting paraglacial (Ryder 1971a, 1971b) and contemporary conditions.

We stratified the study area into three broad forest types of similar climate and vegetation using British Columbia's ecologic classification system: coastal rainforests, northern temperate, and sub-boreal forests (Pojar et al. 1987; Banner et al. 1993; Mah et al. 1996). The three zones reflect a gradient from maritime to continental climates. All study fans were forested, although some have been logged to varying degrees. Logging operations have not been conducted in most watersheds, and where present are very limited in extent.

Twenty-five stream gauging stations are operated by the Water Survey of Canada in the study area. Most gauged watersheds are very large compared to the study watersheds, making unit runoff calculations and event dating of particular events 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 peakflows. Spring snowmelt provides the largest runoff volume and, in some years, the highest peakflows. Autumn rain or rain-on-snow events can produce significant peakflows as well as initiating mass movements (debris avalanches and debris flows). The same biannual peakflows occur in the eastern portion of the study area, although in general, the spring snowmelt peaks are significantly larger than the fall peakflows.

Methods

The approach taken in this study was to classify hydrogeomorphic processes in a watershed based on the sediment deposit signatures present on the fan at the mouth of the watershed (Costa 1988; Wells and Harvey 1987; Hungr et al. 2001). The dominant process was determined based on the following order: debris flows, debris floods, and floods.

Debris-flow fans characteristically have marginal levées or terminal lobes (Fig. 2). Debris-flow deposits can have reverse grading, although grading can range from absent to normal. The long-axis (A-axis) orientation of clasts is dominantly parallel to flow.

Flood and debris flood deposits included bars, fans, sheets, and splays, and the stream channels have a large width-to-depth ratio. The differentiation of floods and debris floods involved assessing the volume of sediment deposits relative to the size of stream channel, and determining the orientation of clasts. Debris floods have sediment concentrations of 20 to 47% by volume and characteristically have significant sediment deposits beyond the channel on the fan (e.g., where the sediment load overwhelms the channel on the fan) (Fig. 3). Floods have sediment concentrations of less than 20% by volume and commonly have limited or localized sediment deposits beyond the channel on the fan (the channel can generally contain the sediment load). The A-axes of all clasts in flood deposits are oriented perpendicular to flow. Sediments in flood deposits are well sorted (Fig. 4) and the clasts are usually well imbricated. Clast orientation in debris-flood deposits are mixed, with the A-axes of large cobble to boulder clasts usually perpendicular to the flow and pebbles to small cobbles usually parallel to flow. Debris-flood deposits commonly have weak imbrication and collapse packing.

Fig. 3 A debris flood deposit that overwhelmed a channel

Fig. 2 A steep-sided, 1-m-high levée on a debris flow fan. Post-event activity has created a small terrace between the levée and an incised stream channel

Fig. 4 A profile of sediments on an alluvial (flood) fan showing well sorted layering

Table 1 Watershed attributes used in the analysis

Process	Attribute	Description	Units
Peak flow generation	Area	Topographically defined area of the watershed. (Murphey et. al1977)	km^2
	Watershed length	The planimetric straight-line length from the fan apex to the most distant point on the watershed boundary	km
	Shape	Watershed area (km^2) divided by the square of watershed length (km^2)	km^2/km^2
	Length of channels	The total length of stream channels identified on TRIM maps. (Carlston1963; Patton and Baker1976)	km
	Drainage density	The total length of stream channels (km) divided by watershed area (km^2)	km/km^{-2}
	Hypsometric integral	The hypsometric curve is a plot of the percent watershed area above a relative elevation (100% being the maximum elevation and 0% being the minimum elevation). The hypsometric integral is the area under the curve. (Strahler1952)	%/%
Sediment production	Relief	The elevation difference between the highest and lowest points in a watershed. (Patton1988)	km
	Environmentally sensitive areas for soil stability	ESA's are forest cover map attributes that are identified by forest classifiers or terrain specialists. ESA's are map polygons that contain the initiation sites for natural mass wasting. ESA's are expressed as a percent of the total watershed area. (Anonymous1992)	%
	Environmentally sensitive areas for soil stability and other factors	ESASx's are forest cover map attributes that are identified by forest classifiers or terrain specialists. These map polygons contain initiation sites for natural mass wasting and other factors that are sensitive to forestry activities (e.g., wildlife habitat, reforestation issues such as high moisture levels, visual or landscape retention objectives). ESASx's are expressed as a percent of the total watershed area and for the purpose of this study include the extent of ESA's. (Anonymous1992)	%
	Commercial forest cover	The percent of watershed area with commercial forest cover, defined as areas of mature and immature forest, and areas that are not satisfactorily restocked as a result of logging or natural disturbances (e.g., wildfire)	%
	Extent of terrain greater than 30°, 35°, or 40°	The percent of watershed area that has slopes greater than 30°, 35°, or 40°	%
	Extent of terrain between 30°and 40°	The percent of watershed area that has slopes between 30°and 40°	%
Ratios	Melton ratio	Watershed relief (km) divided by the square root of watershed area (km). (Melton1957; Patton and Baker1976; Jackson et al.1987)	km/km
	Relief ratio	Watershed relief (km) divided by watershed length (km). (Strahler1958; Costa1988)	km/km

