RECOMMENDATIONS FOR ADDING LOGGING, LOGGING ROAD, WILDFIRE, AND MORPHOMETRIC PARAMETERS TO THE SOIL-SLIDE MODEL

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Report Submitted to:

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1. INTRODUCTION AND BACKGROUND

As per the instructions in the Email from Gioachino Roberti 30 May, 2019, I have undertaken to review the scientific literature relevant to the impact of logging on landslides in the mountainous regions of Oregon, Washington, British Columbia and the Alaskan panhandle to identify important and high quality studies relevant improving the probabilistic aspects of your soil slide model including:

- defining the increase of absolute probability of a landslide after clear cut, and, when possible, the temporal probability after 1, 5, 20 year, or other relevant temporal ranges.
- estimating increase of absolute probability of a landslide after wildfires, and, when possible, the temporal probability after 1, 5, 20 year, or other relevant temporal ranges.
- Recommendation in finding relevant Frequency - Magnitude and catchment geomorphic parameters relations for debris flows.
- Geomorphic parameters in identifying fans subject to debris-flows in contrast to those subject to debris flood or those subject to purely fluvial sedimentation.
- Estimation of magnitude and frequency of debris flows on debris flow fans.

I have summarized relevant and important studies of the impact of logging in Appendix 1 and I will refer to these in this report. These studies employ best practices in these investigations. In doing the work, I draw upon my professional judgement after 40 years of investigating debris flows and related hazards in California, Alberta and British Columbia and the Andes. Related issues are discussed in separate section and studies referenced are listed in the references section (6.).

The impact of logging on erosion, particularly highly mobile landslides like debris flows and debris slides have been recognized for many decades. Increasing environmental awareness, particularly during the 1960s, triggered research on forest harvesting practices first in the Pacific Northwest of the USA and subsequently in British Columbia (BC). BC became a center of excellence in these studies and proactive terrain and landslide susceptibility mapping in the late 1970s and continues to be so. Much of the contribution in BC centers on terrain and landslide susceptibility. Many studies have employed terrain mapping polygons in studies of landslides associated with logging. Most notable among them for the purposes of the Soil-Slide Model is Howes (1987, Appendix 1). In many ways, much of this work expanded upon and followed the methodology of Fredrickson (1970) in the H. J. Andrews Experimental Forest in the Oregon Cascades. There, three small drainage basins were monitored so that regression relationships were established with regard to water and sediment discharge between them. One of the basins (a) was logged using roads and patch cuts, the second (b) was clear-cut using cable yarding from a single ridge-top access road and the third (c) was left uncut as a natural reference. The general findings were:

- sediment discharge from (a) averaged over 100 times greater than that recorded in (c)
- sediment discharge from (b) increased over 3 times compare to (c)
- landslides were the main source of increased sediment discharge. These were most frequent where roads crossed stream channels in (a).

All subsequent studies cited in Appendix 1 have produced similar and comparable results. *Logging of any type in mountainous terrain causes an increase in landslide activity and roads are the greatest aggravating factor as compared to undisturbed adjacent slope*s. Adjunct to this study was that of Swanson and Dyrness (1975), also in the H. J. Andrews Experimental Forest. They looked at the sources of landslides in a logged mountainous area (Figure 1). The area studied had pre-existing slope failures prior to logging. They determined that more than 98 percent of the post logging slides took place on older natural slope failures. This underscores the impact of logging in unstable terrain. All subsequent studies have reproduced these findings (Appendix 1). The only caveat comes from Wolter et al. (2010) who suggest that, although roads are still a major aggravating factor, improved forest practices (in BC at least) may have mitigated their effects somewhat. Studies have also routinely shown that slope failures following logging tend to occur on slopes with lower gradients than similar failures in nearby unlogged slopes (see Wolter et al. 2010 in Appendix 1).

2. DEFINING THE PROBABLILITY OF LANDSLIDES AFTER CLEAR CUTTING AND TEMPORAL PROBABILITY

Gray (1969, 1973) was among the first to investigate the factors involved in slope failures following logging. Foremost among them was the progressive decrease in the anchoring effect of roots in keeping colluvial or glacial sediments in place where they overlie bedrock. He recognized that after logging, the root system begins to rot and lose strength. Ziemer and Swanston (1977) made physical measurement of this process in southeastern Alaska and found that it varies somewhat with species (Western hemlock and Sitka spruce occurred in Prince of Wales Island study area): strength loss in smaller roots occurs rapidly for all species the first 2 years; all fine roots had rotted away by 4 years. By 10 years, even the largest roots have lost appreciable strength. Swanston (1970) referred to root-anchoring as "apparent cohesion" of the soil. He postulated that the loss of it released creep generated stresses in the soil-root complex. That along with increasing snowmelt runoff, decreased transpiration (rising water table which decreases effective stress) contributed to increases in landslide frequency after logging.

Without exception, all studies of landslide activity following logging recorded the cumulative frequency of landslides with time (usually the total area or volume or both) and not the occurrence of each landslide or landslides per month or year with time from which more rigorous probabilities could be generated. Figure 1 (from Gray (1969), plots cumulative landslide activity near Hollis, Alaska) shows the way that data has been collected and presented in subsequent studies. The reason for this is that the data collection was limited by the intervals between air photo surveys. These vary from 1 to 10 years for studies. The use of repetitive high-resolution satellite imagery or SAR, and airborne LiDAR surveys post-dated studies in much of the literature or were unaffordable or unavailable. This makes assigning hard numerical probabilities to landslide occurrence following logging impractical. Also, the occurrence of landslide events is often determined by the frequency of intense storm events. In some areas such as the west coast of Vancouver Island (e.g. Jakob (2000) in Appendix 1) they may occur yearly whereas in other locations they are irregularly distributed over time. Experience-based tendencies that can be stated as unlikely, likely or very likely over the 1, 5 or 10 years based on past studies are the best that can be offered.

