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An examination of controls on debris flow mobility: Evidence from coastal British Columbia

R.H. Guthrie [a,b,*], A. Hockin [c], L. Colquhoun [c], T. Nagy [c], S.G. Evans [b], C. Ayles [c]

[a] British Columbia Ministry of Environment, 2080A Labieux Road Nanaimo, BC, Canada V9T 6J9
[b] University of Waterloo, Waterloo, ON, Canada
[c] Camosun College, Victoria, BC, Canada

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ABSTRACT

We characterize and consider controls to runout distance of debris slides and debris flows using 1700 field observations supplemented by air photograph interpretation from coastal British Columbia. We examine the role of slope on deposition and scour and determine that they occur on steeper and flatter slopes (respectively) than previously reported. Mean net deposition occurred on slopes between 18° and 24° for open slope failures and between 12° and 15° for channelized debris flows. We demonstrate a practical method for estimating both entrainment and runout in the field and in a GIS and provide an example entrainment map for Vancouver Island, British Columbia. We consider other controls to post failure landslide mobility, including the role of gullies and stream channels, roads and benches, and intact forests. Shallow landslides that hit streams and gullies at acute angles had a high probability of transforming into a channelized debris flow, whereas landslides that hit streams and gullies at obtuse angles did not. Forests played a substantial role in landslide runout: debris flows travelling through a logged slope deposited much of their load when hitting a forest boundary and stopped entirely within 50 m of that boundary in 72% of the cases examined. Roads also tended to stop or reduce the size of open slope debris flows in 52% of the cases. The results are expected to be useful to land management applications in regions with frequent shallow landsliding.

1. Introduction

The Canadian Cordillera is contained almost entirely by the province of British Columbia (BC) and is comprised of ~800 000 km^2 of rugged mountains and, to a lesser extent, interior plateaus. Forestry has been the primary resource-based industry in BC over the last century, exploiting ~400 000 km^2 of merchantable timber. Unfortunately, forest operations are not without impact; and the occurrence of landslides, naturally common on BC's steep terrain, increased by about an order of magnitude in the last several decades (Schwab, 1983; Jakob, 2000; Guthrie, 2002; Guthrie and Brown, 2008). Guthrie and Brown (2008) reported that human-induced landslides have approximately doubled landscape erosion over the next highest millennia (the Holocene). Environmental values (clean running water, scenic vistas, clean air, and abundant fish and wildlife) are part of the collective conscience in BC in spite of the physical cost of resource extraction, and as such the pressure to minimize the impact of landslides is considerable. Local geotechnical consultants and industry professionals are faced with the daunting task of building roads, harvesting forests, and otherwise managing vast landscapes in some of the most rugged conditions in the world while minimizing impacts at a very low cost per unit area. Nowhere is this truer than for coastal BC where high rainfall on remote rugged terrain produces massive forests and frequent landslides.

1.1. Definitions

Landslides in coastal BC are predominantly debris slides, debris avalanches, or debris flows according to Varnes (1978), Swanston and Howes (1994) and Cruden and Varnes (1996). They are rapid, shallow landslides from steep slopes, involving surficial rock, soil, and debris. Most coastal BC landslides begin as debris slides but typically evolve to debris flows or debris avalanches (debris flows are saturated, debris avalanches are not) as they break up with increased velocity downslope. We have elected to use the term *debris flow* to describe the suite of shallow, rapid, unconsolidated mass movements on a steep hillslope (Fig. 1). The term is meant to be inclusive of landslides that might otherwise be classified as debris slides or debris avalanches.

Debris flows tend to choose paths based on topographic expression (including swales, gullies, and channels), except at the scale where that expression is overwhelmed by the volume of the debris flow. Where possible, we have distinguished between open slope debris

* Corresponding author. British Columbia Ministry of Environment, 2080A Labieux Road Nanaimo, BC, Canada V9T 6J9. Tel.: +1 250 751 3138.
E-mail address: richard.guthrie@gov.bc.ca (R.H. Guthrie).

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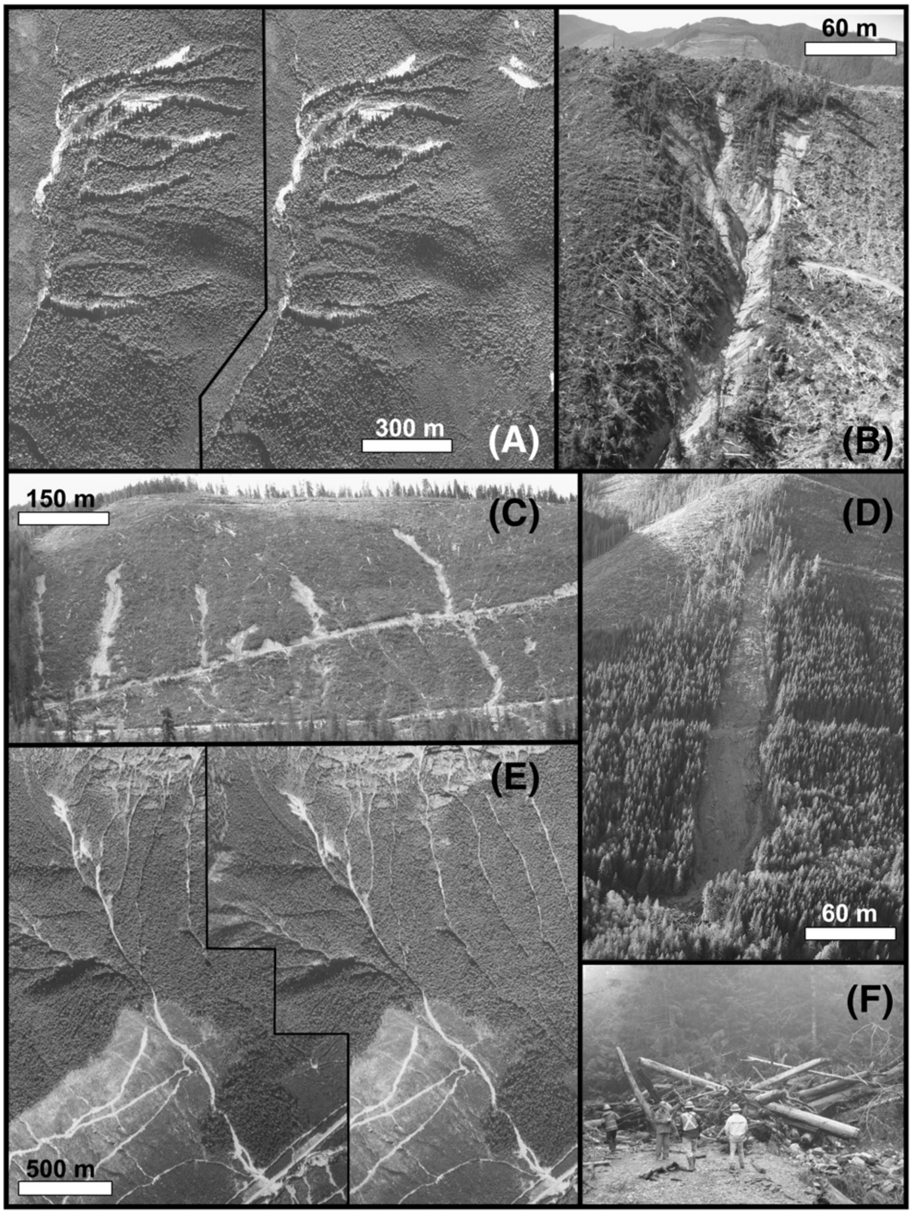

Fig. 1. Examples of debris flows from coastal BC: (A) Stereopair of several debris flows in a forested watershed. (B) Three debris flows that coalesce to a single path, entraining considerable material along the way. (C) Debris flows in a logging block. (D) A debris flow initiated in second growth. (E) Stereopair of a channelized debris flow. (F) The impact of a debris flow at a road crossing.

flows and channelized debris flows (Fig. 1); however, the reader is advised that despite distinct end members the transition between the two is gradational and not always distinguished clearly.