The selection of fans involved several criteria. Fans were selected to provide a reasonable cross section of hydrogeomorphic processes and geographic distribution across the study area. To gain an understanding of natural processes, it was essential that the hydrogeomorphic processes not be influenced by human land use, thus only watersheds with no, or very limited, human land use activities were included (e.g., logging, mining, road building). Fans with human use were included only if the use did not obscure identification of the hydrogeomorphic processes.

Sixteen basic biophysical watershed attributes were selected based on their influence on peak flow generation and the production of sediment (Table 1). Six of these attributes are related to peak flow generation, eight are related to sediment production, and two are ratios that integrate watershed area and relief were used as watershed attributes. Slope stability mapping (Anonymous 1999) was not available for the study watersheds so alternate watershed attributes were selected as surrogates: four slope gradient classes, and environmentally sensitive areas (ESA's) an attribute used on forest cover maps in British Columbia (Anonymous 1992). The percentage of a watershed with commercial forest cover (i.e., excluding alpine forests) was selected due to the role of forests in moderating runoff and enhancing slope stability (Sidle et al. 1985; Hetherington 1987).

Watershed boundaries were established using a digital elevation model (DEM) and GIS (Geographic Information Systems). The DEM has a cell size of 25×25 m and 90% of the vertical data are accurate to within 10 m of their true elevation. The lowest point in a watershed was the apex of the fan (i.e., fans were not included in the watersheds). Overlays were made using water features (stream channels), forest cover, and digital elevation models. From these overlays, the 16 watershed attributes were derived.

The first step in the statistical analysis was to group watersheds by hydrogeomorphic process based on field identification of deposits on the fans. One-way analysis of variance (ANOVA) was used to identify if watershed attribute means were significantly different. If differences were detected, Bonferroni multiple comparisons were conducted to determine which groups had different means (Milliken and Johnson 1992). Differences were considered to have been detected if the P-values were less than 0.05. Data from combinations of the attributes were then plotted with linear scales and, given the limited sample size for floods (16) and debris flows (13), the maximum number of differentiating attributes was set at two.

Class limits or boundaries were first determined visually from the plots. Logistic regression was then used to estimate the class boundary values for some of the plots. This was done by fitting the probability that a particular watershed belonged in one of two groups. The probability for the boundary between floods and debris floods was chosen to be 0.5/0.5 so that a watershed on that boundary would have an equal chance of belonging to either group. The probability for the boundary between debris flows and debris floods was chosen to be 0.75/0.25 to ensure a high level of capture of debris flow watersheds. Since debris flows are

Table 2 Selected watershed attributes by hydrogeomorphic process

Watershed attribute	Hydrogeomorphic process		
	Flood	Debris flood	Debris flow
Melton ratio			
Mean	0.23	0.57	0.95
Standard deviation	0.1	0.26	0.19
Range	0.08–0.49	0.26–1.21	0.66–1.21
Length			
Mean	8.90 km	4.40 km	2.06 km
Standard deviation	4.83 km	1.92 km	1.00 km
Range	2.27–18.46 km	1.68–10.73 km	0.28–4.68 km
Relief ratio			
Mean	0.12	0.30	0.49
Standard deviation	0.06	0.11	0.11
Range	0.04–0.25	0.13–0.52	0.3–0.49
B3040			
Mean	10%	24%	35%
Standard deviation	13%	14%	8%
Range	0–35%	1–60%	20–45%
Area			
Mean	34.3 km^2	7.0 km^2	1.3 km^2
Standard deviation	31.4 km^2	6.7 km^2	1.1 km^2
Range	1.4–99.3 km^2	0.7–31.4 km^2	0.2–4.1 km^2
Relief			
Mean	1.1 km	1.2 km	1.0 km
Standard deviation	0.6 km	0.3 km	0.4 km
Range	0.4–2.1 km	0.5–1.7 km	0.6–1.4 km