The unstable period following logging is bracketed by the loss of root strength and recovery of root strength as reforestation progresses (Figure 2). In the case of Figure 3, the cumulative number of landsides would plateau with time as reforestation progressed giving a skewed curve as shown in Figure 1. Table 1 lists some values from the literature for the start and end of landslide activity. For areas with reliable intense rainstorms, landslide activity would be likely the first year, extremely likely by five years and unlikely by 20 years for relative probability compared to unlogged areas.

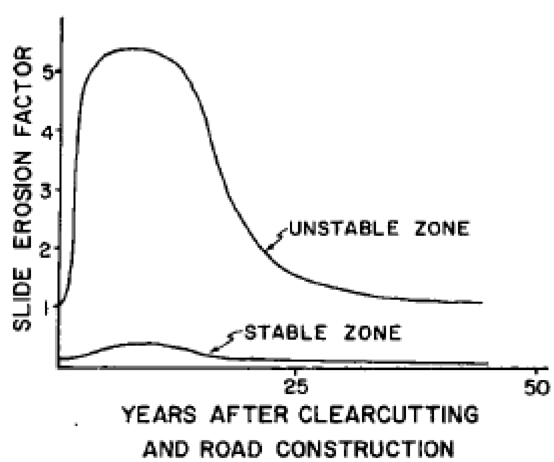

Figure 1. The occurrence of landslides over time following logging on stable and unstable terrain from Swanson and Dyrness (1975: their figure 1). The soil erosion factor is a running average of occurrence over time. Extrapolation beyond 25 years is speculative.

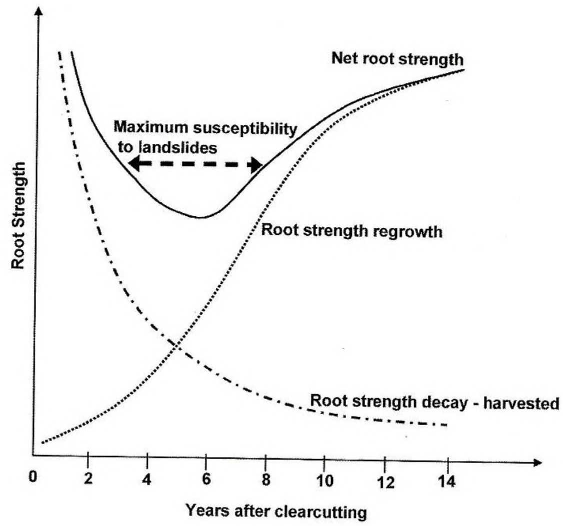

Figure 2. Relationship between net root strength and susceptibility to landslides of slopes following logging (Sidle, 2005, his figure 16.2)

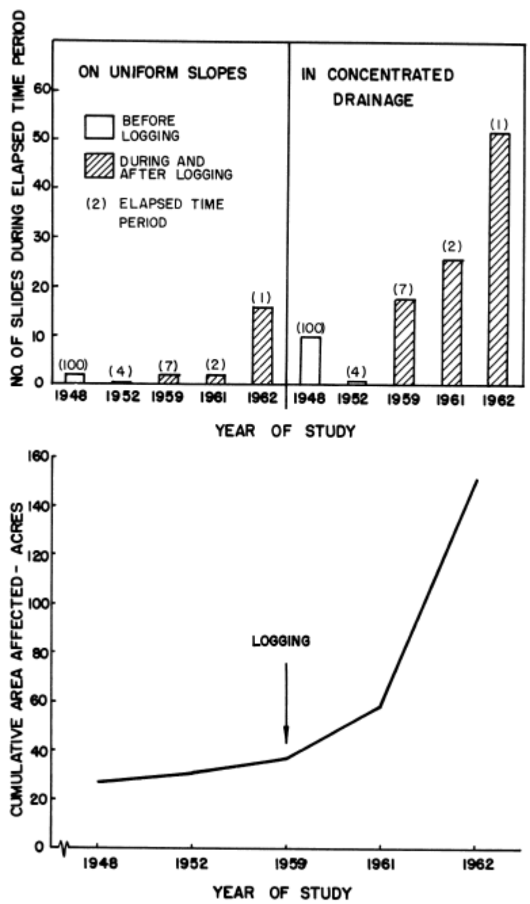

Figure 3. An example of cumulative landslide frequency data from Gray (1969). Note the variability of time between observations due to the availability of air photo surveys.