Linear relationships have been observed between measures of debris flow length, volume, source area, and total area (e.g. Innes, 1983; Guthrie and Evans, 2004a,b; Guthrie et al., 2008; Hungr et al., 2008). Total area has become the common measure for shallow debris slides and debris flows as it is consistently and reliably obtained from remote inventories (Hovius et al., 1997; Guzzetti et al., 2002a, b; Guthrie and Evans 2004a, b; Malamud et al., 2004; among others), however, other measures of magnitude are still used (e.g. Hungr et al., 2008). In each case, magnitude is a measure of the relative size or extent of an individual or group of individual debris flows within a population. Consequently, general comparisons may be made between different measures of magnitude; however, specific comparisons require similar units of measure.

Total area in square meters of a debris flow, includes all visible signs of source, entrainment, and deposition.

Volume of shallow debris slides and debris flows is largely controlled by entrainment (Benda and Cundy, 1990; Dunne, 1998; Hungr et al., 2008) rather than by initial failure (e.g., Corominas, 1996), and therefore volume refers to the total transported volume in cubic meters, including both the initial failure and the subsequent entrainment.

A hazard is generally defined as a condition that threatens humans and what they value (Cruden and Fell, 1997; Lee and Jones, 2004), and hazard mapping delineates those hazards. Recently, susceptibility has been used to define the spatial probability of this condition (e.g. steep slopes are more susceptible to landslides than flat slopes), and the term hazard has included a temporal component (e.g. likelihood of a landslide in a given area over a given time). Susceptibility mapping and hazard mapping are not differentiated in this study, and hazard mapping is generically used. Since we are not reporting on frequencies, this has no impact on the results.

Runout is the total length of the debris flow path, and reaches are defined for debris flows as they are for streams in hydrologic nomenclature: a length along the debris flow path, uniform with respect to discharge, depth, area, and slope.

Erosion is the removal of rock, sediment, and debris from a slope by a landslide — material that is then transported downslope. Entrainment is normally considered to be the amount of material eroded by the landslide by following the initial failure. Deposition is defined as the placement of rock, sediment, and debris along the path from an upslope source. Transition is the portion of the landslide path that contains both entrainment and deposition, but where the net balance of material lost or gained approaches zero. In BC and elsewhere, debris flows grade between zones of erosion, entrainment, transition, and deposition.

1.2. Objectives

We employ, herein, both field data and GIS analysis to consider the roles of slope, channel confinement, forest cover, and roads to landslide runout. Specifically;

(i) we examine the role of slope on erosion and deposition of material along the debris flow path, calculate net sediment balance, and determine how changes in the topographic profile affect entrainment of rock, sediment, and debris for confined and unconfined debris flows;
(ii) we examine, based on the same data, the likelihood that a debris flow entering a channel will continue as a channelized debris flow;
(iii) we examine the ability of roads and forests to increase, decrease, or stop debris flows;
(iv) we develop a simple rule-based methodology for estimating debris flow runout that can be used by practitioners in the field or in a GIS environment; and
(v) finally, we consider the broader implications of slope, confinement, roads and forests for runout prediction and derive, wherever possible, practical relationships between debris flows and their limiting factors in coastal British Columbia.

We intend for the results to contribute to direct assessments of debris flow hazard mapping and susceptibility mapping techniques across similar settings and suggest that they also enable calibration of modelled results.

2. Regional setting

Data were acquired from two locations in coastal British Columbia: Vancouver Island (VI) and the Queen Charlotte Islands (QCI) (Fig. 2).

Vancouver Island (Fig. 2) is comprised of 31 788 km^2 of predominantly steep rugged topography ranging from sea level to 2200 m. The central and largest part of the island consists of steep volcanic mountains intruded by granitic batholiths. Deep fjords and long inlets dissect a western coastline severely modified by Pleistocene glaciations that steepened and deepened the terrain and veneered the mid and upper slopes of valleys with shallow surficial sediments (Guthrie, 2005).

Precipitation falls primarily as rain during the winter months with most locations on the west coast receiving more than 3000 mm y^{-1} at sea level (Environment Canada, 1993). Landslides on VI are commonly attributed to large storms (e.g., Guthrie and Evans 2004a, b) though

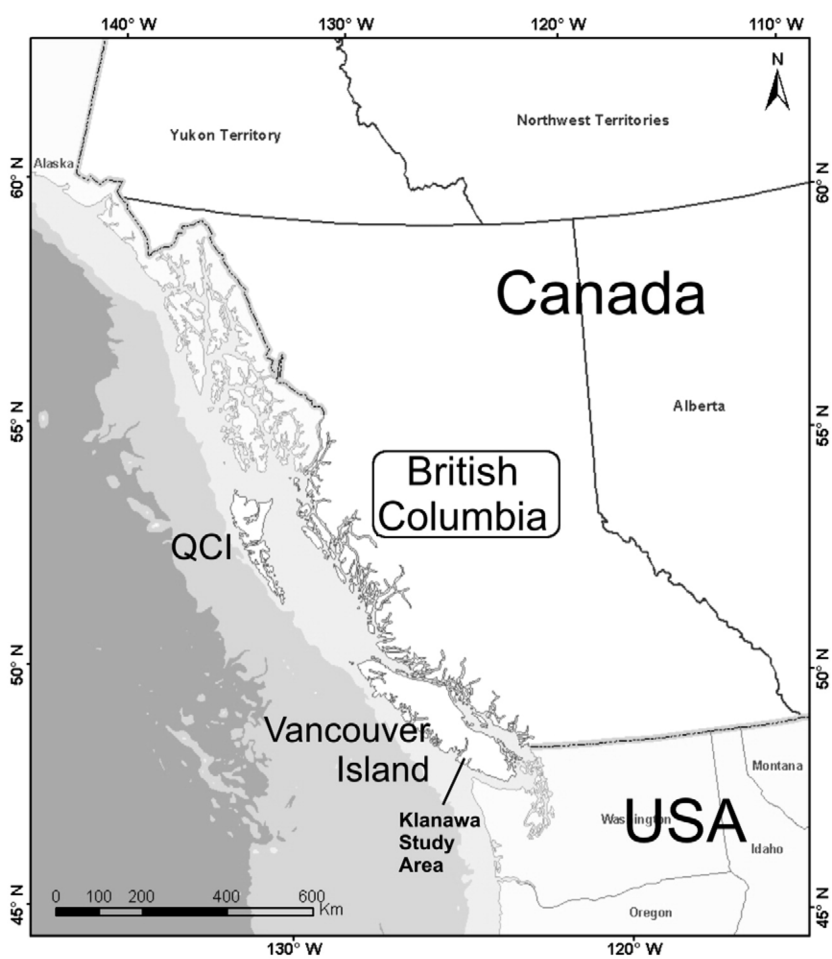

Fig. 2. The Queen Charlotte Islands (QCI) and Vancouver Island (VI) off the west coast of British Columbia, Canada, combined represent a study area of >40 000 km^2.

they may also be triggered by earthquakes (Mathews, 1979; Evans, 1989).

The Klanawa study area is a 3000-km^2 study area on the SW portion of VI (Fig. 2; Guthrie et al., 2008).

The QCI (Fig. 2) are comprised of 10 180 km^2 of terrain off the west coast of Canada, north of VI and south of Alaska's Alexander Archipelago (Brown, 1968). Formed of seven major islands, Graham Island and Moresby Island dominate the set. With a total relief of ~1200 m, the physiography varies from dissected coastlines and fjords, to coastal alpine ranges, to plateaus and plains. The mountains along the west coast are steep and end abruptly at the western edge, essentially demarcating the continental shelf. Geomorphic features relate largely to Pleistocene glaciations, including matterhorn peaks, U-shaped valleys, outwash plains and fjordal inlets.

The QCI are comprised largely of volcanics with interbedded fossiliferous sedimentary rocks, intruded in the Jurassic by granites contemporaneous with similar events on VI.

Precipitation falls largely as rain in winter months and the west coast receives annual average amounts in excess of 4200 mm (Hogan and Schwab, 1990). Debris slides and debris flows are common and are typically related to precipitation events (Gimbarzevsky, 1988; Hogan and Schwab, 1991).

3. Methods

Field data was acquired for 850 landslide reaches (Table 1): Seven hundred and seventy-three landslide reaches were measured in the QCI by T. Rollerson and employees of the MacMillan Bloedel Company in 1984 and 1985 (Rollerson, 1992; Fannin and Rollerson, 1993; Wise, 1997; Fannin and Wise, 2001). For each reach, field measurements of erosion, deposition, slope, channel confinement (open slope or gullied), area, and volume were taken. Queen Charlotte Islands data were analyzed in aggregate and separated into open slope and gullied data (515 and 258 landslide reaches respectively) for analysis.

