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Modeling the travel distances of debris flows and debris slides: quantifying hillside morphology

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Abstract. A travel distance model for debris flows and slides is presented based on information collected in southeast British Columbia, Canada. The model incorporates a variable that represents terrain morphology by a single number, quantification made using a one-to-one correspondence between the binary and decimal numeration systems. The terrain morphology coding has a site-specific character, providing a process-based representation of local conditions. Multiple regression analysis was used to assess the dependence of event travel distance on terrain morphology, slope, stand height, terrain curvature and canopy closure ($R^2 = 0.975$, $p < 0.001$). The model fulfills all the assumptions and requirements of regression analysis (i.e. normality, homoscedasticity, non – correlated errors, lack of colinearity or outliers). An independent data set was used to test the model. The model successfully predicted all but one of the test dataset events, and one of four outliers. The model consists of an equation that can be used in mass movement risk assessment associated, with different forest activities (e.g. harvesting, road building).
Keywords reach, binary codification, number theory, regression analysis, British Columbia.

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Introduction

The accurate modeling of debris flows and debris slides plays a crucial role in terrain mass movement disasters preparedness, prevention and mitigation. Forecasting debris flows and debris slides is commonly separated into two parts: initiation and travel distance. Debris slide-flow initiation has been investigated using a large variety of theoretical framework, such as fluid mechanics (Innes 1983, Hungr et al. 1984, Takahashi 1991, Iverson 1997) statistics (Atkinson & Massari 1996), vegetation combined with a topographic index (Wu & Sidle 1995), or forest practices (Fannin et al. 1996). The travel distance of mass-movement events were also examined within the fluid mechanics (Takahashi 1981, 1991, Hungr et al. 1984) and statistical framework (Fanin & Wise 2001). However, rheological investi-

gations besides considering a series of parameters characterizing the flow that are difficult to measure (e.g., ratio between the longitudinal section area of a moving earth block and the square depth of the surface water flow behind the moving earth block, the angle of particle encounter or the slope deposition/upward section of the debris flow), and do not include terrain configuration in the analysis. Statistical procedures, which are used to overcome the difficulties associated with the measurements of rheological variables, consider a reduced set of predictors, such as slope or volume at initiation point, number of reaches (Cannon 1993, Megahan & Ketcheson 1996, Corominas 1996, Finlay et al. 1999, Fannin & Wise 1995, 2001). Statistical models are easier to implement but the confidence intervals associated with the predicted values are too large to provide useful results; in some cases the confidence intervals being greater than 200% of the actual length (Neter et al. 1996).

To objective of this study is to develop an accurate method of calculating debris flow – debris slide travel distance using attributes describing hillside and path of the event. To ensure the accuracy of the predicted travel distance, special consideration will be given to the attributes describing hillside variability (i.e., change in the slope of the hillside), which was argued that it plays a significant role in the magnitude of the terrain failures (Takahashi 1991, Iverson 1997).

Methods

Study area

To develop the travel distance method a set of 582 terrain failure events that occurred in the south-eastern British Columbia, Kootenay Mountains (Fig. 1), were considered, events identified using aerial photographs (Jordan 2002). The soils in the area are dominated by humo-ferric podzols and dystric brunisols (Agriculture & Agri-food Canada 2002), developed from a range of different lithologies, spanning both metamorphic and intrusive rocks (e.g., quartz monzonite, grantite, granodiorite or gneiss). The forest vegetation is dominated by Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), fir (*Abies* sp.), pine (*Pinus* sp.), & larch (*Larix* sp.), the major biogeoclinatic zones in the area being Interior Cedar-Hemlock zone and Engelmann Spruce-Subalpine Fir zone (BC Ministry of Forests 2000).