Table 1 Experienced-based prediction of initiation and cessation of landslides post logging		
Study	**Expected initiation of landslides**	**Expected cessation of Landslides**
Gray 1969	Immediate and accelerating after two years	No data
Swanson 1973	Dependent on occurrence of storms: 4 to five years	12 years
Swanson and Dyrness 1975	Storm dependent	12 years; impact of roads probably occurs during the first few severe storms after disturbance unless reconstructed.
Ziemer and Swanson 1977	Substantial loss of root strength 2 years after logging; roots rotted completely by 4 years	No data
Rollerson et al. 1997	6 years	No data
Jakob 2000	Immediate	20 years
Bradinoni et al. 2002 (annotated in Appendix 1)	Not specifically addressed	20 years: continuing logging activity can extend this.
Guthrie 2002 (annotated in Appendix 1)	Not specifically addressed	10 years a reasonable time to expect an increase of landslide frequency over natural rates
Sidle 2005 (based on global data)	Within about 2 years	Decrease in susceptibility after 8 years; peak susceptibility ~3-8years

3. TEMPORAL PROBABILITY OF DEBRIS FLOWS FOLLOWING WILDFIRES

There is an extensive literature on the effects of wildfires on soil in mountain terrain in western North America primarily in semi-arid and Mediterranean climatic areas such as central and southern coastal California. The cycle of summer wildfires followed by debris flows triggered by winter rains is well known (e.g. Cleveland 1972). Their proximity to and impact on urban areas has caused them to be extensively studied. Two classes of post fire debris avalanches and debris flows have been recognized: runoff-triggered and infiltration-triggered (Cannon and Gartner, 2005).

3.1 Post wildfire runoff-triggered debris flows

Severe wildfires combust forest floor organic detritus and vegetation that stabilize the soil: heating combusts soil organic matter that binds soil aggregates and dries the soil decreasing soil cohesion and fire consumes logs and other organic barriers that store sediment that would normally impede erosion and transport during rain storms (Wonzell and King, 2003). Precipitation of tarry substances at shallow depth from gases created by partial combustion of soil organics creates non-wettable or water-repellent soil horizons (see the benchmark summary of De Bano,1981). These cause rapid saturation and fluvial erosion or debris slides and flows on a micro-scale in the overlying scorched sediments. I observed this first-hand in 1972 while investigating the origin of debris flows that devasted Big Sur Village that year (Jackson, 1977). The steep mountainsides burned over in the summer of 1972 by the Molera Fire were covered by countless rills 10 to 20 cm wide bounded by 2 or 3 cm high levees created by the spontaneous initiation of shallow unchanneled debris flows that coalesced and bulked as they merged in steep first order stream channels. Furthermore, wildfire can cause dry ravel (or dry sliding) on steep slopes that fill small water courses adding sediment that can be mobilized into debris flows. Wells (1987) documents this rill-phenomena and dry ravel. Cannon and Gartner reported (in their 2005 review paper) that this source of post-wildfire debris flows accounted for about 75% of those that occurred in 212 studied basins in the American west.

3.2 Post- wildfire infiltration-triggered debris flows and debris slides

These failures occur in years following wildfires and after runoff-triggered debris flows. The death of the tree cover triggers decay of roots and their stabilizing effect on the colluvium or till covering of mountain slopes. The death of the forest permits greater infiltration of precipitation while the loss of forest transpiration causes a net rise in pore water pressure in slope sediments and a reduction in slope stability. This effect is analogous to clearcutting of slopes without using roads (see Roberts et al., 2004 and Wolter et al 2010 in Appendix 1). Cannon and Gartner (2005) attributed 15% of failures in the 212 studied basins in the American west. Only about 8% of the basins experienced both post fire runoff- and infiltration-triggered events.

3.3 Post-wildfire triggered debris flows and debris slides in the USA Pacific Northwest and BC

Wonzell and King (2003) reported that the phenomenon of wildfire-primed debris flow is sparsely studied in the Pacific Northwest. Phenomena like wildfire-induced non-wettable soils and ravel have been documented in the Cascades and the Oregon Coastal Mountains but wildfire-primed runoff-induced debris flows have yet to be documented in coastal areas of the Pacific Northwest, BC and Alaska as far as I could determine from my literature review. Documented cases are restricted to semi-arid interior forests in eastern Washington, Idaho and Montana. Lack of documentation is not evidence of absence. With climatic warming and the likelihood of hotter and drier summers in the Coast Mountains, Vancouver Island and western Cascades, such events should be considered likely. Assuming an intense fire that essentially kills off the extant forest, it is prudent to assume that post-fire debris flows or debris slides will occur on steeper slope (generally those above 20° are considered in most studies (Appendix 1). In the absence of relevant studies in coastal environments, studies from interior forests provide reasonable guidelines. Meyer and Wells (1997) and Meyer et al. (2001) postulated that runoff-initiated debris flows should occur within 1-2 years after a fire when the shallow soil is least cohesive. Past that, regeneration of ground-covering plants will stabilize the surface and water-repellant horizons will degrade. Because the forest is essentially dead, a situation analogous to clear-cut logging without roads exists. A second period of debris slides and debris flow would be expected as infiltration increases, tree roots decay and their 'effective cohesion' anchoring effect is eliminated. This second period of instability would be expected 5 to ten years after the fire.

3.4 Recommendations for assigning semiquantitative probability for debris flows and related phenomena post wildfires

Based upon the studies discussed above, the probability of increased erosion and sediment transport and debris flows or floods following a severe forest fire would be 'very likely' for 2 years and 'likely' 5 to 10 years after the fire with likelihood diminishing beyond 10 years.