Table 3 Differentiating watershed attributes for floods, debris floods, and debris flows, and their associated P-values from the results of the Bonferroni multiple comparison tests

	Debris floods	Debris flows
Floods	Area<0.0001 Length<0.0001 Channels<0.0001 Melton<0.0001 Relief ratio<0.0001 B3040 0.0020 Comm forest 0.035	Area <0.0001 Length <0.0001 Channels <0.0001 Melton <0.0001 Relief ratio<0.0001 Drain den 0.0037 G30 <0.0001 G35 0.0001 G40 <0.0001 B3040 <0.0001 Esasx 0.0279
Debris floods		Length 0.0375 Melton <0.0001 Relief ratio <0.0001 Drain den 0.0036 G30 0.0005 G35<0.0001 G40<0.0001 B3040 0.0238

generally more hazardous than debris floods, logical application of the precautionary principle leads us to over-estimate the debris flow hazard during the planning phase. Selection of the best pair of attributes was based on two key criteria: least number of incorrectly classified watersheds and the least number of incorrectly classified debris flow watersheds. Details of misclassified watersheds and their fans were explored.

Results and discussion

Fieldwork and GIS analysis was undertaken on 65 fans: 16 flood fans, 36 debris flood fans and 13 debris flow fans. Since debris food watersheds have not been described in the literature, sampling was biased in favour of debris floods to ensure adequate representation to define boundaries between the other two other processes. The ANOVA determined that four attributes had statistically different means for the three hydrogeomorphic processes: watershed length, the Melton ratio, relief ratio, and the proportion of a watershed between 30 and 40° (B3040) (Table 2). Results from the Bonferroni multiple comparisons test are presented in Table 3. The class boundaries as determined through logistic regression are presented in Table 4. The Melton ratio and watershed length provided the best differentiation of the hydrogeomorphic processes, with a low of 9 misclassified watersheds (Fig. 5). The class limits fit well with previously reported values; flood watersheds have Melton ratios <0.3 (Jackson et al. 1987) and debris flows watersheds have Melton ratios >0.6 (slightly higher than the lowest value of 0.53 observed by Bovis and Jakob 1999). The addition of watershed length effectively differentiated debris flow and debris flood watersheds. The other attribute combinations were reasonably close in the number of misclassified watersheds. However, from a hazard perspective, it is important to differentiate debris-flow from debris-flood watersheds as debris flows can have a peak discharge of up to 20 times greater than debris floods. Three attribute combinations misidentified only one debris-flow watershed: Melton ratio—length, relief ratio—length, and B3040—length.

Melton ratio and watershed length were selected as the most appropriate pair of differentiating attributes because: (1) they correctly identified the largest number of watersheds; (2) were in the group with the highest number of correctly identified debris flow watersheds; (3) are relatively simple to determine: and (4) the Melton ratio was used in the past as a differentiating attribute. The class limits correctly identified 14 (88%) of the field classified flood fans. The two misidentified flood watersheds could have been the result of misclassification in the field. One was the smallest "flood" watershed (1.4 km^2). The watershed and stream channel appeared to be very stable aside from a mid-fan reach that had a recent, large accumulation of bedload. No other evidence of hydrogeomorphic activity was found in the channel or on the fan surface. On the other misidentified fan, deposits were very challenging to classify (i.e., flood versus debris flood deposits). Field classification of hydrogeomorphic processes on forested fans can be difficult because of the influence of forests: clast orientation can be influenced by turbulence around stems and downed woody debris, and characteristic signatures can be obscured or enhanced by woody debris and trees. Also, as with fans lacking forest cover, post-event fluvial reworking of sediments can alter characteristic signatures of sediment. While this reworking also occurs on fans without forest cover, the direction of water flow for the reworking can be significantly modified by the presence of trees and woody debris. To achieve better results, extensive field investigations would be required (e.g., detailed sedimentological descriptions). While such detailed investigations were beyond the scope of this study, the field identification of hydrogeomorphic processes is considered to be reasonably accurate. The class limits correctly identified 12 (92%) of the 13 field classified debris flow fans. The limits placed one as a debris flood; this could have resulted from misclassification in the field. The class limits correctly identified 30 (83%) of the 36 field