The landslide classification proposed by Varnes (1978) and Cruden & Varnes (1996) characterizes the set of investigated events as debris slides or debris flow; therefore, the focus of the present research was only on these type of events, as wells as the combinations of the two. The combination debris slide – debris flow was also considered in the analysis, as many of the observed events appeared to involve both processes; often an events started as a slide which subsequent changed to a flow-dominated movement. From the total of 582 events identified from air photographs by Jordan (2002), 571 were classified as debris slides, debris flows or combinations of the two. A stratified random sampling without replacement (Cochran 1977) was used to select 38 events (assuming a $\alpha = 0.05$ and a coefficient of variation according to Jordan (2002) of 35%). Stratification was used to account for variation in the nature and size of the events. The categories were chosen based of their possible influence on debris slide-flow travel distance: slope (Heim 1989, Cannon 1993, Hungr 1995, Lau & Woods 1997), geology – as an indicator of possible process (Finlay et. al. 1999, Corominas 1996), and event horizontal surface as an indication of length. Each event was surveyed by walking its entire length. The elements to be measured were determined based on their potential ability to influence debris flow travel distance (Table 1). From the 38 sampled events, 30 were used to develop the travel distance model and eight were used to test the model (the usage of an event in the de-

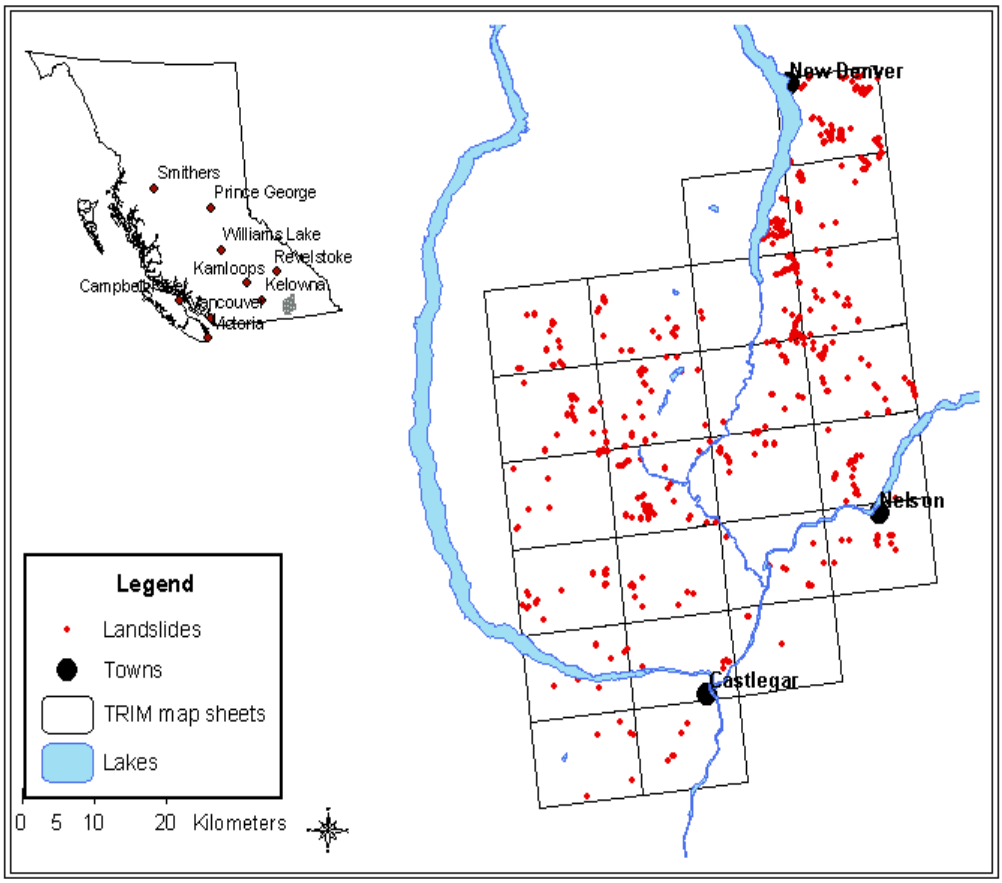

Figure 1 Study area

velopment or the testing phase was performed according to Snee (1977) recommendations, presented in the "Data analysis" section).