4. METHODOLOGIES FOR RAPID SCREENING FOR AND DISCRIMINATION BETWEEN DEBRIS-FLOW, DEBRIS FLOODS AND FANS AFFECTED BY PURELY FLUVIAL PROCESSES

For the purposes of this discussion, the following definition of terms will be used:

A *debris flow* is a fluid that contains mineral sediment ranging from clay to boulders, air and water and variable amounts of organic detritus as a single phase. Deposits are bouldery and largely matrix-supported. Debris flows in this discussion assume transport within a channel that normally is a stream channel. *Debris avalanches* or *debris slides* are spontaneous and rapid failure of partly saturated or saturated superficial slope sediments including organic detritus on steep slopes. They may have the mechanical properties similar to debris flows but are unconfined by channels. They can be sources of debris flows if they enter stream channels See Hungr (2005), Hungr et al. (2005) and Iverson (2005) for detailed discussions of debris flow initiation, rheology and classification.

A *debris flood* is a sediment-charged muddy water flood. Its rapid flow and turbulence allow it to transport large volumes sediment. These floods contain an unusual amount of suspended load along with coarse bed load. Debris flood flows may fall within parameters of what has been called *hyperconcentrated flow:* transitional between a water flood and debris flow (see Pierson 2005). Thick (often a metre or more) deposits of mud and cobble-gravel cover fans following these events. Transport occurs on much lower gradients than are typical of debris flows but damage to buildings and infrastructure due to erosion and burial can be severe. The flood flows that devasted the Cougar Creek fan in Canmore, Alberta on 20 June, 2013 are typical of what are commonly referred to as debris floods (Holm et al. 2016).

During *fluvial transport*, sediments are transported by flowing water so that suspended load (very fine sand to clay) and bed load (sand and coarser clasts) largely distinct during transport. Fan sediments are clast-supported and commonly stratified.

The initiation of debris flow requires significant kinetic energy to transform solid sediments into a surging, viscous fluid. Hydrometeorological conditions such as intense rainfall, rapid snowmelt, and rain-on-snow events along with remolding of sediments in landslides in the environment of steep slopes and narrow, steep channels (often gulleys at the upper limits of channel systems) are factors in the initiation of debris flow (Millard 1999). They may form in other ways such as a glacier outburst flood or the breaching of a moraine or landslide-dammed lake but for this discussion, only their formation from erosion and remolding of landslide and colluvial or glacial sediments, and turbulent mixing and direct entrainment of stream sediments are considered. Both the dilatant fluid (Takahashi, 1981) and the plastico-fluid (Rodine and Johnson, 1976) models that explain the mobility debris flows recognize a minimum channel slope hence shear stress when other factors such as water and clay contents are optimum. Consequently, debris-flow-producing basins are small, steep, with first or second order streams. In the Alberta Rocky Mountains Jackson (1987) found them to be generally in the range of 2-10 km^2 with reliefs of 1000-1500 m. They have narrow bedrock-confined channels that minimize friction along the wetted perimeters of the flows. When channels widen near the heads of fans or at confluences with other streams (Benda and Cundy 1999), flows widen and thin: resisting forces within the flow and marginal friction increase to the point that flow ceases (e.g. Rodine and Johnson 1974). Water, by contrast flows, erodes and transports sediment at lower gradients. Consequently, fans with some or a considerable debris flow content are steeper than fluvial fans, especially the fan-head. Debris-flow fans commonly have a fan-head trench eroded by subsequent water flows (Jackson 1987).

4.1 Identification of debris flow fans from morphometric parameters

Jackson et al. (1987) exploited this relationship between steep fan-heads and ruggedness of their drainage basins to discriminate between debris flow fans and fluvial fans by plotting the tangent of fan head slope against the Melton ruggedness number (R) for drainage basins (Melton, 1965). R is a dimensionless number that is the ratio of basin relief and the square root of the basin area (which is broadly proportional to average channel gradient) so that:

$$R=H_bA_b^{-0.5}$$

where $\mathbf{H_b}$ is the relief from the fan head to the highest point in a drainage basin and $\mathbf{A_b}$ is the area of drainage basin. Field work by Jackson et al. (1987) identified the presence or absence of debris flow deposits in fan-heads. The relationship between fan-head slope and R proved to be statistically valid for discriminating between purely fluvial and debris flow fans in the Rocky Mountains and as a quick filter: basins with R >0.3 proved to have a debris flow hazard. This technique was applied to the Coast Mountains (Figure 4) by Bovis and Jakob (1999).