On VI, for this study, an additional 77 landslide reaches were measured by R. Guthrie between 2006 and 2007 (VI data), and again field measurements included erosion, deposition, slope, area, and volume. Channel confinement was not explicitly recorded for the 77 landslide reaches measured on VI. In both data sets, erosion and deposition were considered independently.

Field data were compiled and analyzed on scatter plots and mean values were determined for 3° slope classes. Net deposition was returned by subtracting mean erosion from mean deposition for each class.

Both data sets rounded off depth measurements to the nearest 0.1 m perpendicular to slope, but show some measurement bias toward half-meter depth breaks. The field results are nevertheless expected to be more accurate than observation by any remote means (air photographs or remote sensing for example). Average depths <0.1 m were considered to be influenced by microtopography not accurately measured in the field and were reduced to 0 (actual 0 measurements were also recorded).

Table 1
Data sets used in current study.

Where	Number of events	Assessment type	Age	Reference
Queen Charlotte Islands	773 debris flow reach sections	Field assessment	Field dates from 1985 to 1986	Wise, 1997
Vancouver Island	77 debris flow reach sections	Field assessment	1995–2007	This study
Vancouver Island, Klanawa Range study area	331 debris flows > 500 m^2 (total inventory of 381 debris flows)	1:15 000–1:20 000 air photograph interpretation	Air photograph dates from 1994 to 2001	Guthrie et al., 2008

Analyses were further supplemented by an air photograph inventory of 331 debris flows acquired for the Klanawa study area on SW VI (Guthrie et al., 2008). Using this data set, the transformation from open slope to channelized debris flows (thereby increasing debris flow mobility and ultimately runout) was considered by measuring the angle of entry of landslides that entered gullies. Azimuthal angles between the landslide direction and the stream direction were measured in degrees in a GIS and compared to runout characteristics.

A model of debris flow runout was created by estimating volumes along the landslide paths in a GIS for 331 debris flows in the Klanawa study area. Volume was calculated by measuring the width of landslides perpendicular to a centerline in 10-m intervals along the path (Fig. 3) and multiplying by the average net deposition determined from field data. The debris flow ended if the net deposition was zero. Based on sediment balance (erosion versus deposition), a modelled debris flow could stop at the same location as the observed debris flow or stop before or after the observed event. When modelled debris flow paths had positive volumes where the observed debris flow terminated, they were extended along an imaginary depositional surface of 6°–9° to predict total travel distance required to deposit the remainder of the landslide material. The reverse was applied to modelled debris flows that had negative volumes where the observed debris flow terminated.

To consider the role of forests to debris flow runout, a subset of 25 debris flows that crossed a forest boundary (from a clearcut into a forested slope) in the Klanawa study area were examined to determine the role of forests as an energy dissipater. In a GIS, a 20 m buffer was placed on either side of the forest contact, and debris flow widths were calculated above and below the buffer. The buffer size was chosen to reduce immediate impact in landslide width from the forest edge. A 20-m buffer was the minimum buffer size to avoid a short-term width change in debris flows upon hitting a mature forest. Relative debris flow widths were calculated as a ratio:

$$\Delta w = \frac{fw}{hw} \quad (1)$$

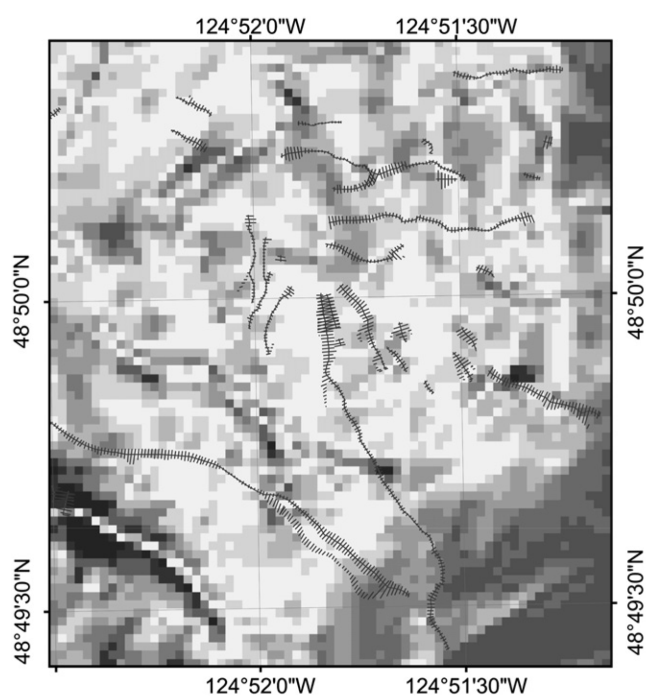

Fig. 3. Widths were calculated along the landslide path by drawing a line perpendicular to the center line in 10-m increments downslope. The background pattern represents a slope map broken into 3° categories.

where Δw = the width ratio, fw = the forested debris flow width, and hw = the harvested debris flow width.

The Δw values equal to 1 indicate that the forest had no effect on debris flow width, $\Delta w > 1$ indicate an increase in debris flow width, $\Delta w < 1$ indicate a decrease in width, and Δw of 0 indicate that the debris flow stopped within the buffered zone.

Similarly, a subset of 60 debris flows that crossed a road in the Klanawa study area was examined to determine the ability of roads to stop debris flows. A 25-m buffer was placed around known forestry road line drawings in a GIS, reflecting the conservative limit of the width of the forestry road. Similar to the forest section above, mean widths were calculated above and below the buffer. Relative widths were determined as a ratio:

$$\Delta r = \frac{r_2}{r_1} \quad (2)$$

where Δr = the road width ratio; r_2 = the width below the road, and r_1 = the width above the road.

The Δr values equal to 1 indicate that the road had no effect on debris flow width, $\Delta r > 1$ indicate an increase in debris flow width, $\Delta r < 1$ indicate a decrease in width, and Δr of 0 indicate that the debris flow stopped at the road.

4. Landslide hazard mapping

Landslide initiation is fairly well understood in BC as it is worldwide. Hazard mapping may take several forms from qualitative to quantitative (Varnes, 1978; Swanston and Howes, 1994; Rollerson et al., 1997; Corominas et al., 2004; Nadim and Lacasse, 2004; Bonnard and Corominas, 2005; Guthrie, 2005; among others). In BC, computer-based models for landslide hazard mapping and runout and risk mapping have not replaced expert judgement and fundamental mapping techniques, nor are they generally considered practicable. The reasons are several: The most accurate digital elevation model (DEM) that covers all of BC has a 25-m maximum resolution. Hazard models at that resolution may produce poor or impractical results and can substantially over-predict the landscape susceptible to landslides (e.g., Pack et al., 1998; Chung et al., 2002). In addition, models typically require considerable adjustments to determine sensitive input parameters that differentiate a stable slope from one that is unstable (Soeters and van Westen, 1996). As a result, computer-based hazard models are more frequently used for site specific cases or linear developments such as along highways where the investment reflects the precise nature of the problem, the consequence, or the financial commitment.