Defining the reach of a debris slide or debris flow

A central element in describing terrain variation along an event trajectory is the reach (Wise 1997). The present study defines a reach as a linear portion of the event trajectory, having the same geology, constant slope, azimuth, width, volumetric behaviour characteristics and confinement type. The variation of the attributes describing a reach that is location - dependent, and is defined using L_1 - space (Kolmogorov & Fomin 1999), namely the range of slope, azimuth and width. The limits of the attributes defining a reach were established using the recorded data, which ensures the homogeneity of the processes characterizing the debris flow – debris slide events within the area and are in agreement with the values of Innes (1983) or Fannin & Wise (2001): (i) the difference in slope or azimuth of two adjacent reaches should be at least 3° for the former and 20° for the latter, (ii) the length of the first or last (i.e., fan) reach should be greater than 10 m, (iii) the length of any reach, except the first and the last, should be greater than 25 m, (iv)

Table 1 Attributes measured for each event

Category	Element	Values
Vegetation	Stand composition	Composition expressed in % canopy closure (i.e. 90% Hemlock 10% Cedar)
	Canopy closure	Percentage from 0% to 100%, in 10% steps
	Average diameter of each species	Continuous (cm)
	Average height of each species	Continuous (m)
Geomorphology	Plan curvature	Plane, convex, concave
	Vertical curvature	Plane, convex, concave
	Type of reach	Entering, deposition or both
	Slope of the reach	In ° (degrees)
	Azimuth of the reach	In ° (degrees)
	Gully	Presence vs. absence
	Position on the slope	Top, middle, bottom
Geometrical	Length of each reach	Continuous (m)
	Width at the top part of the reach	Continuous (m)
	Width at the bottom part of the reach	Continuous (m)
	Depth of the top part of the reach measured at the ¼ of the width	Continuous (m)
	Depth of the top part of the reach measured at the ½ of the width	Continuous (m)
	Depth of the top part of the reach measured at the ¾ of the width	Continuous (m)
Risk	The event reaches the stream or not	Yes vs. No
Terrain state	Human activity	clearcut, road, absence

the maximum length of a reach should be less than 200 m, (v) the ratio between the lengths of two adjacent reaches should be greater than 20% and smaller than 500%, except when one is the fan. In such a case, the ratio should lie between 16% and 625%. This means that a reach cannot be five times longer or shorter than any adjacent reach, except when one of the reaches is the fan, (vi) the event stops when the slope is less than 18º. The stopping rule is established empirically, based on the available data; therefore, reflects the processes governing the terrain movement within a specific region, (vii) Similarly to length, azimuth and slope, the width of a reach expresses the lack of significant linear changes across the direction of event movement. An alternative to the linear dimension describing the width is the lateral angle of the trapezoid representing the cross-section of a reach, γ in Figure 2:

$$\gamma = \arctan \frac{W_{top} - W_{bottom}}{2 \times l} \quad (1)$$

where γ - lateral angle of the trapeze, W_{top}, W_{bottom} - width of the top and bottom of the reach, and l - slope length of the reach.

Based on the dataset, the criterion can be stated as: the width of a reach is considered uniform if the lateral slope angle is less than 15º, except for fan.

The set of seven criteria determined the trajectory of debris slide - flow. Additionally, the mass movement processes in an event were assumed to be the same along a reach, and all multi-reaches events occurred within mature forest stands, except, possibly, for the first and last reach.

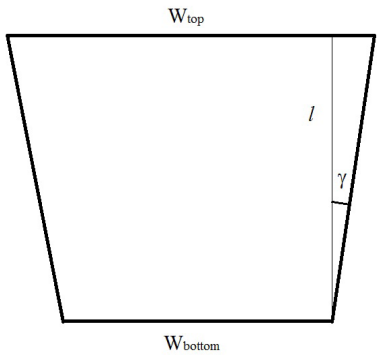

Figure 2 Lateral angle (γ) of a reach with trapezoidal shape

Defining the path of a debris slide or debris flow as a variable

The profile of an event plays a crucial role in the travel distance of any mass failure, as it integrate the morphology of the hillside within the dynamics of the terrain movement (Takahashi 1991). Therefore, the quantification of the profile could increase the prediction accuracy, when included in the models used to express the travel distance of the terrain failure. A possible quantification of the profile can be performed by representing the succession of reaches along trajectory of debris slide - flow using the binary set {0,1}, which could describe the profile as a single number. The quantification of terrain variation along the path of debris slide-flow event based on binary set uses the correspondence between any two numeration systems, namely the theorem that the transformation from one numeration system to another is a bijective function (Creangă 1965). The representation of the trajectory of an event as a series of 0 and 1, and the unique transformation from binary to decimal system ensures not only the quantification of the event longitudinal profile but also the computational compatibility of different attributes describing the mass movement.