Table 4 Class boundaries for the hydrogeomorphic processes and the number of incorrectly classified watersheds

Variables	Class boundaries			Number incorrect and details
	Floods	Debris floods	Debris flows	
Melton and length	Melton <0.3	Melton 0.3 to 0.6 Melton >0.6 and length >2.7 km	Melton >0.6 and length <2.7 km	9 2 floods as D. floods 2 D. floods as floods 4 D. floods as D. flows 1 D. flow as D. flood
Melton and relief ratio	Melton <0.3	Melton 0.3 to 0.77 Melton >0.77 and relief ratio <0.42	Melton >0.77 and relief ratio >0.42	10 2 floods as D. floods 2 D. floods as floods 3 D. floods as D. flows 3 D. flows as D. floods
B3040 and length	Length >9 km or if length <9 km then B3040<4.5%	B3040 4.5% to 18% and length <9 km B3040>18% and length >2.7 km and <9 km	B3040>18% and length <2.7 km	10 1 flood as D. flood 5 D. floods as floods 3 D. floods as D. flows 1 D. flow as D. flood
Relief ratio and length	Relief ratio <0.15	Relief ratio 0.15 to 0.35 relief ratio >0.35 then length >2.7 km	Relief ratio >0.35 and length <2.7 km	11 4 floods as D. floods 2 D. floods as floods 4 D. floods as D. flows 1 D. flow as D. flood
Melton and B3040	Melton <0.3	Melton 0.3 to 0.64 Melton >0.64 then B3040<31.5%	Melton >0.64 and B3040>31.5%	13 2 floods as D. floods 3 D. floods as floods 5 D. floods as D. flows 3 D. flows as D. floods
Relief ratio and B3040	Relief ratio <0.15	Relief ratio 0.15 to 0.35 relief ratio >0.35 then B3040<34%	Relief ratio >0.35 and B3040>34%	14 4 floods as D. floods 2 D. floods as floods 4 D. floods as D. flows 4 D. flows as D. floods

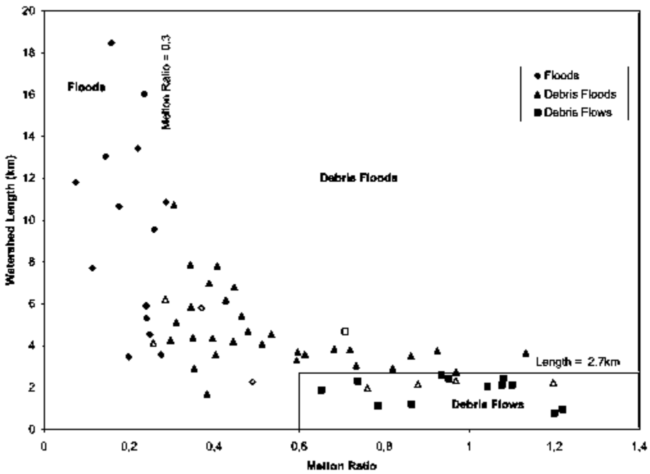

Fig. 5 Scattergram using Melton ratio and watershed length with class limits for the hydrogeomorphic processes. *Symbols without fill colour* are watersheds that do not fall within the appropriate process class limits

classified debris flood fans. Two were identified as flood fans, and could have resulted from misclassification in the field. Four were identified as debris flow fans. Three of these watersheds have snow avalanches that influence a major portion of the stream channel directly above the fans. It is possible that the snow avalanches in these watersheds are distributing sediments more uniformly along the channels, reducing the potential for debris flows and enhancing the potential for debris floods. The fourth "debris flow" watershed may have been misclassified in the field, although this is unlikely as there were no sediment signatures of debris flows.