British Columbia and many other jurisdictions worldwide use instead a terrain and hazard mapping system employing direct mapping methods: experience, expert judgement, and empirical evidence that codify the landscape into morphologically consistent polygons that can, in turn, be rolled up into hazard classes (Fig. 4). In BC those classes relate to management decisions through provincial guidelines and legislation. The methods are approximately similar at different scales, with the greatest difference being that coarser scales are more conservative thereby triggering detailed mapping where required. Attempts to better quantify the results occur in combination with statistical methods, and these results can feed into regional models; but the fundamental approach is still direct mapping. Soeters and van Westen (1996) observed that an ideal map of slope instability includes spatial and temporal probability, landslide type

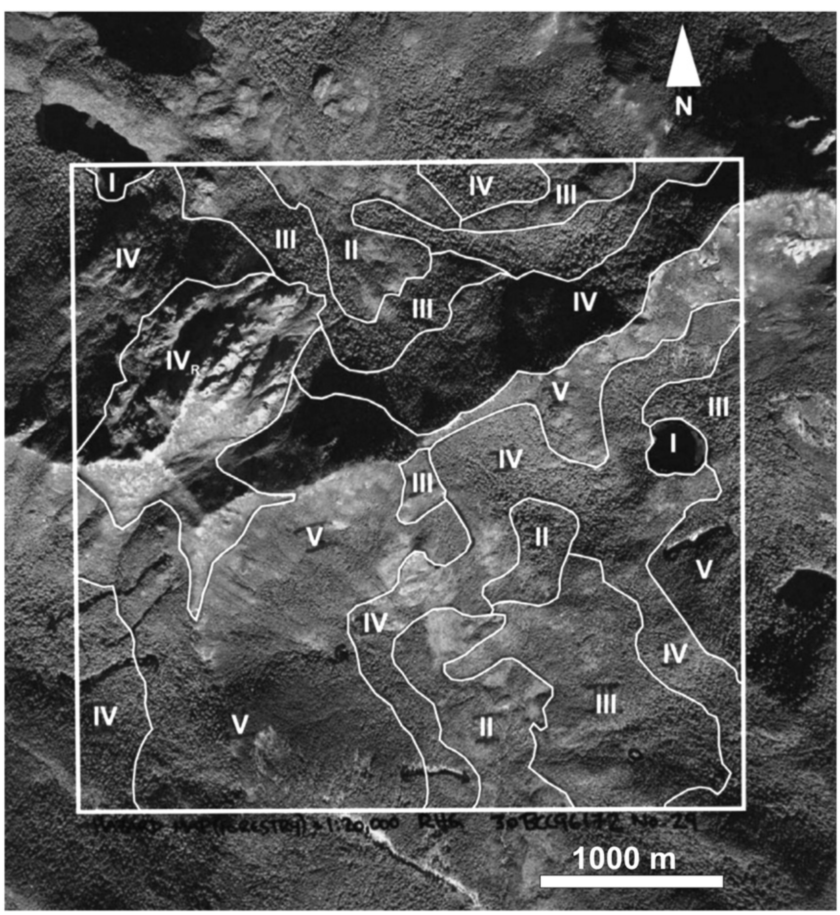

Fig. 4. A five class terrain hazard map produced for forest harvesting and road construction in coastal BC. Hazard class are: very low (I), low (II), moderate (III), high (IV), and very high (V). Areas designated as class IV and V would require more detailed assessment before harvesting.

and magnitude, as well as velocity and runout distance. Calculating runout distance remains problematic.

5. Landslide runout

For debris flows, several models attempt to describe landslide travel distance or runout including various numerical and analytical models (Hungr, 1995; Corominas 1996; Di Gregorio et al. 1999; Findlay et al., 1999; Fannin and Wise, 2001; Turcotte et al. 2002; D'Ambrosio et al. 2003; McDougall and Hungr, 2004; Kwan and Sun, 2006; Guthrie et al., 2008; Miller and Burnett, 2008; among others). However, many of the parameters required to run these models are calibrated or determined using empirical methods.

In addition to increasing the accuracy of numeric and analytical models, empirical methods have been developed that rely on established relationships between, for example, runout distance, volume, peak flow, and slope geometry (Heim, 1932; Scheidegger, 1973; Hsu, 1975; Takahashi, 1981; Hungr et al., 1984; Corominas, 1996; Fannin and Rollerson, 1996; Findlay et al., 1999; Horel, 2007; among others) and may therefore be used on their own to predict debris flow runout. These methods may also include changes to mobility as a result of major topographic controls, such as entering an adjacent channel (Benda and Cundy, 1990; Millard, 1999; Miller and Burnett, 2008). In such instances, mobility may be decreased if the entry angle to the adjacent channel approaches the perpindicular or increased if the entry angle is very low (Benda and Cundy, 1990; Millard, 1999; Miller and Burnett, 2008).

Empirical models are essentially of two types. The first type relies heavily on the initial or total volume component of a debris flow (e.g., Corominas, 1996; Rickenmann, 1999; Hürlimann et al., 2008). Rickenmann (1999), for instance, determined the relationship between maximum runout distance ($L_{\max}$), debris flow total volume (V), and the vertical drop along the path (H):

$$L_{\max} = 1.9V^{0.16}H^{0.83} \quad (3)$$

Several authors have observed that debris flow volume is dependant not only on the volume of initiation, but on the entrained material along the path (Benda and Cundy, 1990; Dunne, 1998; Guthrie et al., 2008; Hungr et al., 2008; among others). Debris flows become increasingly destructive with increased entrainment; and for those that extend beyond a first-order channel, the entrained volume may exceed the volume of the initial failure by an order of magnitude (Benda and Cundy, 1990). As a consequence, those empirical relationships that rely on volume as a key parameter are not adequate to predict the debris flow path *a priori*.

The second type of empirical model depends on the entrained component of volume and on volume balance along the flow path (Benda and Cundy, 1990; Cannon 1993; Fannin and Wise, 2001; Miller and Burnett, 2008). This sediment balance approach is based on the premise that a debris flow will continue to propagate until such time as the volume or mass of the event reaches zero. On flatter slopes, the tendency is to deposit sediment; and on steeper slopes, the tendency is to erode. Consequently, the role of topography as a controlling mechanism to landslide runout is fundamentally reliant on slopes at all scales. Hürlimann et al. (2008) observed that the weakness of these methods is that they require detailed channel information. However, recent work by Miller and Burnett (2008) for Oregon state suggested that volume balance can be used to predict regional debris flow runout characteristics.

5.1. The impact of forests, roads and benches on landslide runout

In the Pacific Northwest, the absence of mature timber appears to increase not only the frequency of debris flow activity (Schwab, 1983; Rood, 1984; Jakob, 2000; Guthrie, 2002, 2005; Guthrie and Brown, 2008), but also the magnitude and travel distance of individual events (Robison et al., 1999; Bunn and Montgomery, 2000; Lancaster et al., 2003; May and Gresswell, 2003; Miller and Burnett, 2008; among others). Landslide research from the Coast Range of Oregon demonstrates several ways in which forests can influence debris flow runout: Debris flows have lower mean runout lengths and shorter depositional zones in mature forests (Robison, et al., 1999; May and Gresswell, 2003; Miller and Burnett, 2008), while landslides in younger stands (< 9 years) have increased volumes of erosion compared to regenerating stands (9-100 years) (Robison et al., 1999). In addition, wood entrained from forested slopes may reduce runout length by changing the behaviour of the leading edge of the debris flow (Lancaster et al., 2003).

Johnson et al. (2000) reported in SE Alaska that net deposition of debris flows in forested and clearcut slopes was 29° and 19° respectively. In the same study, the mean gradient of terminal deposition for debris flows was 10°–13° in forested terrain and 7° in clearcuts, respectively.

Roads are essentially human made benches in the landscape, typically too small to show up on the DEM (<25 m in width). Roads are often the cause of landslides in the Pacific Northwest (Jakob, 2000; Wemple et al., 2001; Guthrie, 2002, 2005; among others); however, field experience shows that in some cases roads play a mitigating role capturing sediment and reducing or even eliminating the impact of the debris flow on downslope resources. The role of roads in stopping landslides is similar to that of a range of topographically flat areas too small to detect remotely.

6. Results and discussion

6.1. The role of slope

Despite considerable data scatter, trends showing decreasing deposition and increasing scour with increasing slope are evident in each plot (Fig. 5). In addition, some scour was measured on all but the flattest slopes in the study, and deposition was measured on all but the steepest. While this result is intuitive, the extent to which it is true exceeded what was reported from previous studies. For example, almost half a meter of deposition was recorded at slopes of 36° on the QCI, substantially greater than the 23° previously reported for the QCI data (Fannin and Rollerson, 1996). Similarly, on VI, the upper limit of deposition was almost 35° (0.1 m), substantially higher than the 15° reported by Horel (2007), for 33 debris flows on VI.

The deposition slope limits reported here are close to the angle of internal friction for gravel or wet sand (~35°), therefore, while deposition on those slopes may be uncommon in shallow debris flows, a physical explanation for their occurrence is likely and we would argue that similar conditions probably occurred unrecorded in previous studies. Our own field experience indicates that some deposition may occur on steep slopes based on friction alone. In addition, topographic features and intact forests may influence deposition characteristics. In Alaska, for example, Johnson et al. (2000) reported that net deposition began in slopes as steep as 29° in old growth forests and 19° in clearcuts.