The profile of an event uses the values of the binary system {0,1} to describes each reach according to its neighbouring reaches. The focus of the description of the set of successive reaches is to explain the variability along the event path, namely the morphologic variation of the hillside on which the event occurred. The idea behind the usage of 0 or 1 in describing the variation of hillside morphology is that sections of an event (i.e., reaches) that increase the likelihood of maintaining the event movement should be represented by larger values than sections that could terminate the event. Consequently, as the first reach exhibits a mass movement larger than its surroundings, it is represented by the value 1. The remaining reaches obeyed the rule that the reach had the value 0 if the slope of the reach immediately above was greater (i.e., the likelihood of event termination increases), and 1 if the opposite held (i.e., the chance of event maintenance increases). In eventuality that the event ended in a stream, the end of the hillside, there was no value assigned to the reach containing the stream. For example, the event in Figure 3 has the following slopes: Reach 1: 33º, Reach 2: 28º, Reach 3: 33º and Reach 4: stream. The lack of representation of the stream for events ending in a stream (i.e., no value for the stream, which is the final reach) is related to the absence of any element of variability in the hillside morphology associated with the stream (i.e., the stream is not a part of the hillside; therefore, no binary representation is needed). The binary coding for the event in Figure 3 is 1 0 1. The succession of 1s and 0s follows the ideas that an increase in variability is associated with 1, while a decrease with 0; consequently, the first 1 is for the first reach, the 0 is for the second reach, as its slope is less than that of the first, and the last 1 is for the reach that has a slope greater than the slope of the second reach.

Binary coding obtained in this way was transformed into the decimal system to be interpreted with the remaining variables. As the binary system identifies each event path based on reaches, two different debris slide-flows were always represented by two different num

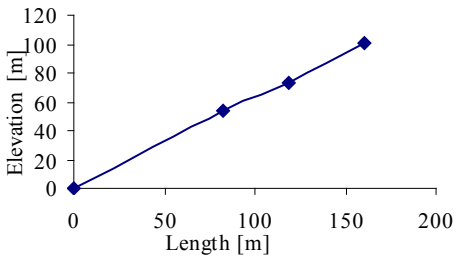

Figure 3 Longitudinal profile of event 52-13

bers (Fig. 4). The coding explains the variation from two perspectives, slope modification along the path (based on the binary coding), and changes in flow direction (expressed by azimuth) along the path (based on reach characterization). The slope variation explained by the binary coding also crudely characterizes the energy variation along the debris slide-flow path, as increase in slope (i.e., increase in the available kinetic energy) is associated with 1, which would lead to a larger binary number than for a decrease in slope.

A new reach, identified as a change in the azimuth, was considered at the energetic level as an increase in kinetic energy of the mass movement, irrespective the slope change (i.e., increase or decrease). A new reach leads to a larger number in the binary coding and consequently in the decimal system, consistent with the energetic variation of the event. The variable describing the path, which quantifies the hillside morphology, was dependent only on the terrain (i.e., slope and azimuth), as its value represents the terrain variation along the trajectory of the debris slide-flow from the perspective of the processes of interest.

Data analysis

The hillside morphologic attributes considered as having a possible impact on debris slide – debris flow travel distance were path, slope, azimuth, plan and profile curvature, and position on the slope, consistent with Takahashi (1991) and Selby (1993). It was hypothesized that there is a significant relationship between the debris slide-flow travel distance and hillside morphology, geology, tree species, stand characteristics, canopy closure and soil attributes, with hillside morphology being the most important attribute describing the run-out. The soil attributes included in investigation were granulometry, fine particle content, and specific gravity. The average height and diameter at breast height of the forest stand at the initiation point (first reach) were used to indicate stand characteristics that could influence event travel distance (e.g. root strength and structure, stand mass etc). The height and the diameter at breast height of the stands crossed by an event were not measured, except