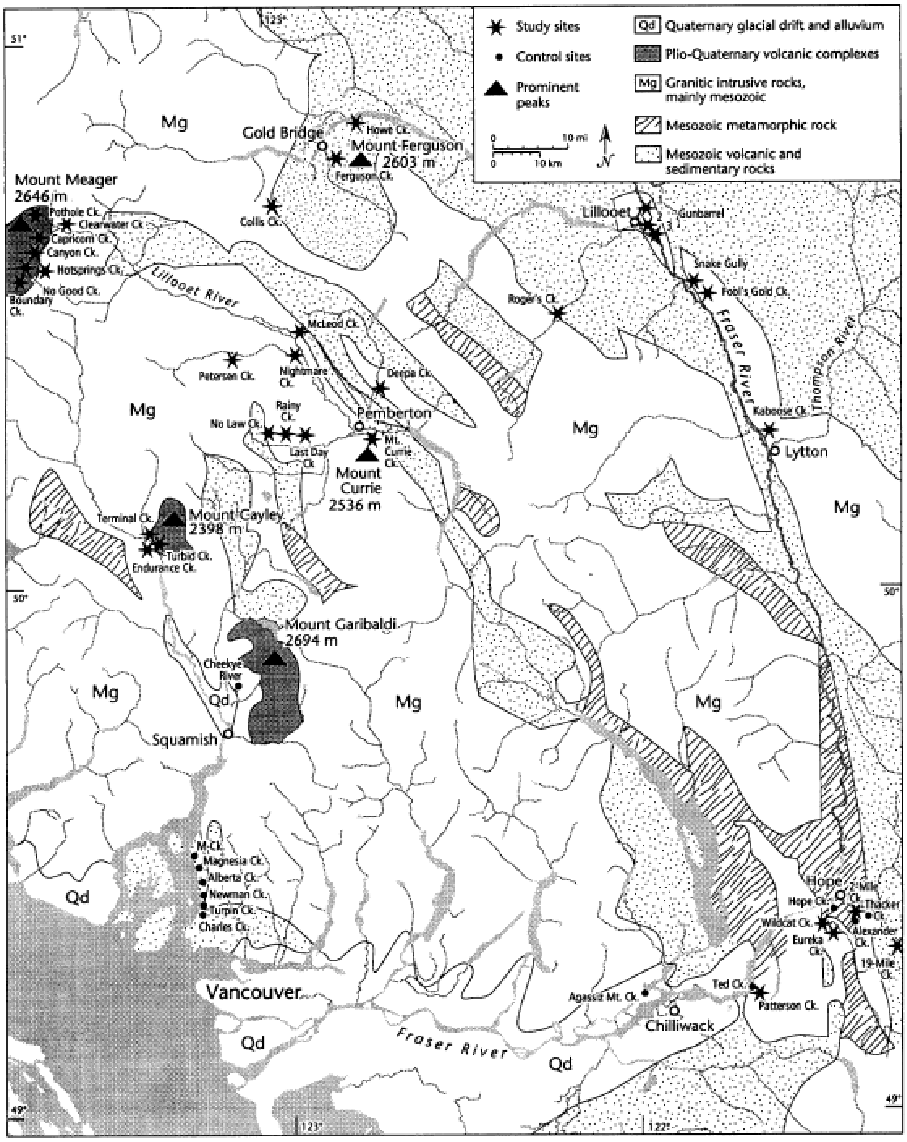

Figure 4. Locations of fans and basins studied by Bovis and Jakob (1999; their figure 1).

They determined that debris flow watersheds in their study area had Melton ratios >0.53[1]. They sampled a diverse representation of underlying geology from crystalline plutonic rocks to highly erodible and unstable Pleistocene volcanic centers.

[1]The reason for differences between their findings and the R >0.3 determined for the Rocky Mountains is not clear. I suspect that it reflects differences in geology and climate. However, I contributed only part of the data to our 1987 study. I can vouch for the presence of debris flows in the fans that I studied. Milford et al. (2004) suggested that some of the fans included that were debris flood fans (see below) and not debris flow fans. This is a valid criticism. A field-based reinvestigation would be required to resolve this.

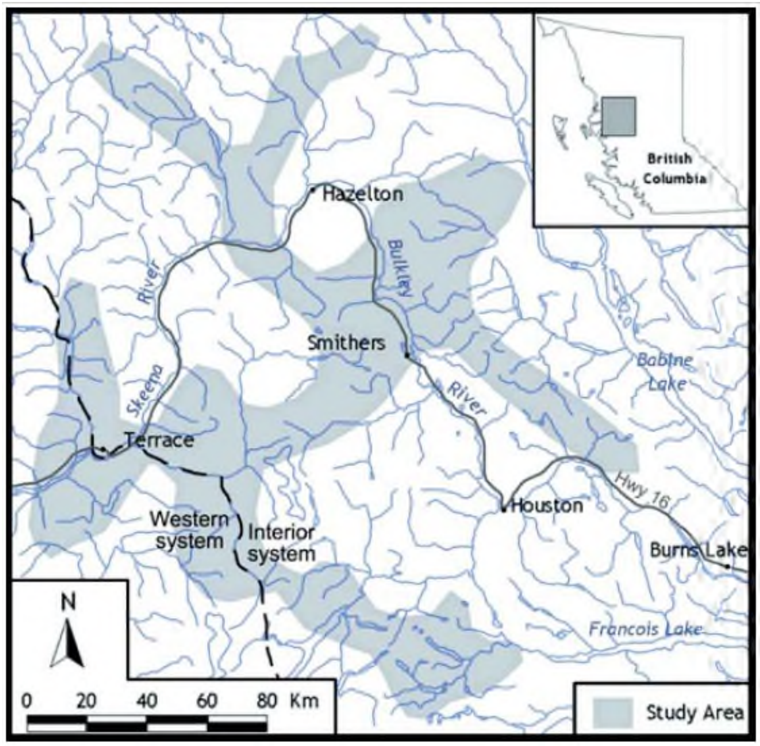

Figure 5. Locations of fans and basins studied by Milford et al. (2004; their figure 1)

4.2 Discrimination between debris-flow fans and debris flood fans from morphometric parameters

In drainage basins that are larger than ones that produce debris flows that reach fans, channel gradients in lower parts of these basins decrease so that debris flows may deposit large volumes of sediment upstream of fans. Simultaneous or subsequent high fluvial discharges may then erode and transport the sediment to fans as a debris floods. The disastrous flood on the Cougar Creek fan in Canmore, Alberta in 2013 is an important example (Holm et al. 2016).