A final consideration is that this study measured erosion and deposition independently in an attempt to better define the role of slope. Horel (2007), in contrast, was almost certainly describing net deposition at 15°. Fannin and Wise (2001) estimated that net erosion occurred on unconfined slopes above 19° and on confined slopes above 10° in the Queen Charolotte Islands, but observed erosion and deposition at a range of slopes. Hungr et al. (1984) reported the onset of net deposition to take place between 10° and 16° and suggested overall that 10°–14° was appropriate for unconfined debris flows and 8°–12° was appropriate for channelized debris flows. Hungr et al. (1984) reported that similar results were found in Japan. We consider net deposition below.

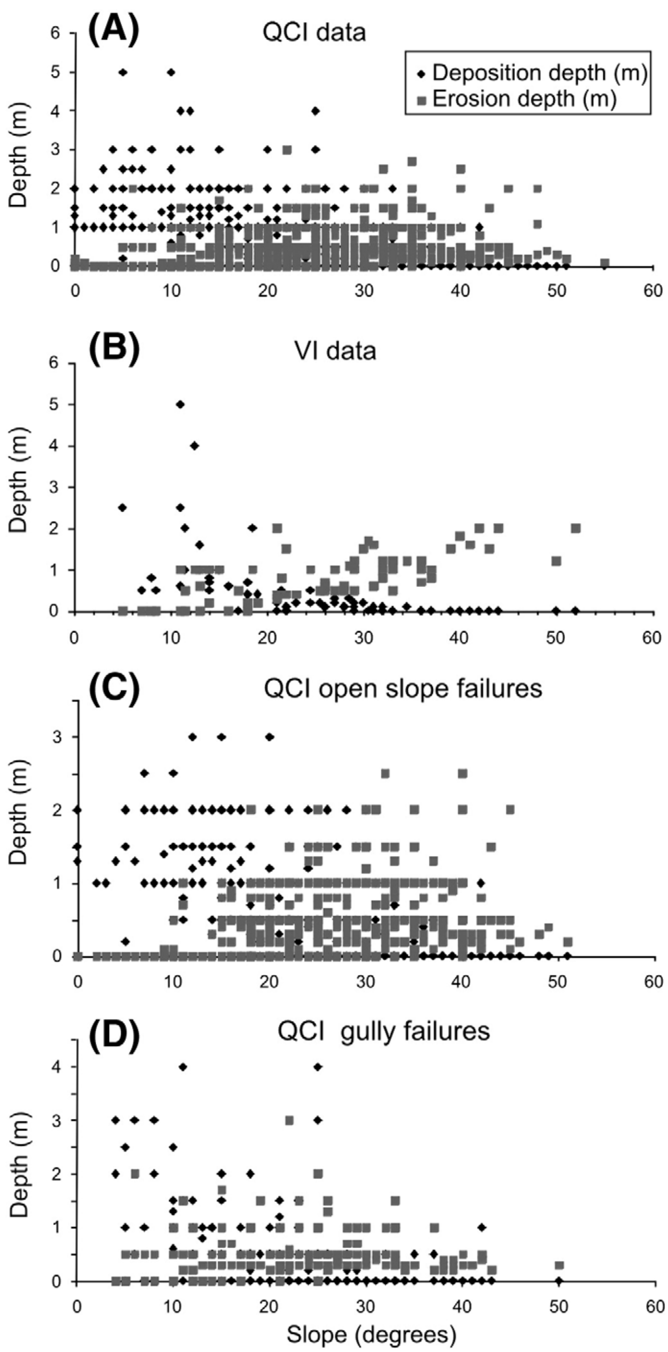

Fig. 5. Scatter plots of deposition and erosion at 850 field stations compared to slope at each location. The QCI data is presented in aggregate in A, VI data in B. QCI data is further broken into open slope (C) and gullied (D) data. QCI data published in Wise (1997).

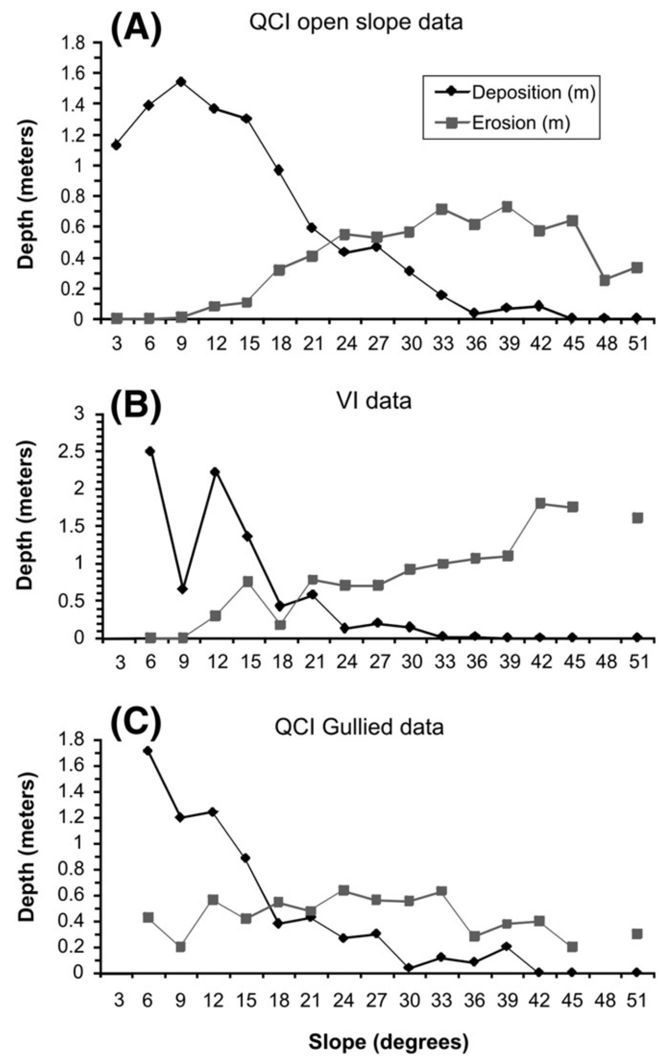

Fig. 6. Mean erosion and deposition in 3° slope classes for (A) QCI open slope debris flows, (B) VI open slope debris flows, and (C) QCI gullied debris flows.

Erosion in this study was measured on low angle slopes: 10° on VI and the QCI and 5° for gullied debris flows on QCI. The erosion typically occurs in the center of the landslide track and may be difficult to distinguish from post-landslide fluvial reworking. Nonetheless, erosion is evident, particularly where the landslide is partially confined.

While the scatter plots show the variability in the data, the overall impact of slope is easier to understand if we consider the mean erosion and deposition of all measurements in 3° classes (Fig. 6A–C). Analyzed in this manner, further trends are evident: erosion levels at the steep end of the slope range due to limited deposits that cover the majority of coastal BC slopes. This paucity of sediment also limits total failure volumes: debris flow erosion won't exceed the depth to bedrock, and in BC, bedrock is often within 1 m of the surface. Deposition, on the other hand, is not so constrained, and terrain maps commonly reveal thicker colluvial and morainal deposits on flatter slopes approaching the valley bottom. Deposition increases rapidly with a drop in slope angle, peaking at almost twice the erosion depths (Fig. 6). A crossover point between deposition and erosion, and related to slope reveals where net deposition is expected along the landslide path. That crossover point is between 18° and 21° for the VI data (Fig. 6C) and between 21° and 24° for the open slope QCI data (Fig. 6A). This means that net deposition occurred on slopes steeper than previously reported for coastal BC (Hungr et al., 1984; Fannin and Wise, 2001; Horel, 2007).

An anomalous drop in deposition for the VI data at the 9° slope bin has no obvious reasonable physical explanation. Instead, it is likely an artifact of too few data entries in that bin; similar problems occur above the 39° slope bin for erosion where depth of sediment seems anomalously high. Because sediment on steeper slopes is usually thinner, VI results were expected to be similar to those from the QCI data (Fig. 6A). Notably, however, field samples are inherently biased to steep slopes with sediment (the only kind on which debris flows occur), perhaps in greater proportions than on adjacent terrain. Depth of sediment may be symptomatic of failure-prone slopes rather than indicative of a trend to deeper material on steeper slopes.