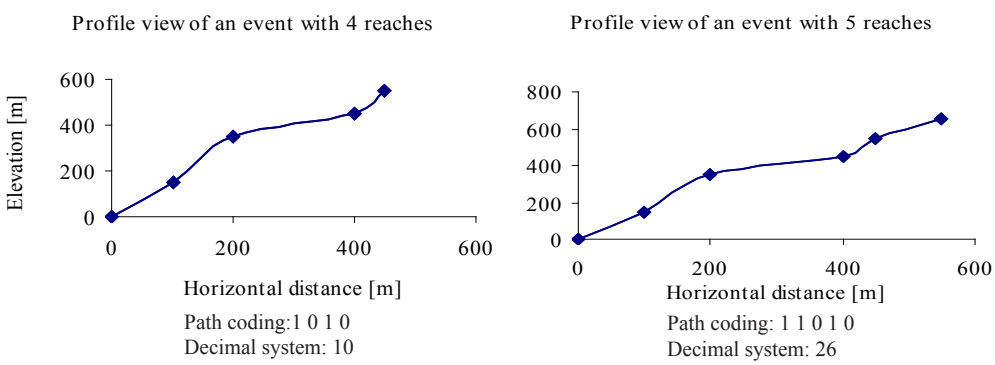

Figure 4 Two different debris slide-flows coded by two different numbers

the presence or absence of mature forest. All events occurred within well established stands, with the first reach or the fan possible being on a clearcut or beside the road.

The underlying assumption of the investigation was that the mass movement travel distance could be explained by mass movement attributes. This assumption requires that the attributes describing the event completely portray the behaviour of the movement in time and space. However, the exhaustive description of an event travel distance is not only impossible but also does little in providing significant information gain when a large number of attributes are considered. The selection of the attributes playing a significant role in describing the mass movement depends on the set of attributes considered in a study (Neter et al. 1996), as one set could lead to some significant attributes while another set could lead to a different group (e.g., slope, gully profile and soil granulometric properties lead to one result, while slope, species and terrain curvature lead to a different result, not necessarily wrong). The set of attributes used in the present study was consistent with previous studies which considered slope and volume (Corominas 1996), volume and obstruction length (Megahan & Katcheson 1996), slope, transverse radius of channel curvature, and volume (Cannon 1993), or slope and height of failure (Finlay et al. 1999). Some studies have also considered rheological attributes, besides descriptors of hillside morphology, such as horizontal interslice force, horizontal stress, deformation energy, dynamic friction coefficient or uplift pressure (McLellan & Kaiser 1984, Fang & Zhang 1988, Miao et al. 2001). However, rheological attributes were not included in the present study, as commonly they are insignificant when used in conjunction with the common hillside morphology descriptors (such as slope or exposition). The set of attributes used in present investigation enhanced previous studies by considering a wider set of descriptors of the hillside geomorphology as well as the ecosystems located on the hillside: (i) geomorphology: introduction of a succession of different slope angles along the event trajectory (i.e., path), terrain curvature and position on the slope, (ii) vegetation: introduction of species structure, stand characteristics (average height and diameter), (iii) geometry of an event: depth at ¼, ½ and ¾ of the width.

The field measurements assumption that governs most landslide investigations is that the attributes do not change from the moment of occurrence until the moment when their value is measured. The measurement assumption is crucial; as it is consider that the initiation point of a landslide occurs at the highest elevation point (the extent of backward erosion of the head scarp following the initial failure is generally unknown, especially in failure planes involving unconsolidated sediments). Additionally, it was assumed that the unconfined event path follows the greatest slope trajectory. In the case of debris flows, local elements can influence the event trajectory dramatically, as event path might violate the latter assumption (e.g., a large rock or a tree can deflect the landslide trajectory in a direction that does not have the greatest slope). However, after such a point is passed, the trajectory follows the steepest slope.

The attributes with a significant impact on event travel distance were selected using stepwise, backward and forward methods, with a significance level $\alpha = 0.05$ (Neter et al. 1996), whereas the significance level used in past debris flow studies has varied from $\alpha = 0.2$ (Wise 1997) to $\alpha = 0.05$ (Megahan and Ketcheson, 1996). The ordinary least square estimators were used to identify relationships between dependent (i.e., travel distance) and independent variables (Table 2). The ordinary least square estimation method provides the smallest confidence intervals for the predicted values if all assumptions are fulfilled (Ciucu 1963, Mihoc & Firescu 1966).