Conclusions

Hydrogeomorphic hazards must be identified in order to develop appropriate management strategies and design protective works. Field identification of hydrogeomorphic processes is necessary, although for site or regional planning purposes, it is often convenient to forecast processes based on elementary topographic map measurements. This study explored the use of such elementary measurements for predicting hydrogeomorphic processes. The utility of the Melton ratio (watershed relief divided by the square root of watershed area) was confirmed for the identification of watersheds prone to flooding. In addition, this study has demonstrated that the Melton ratio, in combination with watershed length, can be used to differentiate between watersheds prone to debris flows and debris floods. GIS analysis of topographic data sets can readily generate these simple watershed morphometric properties. The predictive capability of these properties for the 65 study watersheds was very good: 92% of the debris flow watersheds, 88% of the flood watersheds, and 82% of the debris flood watersheds were correctly identified based on field classification of sediment deposits. With adaptation for different regional conditions, the use of basic watershed morphometrics could assist land managers, scientists, and engineers with the identification of hydrogeomorphic hazards.

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References

Alley NF, Young GK (1978) Environmental significance of geomorphic processes in the northern Skeena Mountains and southern Stikine Plateau. BC Min Environ Res Anal Br Bull 3

Anonymous (1992) Forest inventory manual. BC Min Forests

Anonymous (1999) Mapping and assessing terrain stability guidebook. Forest practices code guidebook. BC Min Forests and BC Environ

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

Bovis MJ, Jakob M (1999) The role of debris supply conditions in predicting debris flow activity. Earth Surf Process Landforms 24:1039–1054

Carlston CW (1963) Drainage density and streamflow. US Geol Surv Prof Pap 422-C

Clague JJ (1984) Quaternary geology and geomorphology, Smithers-Terrace-Prince Rupert area, British Columbia. Geol Surv Can Mem 413

Costa JE (1988) Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker VR, Kochel RC, Patton PC (eds) Flood geomorphology. Wiley, New York

Hetherington ED (1987) The importance of forests in the hydrological regime. In: Healey MC, Wallace RR (eds) Canadian aquatic resources. Can Bull Fish Aquat Sci 215

Holland SS (1964) Landforms of British Columbia: a physiographic outline. Bull no 48. BC Dept Mines Petrol Resour

Hungr O, Evans SG, Bovis MJ, Hutchinson JN (2001) A review of the classification of landslides of the flow type. Environ Eng Geosci 7(3):221–238

Jackson LE, Kostaschuk RA, MacDonald GM (1987) Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. In: Costa JE, Wieczorek GF (eds) Debris flows/avalanches: process, recognition, and mitigation. Rev Eng Geol vol. VII. Geol Soc Am

Mah S, Thomson S, Demarchi D (1996) An ecological framework for resource management in British Columbia. Environ Monitor Assess 39:119–125

Melton MA (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

Milliken GA, Dallas E, Johnson DE (1992) Analysis of messy data, vol 1: Designed experiments. Van Nostrand Reinhold, New York

Murphey JB, Wallace DE, Lane LJ (1977) Geomorphic parameters predict hydrograph characteristics in the southwest. Water Resour Bull 13:25–38

Patton PC (1988) Drainage basin morphometry and floods. In: Baker VR, Kochel RC, Patton PC (eds) Flood geomorphology. Wiley, New York

Patton PC, Baker VR (1976) Morphometry and floods in small drainage basins subject to diverse hydrogeomorphic controls. Water Resour Res 12:941–52

Pojar J, Klinka K, Meidinger DV (1987) Biogeoclimatic ecosystem classification in British Columbia. Forest Ecol Manage 22:119–154

Runka GG (1972) Soil resources of the Smithers-Hazelton area. BC Dept Agr Soil Surv Division. Kelowna. BC

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

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

Sidle RC, Pearce AJ, O'Loughlin CL (1985) Hillslope stability and land use. Water Res Monogr 11. Am Geophys Union Wash

Strahler AN (1952) Hypsometric (area-altitude) analysis of erosional topography. Geol Soc Am Bull 63:1117–42

Strahler AN (1958) Dimensional analysis applied to fluvially eroded landforms. Geol Soc Am Bull 69:279–99

VanDine DF (1985) Debris flows and debris torrents in the southern Canadian Cordillera. Can Geotech J 22:44–68

Wells SG, Harvey AM (1987) Sedimentologic and geomorphic variations in storm-generated alluvial fans, Howgill Fells, northwest England. Geol Soc Am Bull 98:182–198

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