Net deposition is obtained by subtracting erosion from deposition (Fig. 7). A line representing a best fit third-order polynomial is drawn

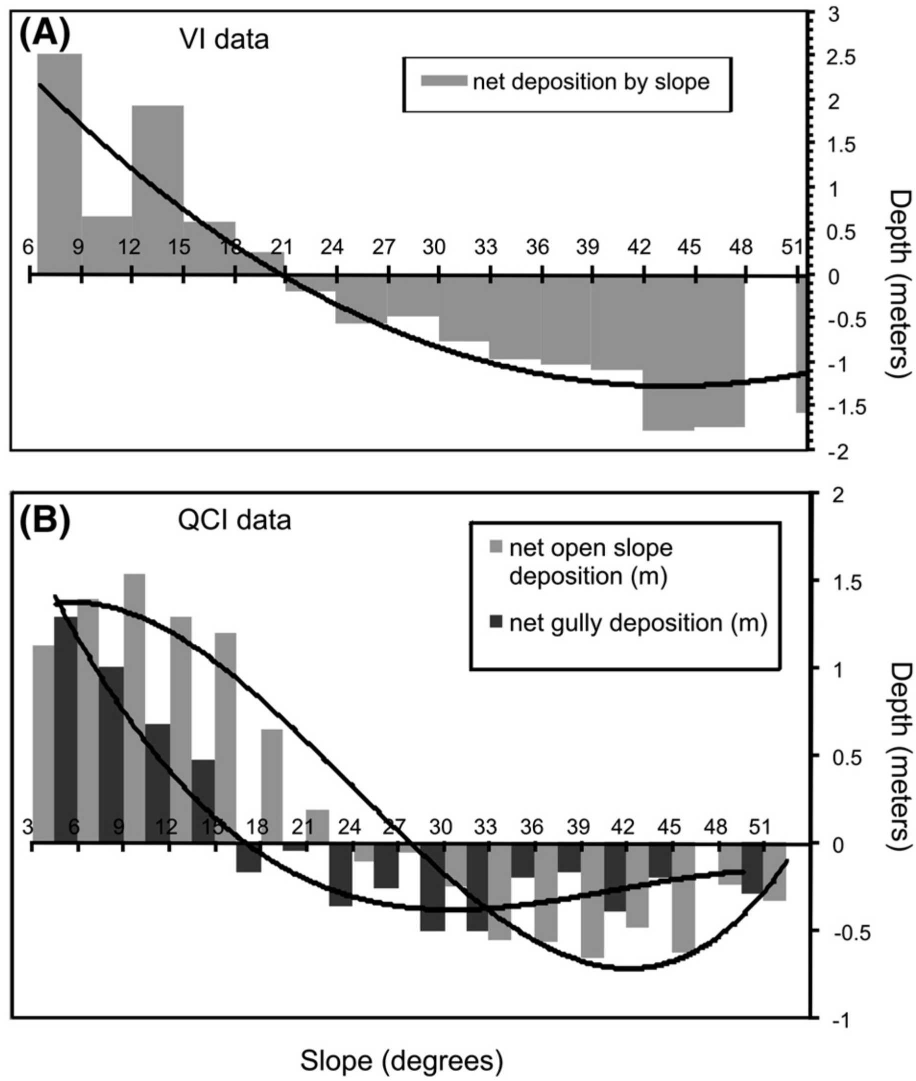

Fig. 7. Net deposition in 3° slope classes for debris flows on VI (A) and QCI (B). Based on 1700 field measurements, these graphs can be used to estimate runout distance requirements of shallow debris flows. Bar data for QCI are meant to represent full bin, but for two separate cases (open slope and gullied).

over the graphs. In addition to the crossover points (the onset of net deposition) being clearly defined, the present study reveals average entrainment and deposition along the landslide path related to slope. Using these measurements, we are able to estimate (based on field measurements) the required runout distance for a given landslide and incorporate the predictions in a consistent way into direct mapping techniques already being utilized. Consider, for example, an open slope landslide following a simple topographic profile: on VI, a landslide initiates on a 36° slope that extends 60 m to a slope break of 27° for another 30 m, 21° for 30 m, and then flattens out to 12° before reaching a stream 50 m away. Is the landslide likely to hit the stream? For simplicity, assume a constant width of 20 m. The result is easily calculated (Table 2) and a credible scenario develops that results in 540 m^3 of material entering into the stream. In this scenario, avoiding the stream would require another 25 m of slope distance at or below 12° or the expectation that the landslide deposit would be deeper. If, for example it was as deep as the observed average (1.9 m), it would have stopped just short of the stream.

The impact of a change in slope on width, and therefore potential sediment balance, was considered: over 13 000 width measurements taken at 10 m increments perpendicular to the landslide path revealed, for 331 landslides in the Klanawa, that the mean width was 22 m. Further, mean widths examined at each of the slope bins indicated that debris flows were widest on the steepest slopes (typically associated with initiation) and on the flattest slopes associated with deposition, but spent most of their length on transitional slopes at a width just slightly < the mean (Fig. 8). While measured widths ranged up to about 300 m, less than 6% were > 50 m wide indicating that the usual morphology of debris flows in coastal BC tend to be long and narrow. Hürlimann et al. (2008) noted that the primary disadvantage to methods that used the concept of volume balance along the flow path was the detailed information necessary about the channel as well as knowing the initial volume. We argue,

Table 2
A simplified example of a debris flow runout estimation based on observed mean net deposition characteristics for Vancouver Island.[a]

Slope (degrees)	Distance (m)	Net deposition from figure (m)	Cumulative volume (m^3)
36	60	−1.1	−1320
27	30	−0.5	−1620
21	30	−0.2	−1740
12	50	+1.2 (using the line rather than the bar)	−540

[a] Net deposition was determined using actual observations rather than the given trendline except for the 12° slope where fewer data points are expected to bias results.

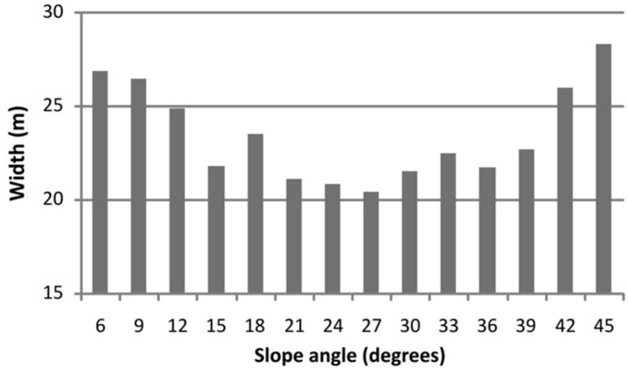

Fig. 8. Mean debris flow widths related to slope for VI. *x*-axis numbers represent the upper limit of each slope bin.

based on the observed relationships between slope and parameters of depth and width, that neither is necessary. The result is important for practitioners, and others.

Generalizing the results, an entrainment map demarcating erosion and deposition zones based on the 3° slope classes for all of VI was created using a 25-m DEM (Fig. 9). This gives a regional perspective of potential debris flow behaviour: Lower order streams tend to be tightly constrained between erosive surfaces where material is likely to be entrained. Large depositional surfaces, from a landslide perspective, are mostly contained by the lower slopes and valley floors of higher order streams. Landslides reaching higher order streams are often larger, having avoided or overwhelmed smaller watershed features along their path, and therefore need greater stopping room.

Debris flow runout, modelled using the methodology outlined in Section 3 above, compared favourably to observed runout (Fig. 10). The trend line indicates that the methods slightly overpredict, on average, debris flow travel distance. Several explanations are proposed: (i) Estimates of erosion and deposition may be wrong, however, field estimations are likely to be more accurate than data acquired remotely. (ii) Streams frequently remove part of the material at the toe of actual debris flows. This was not calculated in the model. (iii) The 25-m resolution of the DEM means that local topography observed in the field and of a size sufficient to influence landslide behaviour, combined with the inherent variability of the results (Fig. 5), is smoothed out considerably in the GIS. Consider the case for a 25-m staircase where the tread and the riser of each step are of equal size. The DEM would register such a staircase as having a 45° slope, but in reality it would be several vertical falls interposed with horizontal benches. Each bench has a significant role in the mobility of the debris flow. We observed the influence of benched topography on both large and small landslides. The discussion of roads below is an excellent case example of the role of topography too small to be observed in the DEM.