The model was developed to fulfill all the regression analysis assumptions: i.e. normal dis-

Table 2 Pearson's correlation coefficients between debris flow-debris slide travel distance and selected attributes of the hillside. Null hypothesis H_o states that there is no relationship between the attribute and event travel distance

Variable	Coefficient of correlation	$Pr > F$	H_O
Path variable	0.36	0.0001	Rejected
Average slope	0.03	0.3	Accepted
Fan slope	0.02	0.39	Accepted
First reach slope	0.002	0.76	Accepted
Initial volume	0.02	0.46	Accepted
Azimuth	0.07	0.1	Accepted
Position on slope	0.07	0.1	Accepted
Plan curvature	0.06	0.34	Accepted
Profile curvature	0.02	0.64	Accepted
Terrain curvature - plan and profile curvature (separate)	0.08	0.56	Accepted
Terrain curvature - plan and profile curvature (interacting)	0.45	0.01	Rejected
Species	0.04	0.67	Accepted
Stand height	0.13	0.027	Rejected
Stand diameter	0.13	0.025	Rejected
Canopy closure	0.001	0.84	Accepted
Geology	0.05	0.39	Accepted
Particle side distribution (PSD) type	0.02	0.72	Accepted
PSD grading	0.12	0.11	Accepted
Soil fine particle content	0.08	0.08	Rejected
Soil specific weight	0.02	0.35	Accepted
Terrain state	0.02	0.62	Accepted

tribution of errors, homoscedasticity of errors, and independence of observations. In addition, the model had to be free of multicollinearity, and the outliers of the dependent or independent variables should be individually investigated. The normal distribution of errors was assessed using Kolmogorov-Smirnov and Shapiro-Wilk tests (Craiu 1998, Conover 1999), while White's test (White 1980) was used to test for heteroscedasticity. Outliers with a significant impact on the ordinary least square estimators can lead to unrealistic models (Montgomery & Dietrich 1994); therefore, Studentized-deleted residuals were used to identify outlying values of the dependent variable (Belsley et al. 1980), while hat matrix leverage and COVRATIO (Belsley et al. 1980) were used to identify outliers present in the independent variables. The influence of all events identified as possible outliers was tested using DFFITS, Cook's distance measure and DFBETAS (Neter et al. 1996). Influential outliers that were not obviously erroneous required further examination, as such cases could provide information about the adequacy of the model (Journel 1983). The final decision over the data set structure was made using robust regression (Rouseeuw & Leroy 1987, Hoaglin et al. 1985), using the iteratively re-weighted least square method.

The data set was divided into a subset used to build the model the estimation data, and a subset used to test the model the validation data, following Snee (1977) recommendations. Events identified as outliers and eliminated from the estimation data were included in the validation data. In eventuality that the incorrectly estimated events from the validation dataset lead to larger than the preset significance level, then the model was rejected and the modeling process was repeated starting with new transformed variables.

Results

The debris slide-flow events varied from small-

scale (192 m^3 - event 73-18) to medium scale (36,446 m^3 - event 61-10), according to Innes (1983) classification. Slope lengths varied from 25.8 m to 1341.7 m. This level of variation suggested that regression analysis could be used to analyze the data (Demaerschalk & Kozak 1974, 1975).

From the set of variables selected initially (Table 2), four were correlated with debris flow – debris slide travel distance: path of the event, terrain curvature (expressed by the combination of plan and profile curvature), height and diameter at breast height of the dominant and codominant trees. Besides the set of four variables, another three, which were not significantly correlated with debris flow – debris slide travel distance, were included in the analysis, but in a transformed form: azimuth, slope and canopy closure. The inclusion of the insignificantly correlated variables with the travel distance in the final model was required to fulfill the regression analysis assumptions. Azimuth expresses the humidity regime associated with different exposures: northerly aspects having wet regimes, southerly exposures having dry regimes, and easterly and westerly exposures having intermediate regimes. A cosine function was chosen as it reflects the hydric regime associated with each exposition: for cases of 0 or 360° (north) its value was 1; for cases of 180° its value was –1 (south); and for cases of 90° or 270° (east and west) its value was 0. Slope at the initiation point was transformed using a sine function, as the sine function can address the variation in elevation. Simple linear regression revealed that there was no significant correlation between the debris flow travel distance and canopy closure. Various attempts to derive an appropriate transformation indicated that a suitable function for improving the relationship between debris flow traveldistance and canopy closure was 1/(k+0.01), where *k* is stand canopy closure.