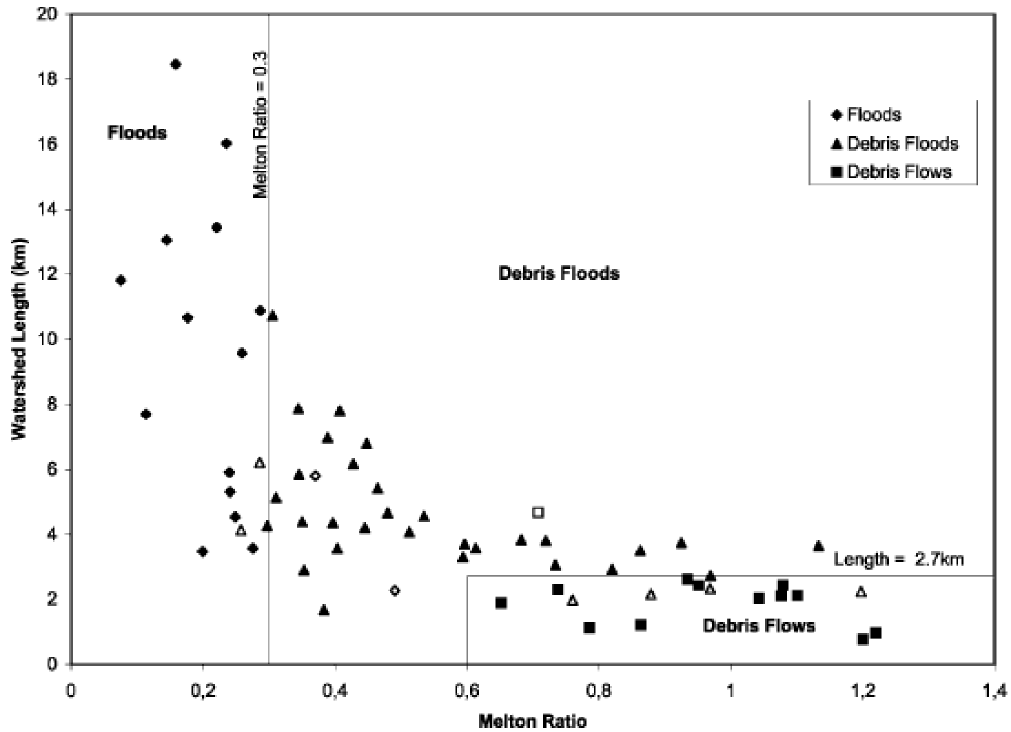

Figure 6. Scattergram using Melton ratio (R) and watershed length with class limits for the hydrogeomorphic processes. Symbols without fill colour are watersheds that do not fall within the appropriate process class limits (Milford et al. 2004, figure 5)

The problem of discriminating debris-flood-prone fans through morphometric parameters was successfully addressed by Wilford et al. (2004). They modified the approach by plotting basin length (the planimetric straight-line length from the fan apex to the most distant point on the watershed boundary) against R. This was arrived at after statistical testing of co-variation of many parametric variables. The study was done in west-central BC (Figure 5).

They found that R values >0.6 characterized debris-flow basins and fans, whereas R= 0.3-0.6 identified debris-flood fans. R values <0.3 defined basins with purely alluvial fans. The accuracy was 88% for identifying debris-flood fans through these morphometric parameters (the nature of the fans had been documented by field work) (Figure 6). The use of planimetric length of the watershed stands to reason as it is a more accurate indicator the concavity of the basin profile: the lower channel of elongated basins would tend to have gradients below the minimum gradients for debris flow mobility than more equant basins.

BGC Engineering used these R ranges to map and assign hazard ratings to 247 alluvial fans crossed by highways in the Rocky Mountains of Alberta following the disaster at Cougar Creek in Canmore (Holm et al. 2016).

4.3 Recommendations for assigning debris-flow and debris-flood hazard to fans in the soil-slide model

I recommend that an algorithm be added to the model that measures Hb and Ab for first, second and third order basins so that R can be computed for them. The semiquantitative probabilities summarized in Table 2 should be assigned after Wilford et al. (2004).

Table 2. Debris flow, debris flood and water flood hazard for fans

Melton number (R)	**Hazard**	**Semiquantitative probability**
< 0.3	Water flood	Likely from storm events
0.3-0.6	Debris flood Debris flow	Likely: dependent on sediment supply and frequency of threshold events for triggering erosive flows or debris flows in the basin. Possible for basins with R values close to 0.6: dependent on sediment supply and frequency of threshold events
>0.6	Debris flow	Likely: dependent on sediment supply and frequency of threshold events; very likely if logged in the last 10 years or the basin is situated in Pleistocene volcanic terrain.

More will be said about this in the next section regarding magnitude and frequency. The caveat for this is that these only indicate tendencies over indefinite periods of time. Assignment of a hazard indicates that further detailed field studies are required to evaluate the hazard at any specific site.