Three landslides extended much farther than predicted (the shortest being > 2.7 km) as channelized debris flows where continued confinement limited opportunities for deposition. The influence of channel confinement on scour and deposition along the landslide path, and therefore mobility, may be discerned from Figs. 5–7. The

Fig. 9. An entrainment map of Vancouver Island with erosional surfaces in red, transitional surfaces in white, and depositional surfaces in brown. Colors grade to one another based on 3° slope classes. Inset figure shows oblique view of entrainment map with landslides superimposed in yellow.

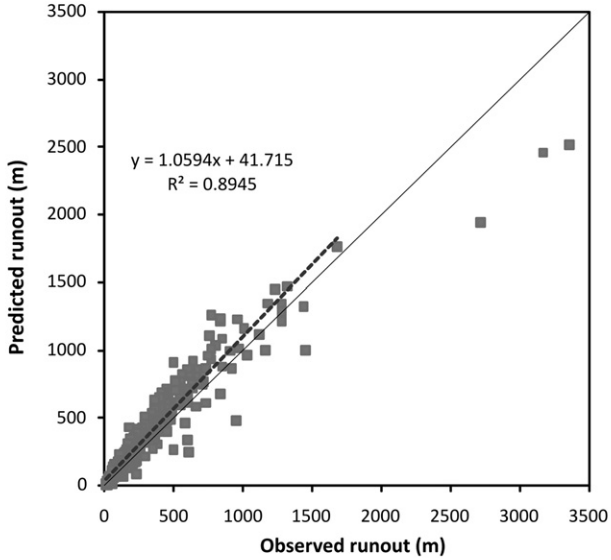

Fig. 10. Predicted versus observed runout using the sediment balance approach for 331 landslides in the Klanawa study area. See text for discussion.

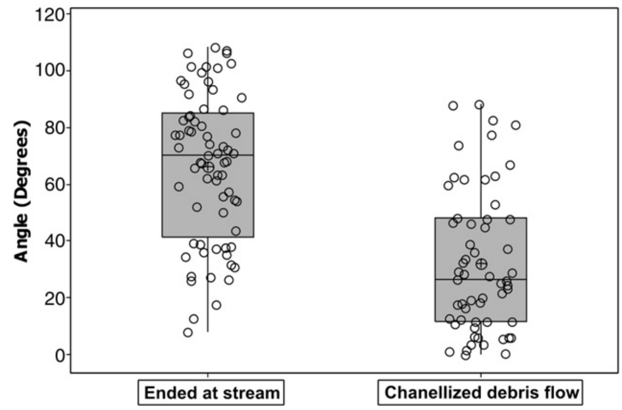

Fig. 11. Box plots showing angle of entry to streams for 127 debris flows — 58 of which carried on as channelized debris flows. Mean angles are shown by the crossed circle, the median by the middle line, the vertical line represents the minimum and maximum values.

crossover to net deposition occurs at slopes about 10° flatter than for open slope events, corroborating previous observations by others (Hungr et al., 1984; Fannin and Rollerson, 1996; Horel, 2007) and indicating substantially increased mobility. However, the slope angle at which the onset of net deposition was observed was again steeper than previously thought.

The limited erosion depth of channelized debris flows is indicative of the active environment within the gully or channel. Essentially, the shallow erosion depth (as indicated on Figs. 6 and 7) is a product of highly efficient systems (repeated fluvial or colluvial erosion) that transport sediment to lower positions on the landscape. This is particularly evident in low-order streams that may be scoured to bedrock following a debris flow, and along which failures recur every several years. In the Klanawa study area, for example, more than 74% of the debris flows ended in first- and second-order streams.

Of the debris flows in the Klanawa study, 127 initiated from single points and hit a stream, thereby allowing discrete analysis in a GIS environment. Those landslides were divided into those that continued as a channelized debris flow ($n=58$) and those that ended at the stream ($n=69$). A comparison of the angles between the landslide path and the stream for each type is shown on Fig. 11. Open slope debris flows had a median angle of entry of 70°, while those that became channelized had a median angle of entry of 26°. Similarly, more than 75% of debris flows that stopped had angles of entry >45° and more than 75% that continued had angles <45°. The results are similar to previous studies (Benda and Cundy, 1990; Millard, 1999; Miller and Burnett, 2008) and indicate, in terms of mobility, that headwall failures into a gully are much more likely to continue as a channelized debris flow than sidewall failures. Results are easily incorporated into direct mapping methods.

6.2. The role of forests

Research indicates that the presence or absence of mature timber can influence the magnitude and travel distance of individual events (Robison et al., 1999; Bunn and Montgomery, 2000; Lancaster et al., 2003; May and Gresswell, 2003; Miller and Burnett, 2008; among others). Previous studies considered changes to mean runout length between landslides through clearcuts and landslides through intact timber (e.g., Robison et al., 1999; May and Gresswell, 2003; Miller and Burnett, 2008). However, causation may be difficult to ascribe to the results that are dependent on other factors, such as slope and available sediment. Herein, we attempt to understand what happens when a landslide travelling through an unvegetated slope hits an intact forest.

Twenty-five open slope debris flows that travelled through a cutblock and crossed a forest edge were analyzed. Specifically we measured the change in width 20 m above and 20 m below the boundary (Table 3). Cutblock boundaries appeared to have a large effect in decreasing the momentum of open-slope debris flows (Fig. 12). Debris flows that crossed boundaries between cutblocks and older forest crossed them at slopes ranging from 12° to 46° (based on a 25-m DEM), yet we observed no discernible effect from slope. In contrast, the Δw ratio ranged from 0 (the slide stopped at the forest boundary) to almost 2 (the slide doubled in width).

Twelve (48%) of the landslides examined stopped within the 40 m buffer against the forest boundary ($\Delta w=0$) and another was reduced to less than a third of the width. Another 7 debris flows (28%) were substantially reduced in width ($\Delta w=0.3$–0.6), and 4 stopped entirely within 50 m of the forest boundary. The remaining three debris flows were reduced in width but continued downslope otherwise unaffected. The largest of these failures continued 400 m farther, eventually depositing onto a river terrace below.

Debris flows that showed no significant change in width (Δw–0.9 – 1.2) were large before they hit the forest boundary; one was the largest in the subset and stopped 170 m downslope at a stream channel. The other was unaffected by the forest boundary continued 210 m downslope, and ended in the middle of the forest.

Table 3
The width ratio (Δw) showing the effects of forest on debris flow width and the road width ratio (Δr), or the change in debris flow width after crossing a road.[a]

Forest boundary			Road		
Δw	Count	%	Δr	Count	%
0.0–0.3	13	52	0–0.3	33	55
0.3–0.6	7	28	0.3–0.6	5	8
0.6–0.9	2	8	0.6–0.9	6	10
0.9–1.2	2	8	0.9–1.2	7	12
1.2–1.5	0	0	1.2–1.5	6	10
1.5–1.8	0	0	1.5–1.8	3	5
>1.8	1	4	>1.8	0	0

[a]The Δw values equal to 1 indicate that the forest had no effect on debris flow width, $\Delta w>1$ indicate an increase in debris flow width, $\Delta w<1$ indicate a decrease in width, and $\Delta w=0$ indicate that the debris flow stopped just inside the forest edge. Similarly, Δr values equal to 1 indicate that the road had no effect on debris flow width, $\Delta r>1$ indicate an increase in debris flow width, $\Delta r<1$ indicate a decrease in width, and $\Delta r=0$ indicate that the debris flow stopped on the road prism. Count and percent show the number and percent of total landslides, respectively, for each score.

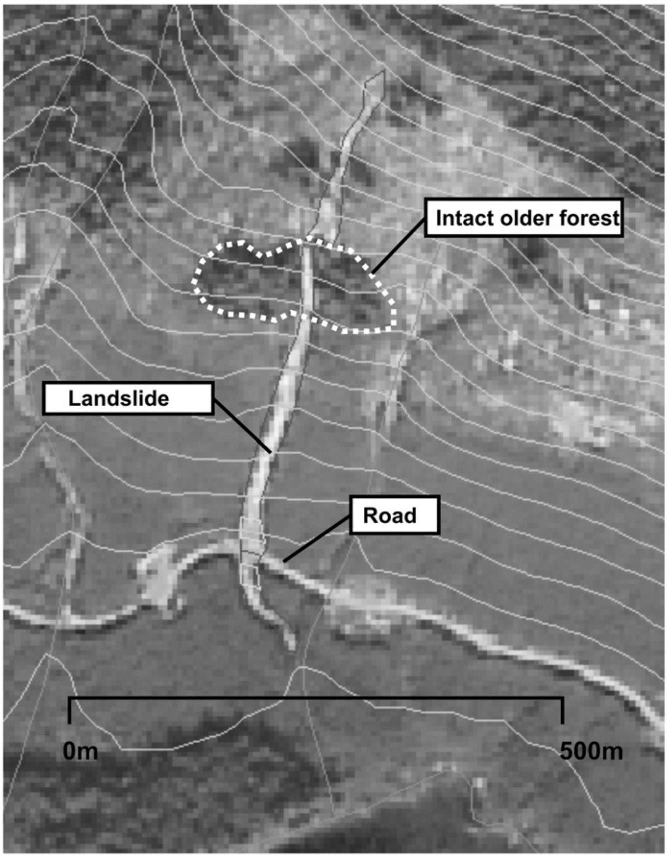

Fig. 12. Debris flow overlain on a SPOT satellite image. An open slope debris flow travels from a clearcut, through a small block of older forest, where it narrows considerably following the contact with the forest edge. The debris flow increases in width as it entrains more material below the intact forest. A slight reduction in width is measurable below the road contact; however, the landslide stops shortly as it reaches the valley floor and flatter slopes.

Only a single failure got significantly larger, in this case doubling in size. However, this small slide deposited just 55 m into the forest from the forest edge, and the width ratio was in this case representative of a depositional phase.

While the sample size was small, we have shown that forests can provide a substantial barrier to shallow debris flows (Fig. 12): impeding debris flow travel, shortening runout distance, and reducing flow volumes. We propose, based on field observations, that forests can also serve to stop debris flows on steeper slopes. This corroborates previous studies (Robison et al., 1999; Bunn and Montgomery, 2000; May and Gresswell, 2003; Lancaster et al., 2003; Miller and Burnett, 2008 among others) and provides a strong argument for retaining mature forests as buffers between harvested areas in forestry management strategies. One could argue that 50-m forested buffers around major streams would dramatically reduce the potential for impact from upslope debris flows.

6.3. The role of roads

Roads are widely recognized as causing increased landslide frequencies in the Pacific Northwest (Jakob, 2000; Wemple et al., 2001; Guthrie, 2002, 2005; among others). Guthrie (2002) observed, for example, that when measured against the relative space that roads occupy they may increase landslide frequencies by two orders of magnitude. However, roads behave as benches in the landscape and this, in turn, is expected to ameliorate landslide impacts. We considered the extent to which this was the case in much the same way we examined the role of forests, by examining the change in open slope debris flow width above and below the contact with the road for 60 events. The results are given in Table 3.

As in the forest contact example, debris flows crossed roads at slopes ranging from 15° to 45° (based on a 25-m DEM). In terms of landslide mobility, the DEM slope alone was not a good indicator of stopping power at the road.

Overall, Δr ratios ranged from 0 (the debris flow stopped on the road) to 1.75 (the debris flow width increased by 75% after crossing road). Half the population stopped at the road ($\Delta r = 0$) and another 3 were reduced to less than 30% of their ($\Delta r < 0.3$) and stopped within 10 m of the road. These slides ranged across all slope classes; however, they had a maximum size above the road of 5800 m^2.

Five debris flows were substantially reduced in width by the road and two stopped within a short distance of the road. In contrast, however, the reduction in width was temporary for the other three and continued down slope with the effect of the road diminishing rapidly with increased distance from the road along the landslide path. This is of critical importance when considering the role of any topographic benches. Essentially, a bench represents a single line of defence across the landscape. If the bench is unable to contain the debris in a landslide, then the downslope rules of entrainment and deposition continue to apply. The bench in such a case has been of limited benefit, reducing only the immediate volume of the debris flow.

Six debris flows had a Δr ratio between 0.6 and 0.9, indicating a slight reduction in width after crossing a road. Of these, five continued down the slope, reduced in width but otherwise unaffected. The road effect was to reduce the immediate volume of the debris flow. If the slopes below the road are largely transitional, entraining and depositing material in equal measure, then the benches and roads do serve a role in reducing the probable impact of debris flows that hit the valley floor or the stream network.

The remaining debris flows continued downslope apparently unaffected by roads, with widths remaining unchanged or even expanding. Of these, 9 debris flows had ratios above 1.2, all continued down slope apparently unaffected by the road crossings, and eight entered higher order streams below. Morphologically, these debris flows were spreading rapidly in a teardrop shape, less typical of the debris flows in this study but not unusual elsewhere. They appeared to overwhelm the road and continued to spread and travel downslope unabated. The largest of these was 67 000 m^2.

Roads were effective at stopping debris flows over half of the time. In addition, in several cases where the debris flows overran the road, they had persistent reduction in volumes as they moved to more transitional slopes. However, unlike forests that provide a frictional barrier with considerable depth, roads represent only a narrow line of defence. Multiple benches in the landscape are likely to be more effective than single benches. Finally, one needs to acknowledge that the stopping power of roads does not adequately compensate for the increase in landslide density as a result of road construction. Both, however, are served better by well built roads with thoughtful application of geoengineering.

7. Conclusions

Coastal British Columbia faces the constant challenge of mapping large remote areas inexpensively and efficiently. Direct mapping in the form of terrain and hazard mapping has been the historical solution and is the method most widely used today as it is in other regions worldwide. Good hazard mapping incorporates runout and associated magnitude, both of which are historically difficult to predict in the field. We therefore examined topographic controls to shallow landslide runout and magnitude using data sets from coastal British Columbia, and based on 1700 field observations, general rules for slopes on which landslides entrain and deposit material were calculated. The field observations were supplemented by a data set of 331 debris flows gathered through air photograph analysis, and both sets of data were analyzed in a GIS environment. From these analyses, we conclude that

(i) Deposition and scour occur on steeper and flatter slopes, respectively, than previously reported, as a result of more detailed analysis of field data. Importantly mean net deposition was determined to occur on slopes between 18° and 24° for open slope failures and between 12° and 15° for gullied or channelized debris flows. The results are likely to be portable to debris flows in the Pacific Northwest, and to other regions dominated by rain-triggered debris flows. Local calibration should be expected.

(ii) Average net deposition or entrainment may be estimated on a variety of slopes in the field using the types of graphs provided (Figs. 5–7), and runout can therefore be calculated in similar terrain (Fig. 10). An example of an entrainment map for VI is provided. An entrainment map may be used to quickly estimate erosion and deposition along a path and give a user a first-order approximation of expected debris flow mobility. Field estimates of mobility based on measured slopes should produce better runout predictions than those based on the 25-m DEM. However, both are useful.

(iii) The simple rule-based methodology for estimating debris flow runout is based on field examples from across VI and the QCI. The methodology was tested in the Klanawa study on VI and found to produce encouraging results where predicted runout matched very well with the observed.

(iv) More than 75% of debris flows that hit channels and transformed to channelized debris flows had angles of entry $<45°$. More than 75% of debris flows that stopped had angles of entry $>45°$ to the channel. Landslide paths that lead to an acute angle with a stream or channel are significantly more likely to have long runout distances.

(v) Mature timber stopped debris flows within 40 m of the forest boundary almost 50% of the time and within 50 m 72% of the time. Debris flow widths were reduced after passing through a mature timber boundary 88% of the time, indicating that forests can act as a substantial frictional barrier. Forest managers are well advised to leave blocks of intact forest between clearcuts and around streams to buffer the potential effects of landslides.

(vi) Roads stopped debris flows in 50% of the cases and reduced the debris flow width 73% of the time. However, landslides that breached roads and continued onto steep slopes continued to entrain material and grow. The road itself can serve both as a point of erosion (steep fill slopes and drainage routing) and deposition. Thoughtful application of geoengineering is an obvious solution to both aspects of the problem.

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