5. COMMENTS ON ASSIGNING MAGNITUDE AND FREQUENCY FOR DEBRIS FLOW AND DEBRIS FLOODS

Unlike basins considered under sections 2. and 3. where logging or wildfire have perturbed slope stability and runoff characteristics, assigning probabilities, even semiquantitative ones for debris flow frequency for basins in a natural state is a different matter. It is site specific and in my considered opinion, not amenable to the soil slide model. A perusal of climate summaries and comments in the summary of studies assembled in Appendix 1 reveals the range of potential triggering hydrometeorological events in the Pacific Northwest: they range from infrequent events over years to multiple events in most years. The most cited reference on this subject is Jacob (2005). Much of the foundation for this reference was detailed in Bovis and Jakob (1999) which addressed the Coast Mountains of southwestern BC (Figure 4). The likelihood of a debris flow (or indeed a debris flood) turns on the availability of sediment for transport: they differentiated weathering-limited or supply-limited versus basins that are supply-unlimited. Debris flows are highly likely to occur virtually every time hydrometeorological events exceed the threshold necessary to initiated events (hence *transport limited*) (Figure 7) (for the former, a survey of a basin needs to be undertaken to determine the state of sediment accumulation. Only where sediment supply-unlimited conditions

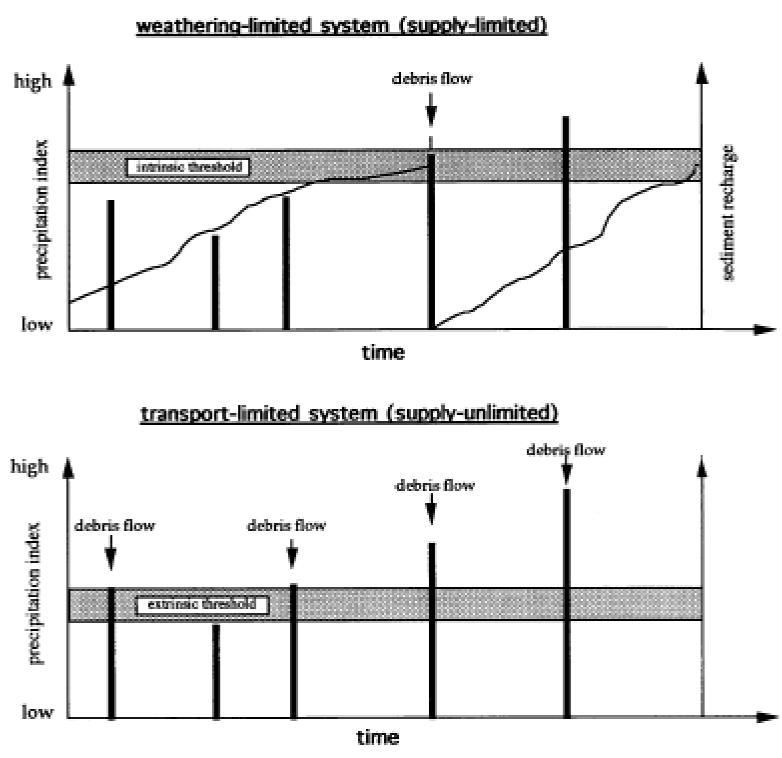

Figure 7. Weathering-limited and transport-limited concepts applied to the occurrence of debris flow events. Bars indicate precipitation, curved rising lines indicate cumulative sediment recharge (Bovis and Jakob, 1999; their figure 4)

prevail, and yearly weather events exceed thresholds transport thresholds can a statement be made that debris flow occurrence is likely on a yearly basis. Basins in Pleistocene volcanic complexes fall within this category. Magnitude is a similar perhaps an even more. In all cases, threshold events are complicated by factors such as antecedent conditions as detailed by Schwab (1999) in a review of events in the Queen Charlotte Islands (Haida Gwii). A history of past debris flow activity is required along with measurement of debris flow volumes over time to estimate typical yield volumes and debris flow runout characteristics for a given basin or nearby basins with similar characteristics (e.g. Brenda and Cuny 1990; González et al. 2008). Magnitude and frequency are within the purview of a separate studies where past threshold events and yield rates have been established.

6. REFERENCES CITED EXCLUDING APPENDIX 1

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

Bovis, B.J. and Jakob, M. 1999. The role of debris supply in predicting debris flow activity. Earth Surface Processes and Landforms v. 24, p.1039-1054.

Cannon, S.H. and Gartner, J.E. 2005. Wildfire-related debris flow from a hazards perspective. In M. Jakob and O. Hungr (eds.) Debris flow hazards and related phenomena. Springer/Praxis Publishing, Chichester, U.K., p. 363-385.

Cleveland, G.B. 1973 Fire+rain=debris flow, Big Sur 1972. California Geology, v. 26, number 6, p. 127-135.

DeBano, L.F. 1981. Water Repellent Soils: a state-of-the art. United States Department of Agriculture, Forest and Range Experiment Station General Technical Report PSW-46, 20p.

González, M.A., Baumann, V., and Jackson, L.E. Jr. 2008. Evaluation of debris flow hazard to Chalala Village, Quebrada de Humahuaca UNESCO World Heritage Site, Jujuy Province, Argentina. In D. de Wrachien, C.A. Bebbia and M.A. Lenzi (eds.) Monitoring, simulation and remediation of dense debris flows II. WIT Press, Southhampton, p. 113-124

Gray, D.H. 1969. The effects of forest clear-cutting on the stability of natural slopes. The University of Michigan, Department of Engineering, College of Civil Engineering, ORA Project 01939, 67 p.

Gray, D.H. 1973. The effects of forest clear-cutting on the stability of natural slopes: the results of field studies. The University of Michigan, Department of Engineering, College of Civil Engineering, DRDA Project 002790, 119 p.

Holm, K., Jakob, M., Scordo, E., Strouth, A., Wang, R. and Adhikari, R. 2016 Identification, Prioritization, and Risk Reduction: Steep Creek Fans Crossed by Highways in Alberta. Proceedings, GEO Vancouver, 2016.

Hungr, O. 2005. Classification and terminology. In M. Jakob and O. Hungr (eds.) Debris flow hazards and related phenomena. Springer/Praxis Publishing, Chichester, U.K., p. 9-23.

Hungr, O., McDougall, S. and Bovis, M. 2005. Entrainment of material by debris flow. In M. Jakob and O. Hungr (eds.) Debris flow hazards and related phenomena. Springer/Praxis Publishing, Chichester, U.K., p. 135-158.

Iverson, R.M. 2005. Debris flow mechanics. In M. Jakob and O. Hungr (eds.) Debris flow hazards and related phenomena. Springer/Praxis Publishing, Chichester, U.K., p. 105-134.

Jakob, M. 2005. Debris flow hazard analysis. In M. Jakob and O. Hungr (eds.) Debris flow hazards and related phenomena. Springer/Praxis Publishing, Chichester, U.K., p. 411-443.

Jackson, L.E. Jr. 1977. Dating and recurrence frequency of prehistoric mudflows near Big Sur, Monterey County, California. United States Geological Survey Journal of Research, v. 5, p. 17-32.

Jackson, L.E. Jr. 1987.Debris flow hazard in the Canadian Rocky Mountains. Geological Survey of Canada Paper 86-11, 20 p.

Jackson, L.E. Jr., Kostaschuk, R.A. and MacDonald, G.M. 1987. Identification of debris flow hazard in the Canadian Rocky Mountains. In J.E. Costa and G.F. Wieczorak (eds.) Debris flows/avalanches: process, recognition and mitigation. Geological Society of America Reviews in Engineering Geology, v. VII, p. 115-124.

Melton, M.A. 1965, The geomorphic and paleoclimatic significance of alluvial deposits in southern Arizona. Journal of Geology, v. 73, p. 1-38.

Meyer, G.A., Wells, S.G., 1997. Fire-related sedimentation events on alluvial fans, Yellowstone National Park, USA. Journal of Sedimentary Research. v 67, p. 776–791.

Meyer, G.A., Pierce, J.L., Wood, S.H., Jull, A.J.T., 2001. Fire, storms, and erosional events in the Idaho batholith. Hydrological Processes. v 15, p. 3025–3038.

Millard, T. 1999. Debris flow inititiation in coastal British Columbia gulleys. British Columbia Forest Service, Vancouver Research Region Technical report TR-002, 22p.

Pierson, T.C. 2005. Hyperconcentrated flow—transitional process between water flow and debris flow. In M. Jakob and O. Hungr (eds.) Debris flow hazards and related phenomena. Springer/Praxis Publishing, Chichester, U.K., p. 159-196.

Rodine, J.S. and Johnson, A.M. 1976. The ability of debris, heavily freighted with coarse, clastic material, to flow on gentle slope. Sedimentology, v. 23, p. 213-234.

Sidle, R.C. 2005. Influence of forest harvesting activities on debris avalanches and debris flows. In M. Jakob and O. Hungr (eds.) Debris flow hazards and related phenomena. Springer/Praxis Publishing, Chichester, U.K., p. 387-409.

Swanston, D. N., 1970, Mechanics of debris avalanching in shallow till soils of southeast Alaska: United States Department of Agriculture, Forest Service Research Paper PNW-103, 17 p.

Schwab, J.W. 1998. Landslides on the Queen Charlotte Islands: processes, rates and climatic events. In D.L. Hogan, P.J. Tschaplinski, and S. Chatwin (eds.). Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: applying 20 years of Coast research to management solutions. British Columbia Ministry of Forests, Land Management Handbook 41, p. 41–46.

Takahashi, T. 1981. Debris flow. Annual Review of Fluid Mechanics, v. 13, p. 57-77.

Wells, W.G. II 1987. The effects of fire on the generation of debris flows in California. In J.E. Costa and G.F. Wieczorak (eds.) Debris flows/avalanches: process, recognition and mitigation. Geological Society of America Reviews in Engineering Geology, v. VII, p. 105-114.

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

Wondzell, S.M. and King, J,G. 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. Forest Ecology and Management 178, p. 75–87.

R. R. Ziemer and D. N. Swanston 1977, Root strength changes after logging in southeast Alaska. United States Department of Agriculture, United States Forest Service, Pacific Northwest Forest and Range Experiment Station, Research note PNW-306, 9 p.

7. LIMITATIONS OF THIS REPORT

This report is a contribution to the understanding of logging, wildfires and drainage basin morphometry on the occurrence of landslides, debris flows and debris floods. It addresses specific questions from the Client (Minerva Intelligence Inc.). It is not intended to evaluate risks or to predict future hazards to people or property in any specific area.

The report has been produced in a manner consistent with the level of professional skill and care normally exercised by professional and academic scientists. This report was prepared for the specific purposes described to Lionel E. Jackson, Jr., PhD., P.Geo. by the Client. Lionel E. Jackson, Jr., PhD, P.Geo. cannot be held responsible for unauthorized use of this report by third parties.