The range of values of stand height, from 0 to 50 m, was one order of magnitude larger than the values of transformed azimuth (from –1 to 1), which questions the validity of comparison among coefficients of different variables (Bernstein et al. 1987). A further transformation of stand height was therefore undertaken, as linear transformations leave the colinearity diagnostics little altered (Belsley et al. 1980). The new height variable was, (h+1)/Φ, where *h* is stand height at the first reach.

The number 1 was added to avoid zero values for the new variable, while the number 10 was selected as reduces the magnitude of height to the azimuth values and supplyes the highest correlation coefficient with debris flow travel distance. The final set of predictor variables considered in model development using regression analysis contains: (i) transformed path variable $(\log(\sqrt{path}+1)^{1.2}$ where path is the decimal representation of the event's trajectory based on binary set, (ii) transformed azimuth: $(\cos(\text{azimuth}))^5$, (iii) transformed variables representing the interaction between slope of the first reach and stand's height: $[(h + 1)/10]^5$ x (1 + sin(slope)), (iv) interaction between plan and profile curvature and transformed canopy closure.

The last variable was a combination of categorical and continuous variables. The quantification of the categorical variables used a binary logic system. This composite variable led to a set of eight variables (Table 3).

The main rock types on which the sampled events occurred were granite, gneiss and fine sedimentary. To assess the impact of hillside morphology on travel distance, the estimation data set contained events that occurred on granite and gneiss and the validation data set had events occurring on fine sedimentary rocks. The lack of consistency between the estimation and validation data could bias the model, however, the analysis of variance of the entire dataset did not indicate that geology has a significant impact on travel distance (p = 0.65). The distinction between the estimation and validation dataset in term of geology should confirm the hypothesis that the most important variability describing the travel distance of a

Table 3 The variables representing the interaction of plane curvature, profile curvature and canopy closure (k). The combination plane –plane, abbreviated "pp", is represented by values of 0 (i.e., the case when all other curvatures are not possible), to avoid the singularity of the matrix used by the leased square method

Variable codification	Plan curvature			Profile curvature			Variable value
	Con-cave	Con-vex	Pla-ne	Con-cave	Con-vex	Pla-ne	
CvcV	1	0	0	1	0	0	if plane curvature is concave and vertical curvature is concave then the variable has the value 1/(k+0.01) else is 0
Cvcx	1	0	0	0	1	0	if plane curvature is concave and vertical curvature is convex then the variable has the value 1/(k+0.01) else is 0
Cvp	1	0	0	0	0	1	if plane curvature is concave and vertical curvature is plane then the variable has the value 1/(k+0.01) else is 0
Cxcv	0	1	0	1	0	0	if plane curvature is convex and vertical curvature is concave then the variable has the value 1/(k+0.01) else is 0
Cxcx	0	1	0	0	1	0	if plane curvature is convex and vertical curvature is convex then the variable has the value 1/(k+0.01) else is 0
Cxp	0	1	0	0	0	1	if plane curvature is convex and vertical curvature is plane then the variable has the value 1/(k+0.01) else is 0
Pcv	0	0	1	1	0	0	if plane curvature is plan and vertical curvature is concave then the variable has the value 1/(k+0.01) else is 0
Pcx	0	0	1	0	1	0	if plane curvature is plane and vertical curvature is convex then the variable has the value 1/(k+0.01) else is 0

mass failure is the hillside variable not geology or slope. Therefore, the validation dataset contains events with travel distances within the range of the travel distance of events from the estimation data, irrespective geology on which event occurred. The debris flows - debris slides in the estimation data had travel distances ranging from 25.8 m to 1341.7 m, while the validation data set contained events with travel distances ranging from 43.3 m to 131.6 m, ensuring the inclusion of the validation dataset in the estimation dataset, from the travel distance perspective. The dataset separation led to 30 events (on granite and gneiss) in the estimation data set and eight events (on fine sedimentary) in the validation data set.

The simple linear regression revealed that the variable quantifying slope morphology had a significant impact on travel distance ($p < 0.001$), with a correlation coefficient larger than any other attribute ($r^2 = 0.68$), consistent with other studies (Corominas 1996, Finlay et al. 1999). Several studies have stressed the influence of the initial volume on debris flow – debris slide travel distance (Fannin & Wise 2001, Wise 1997, Fannin & Rollerson 1993). A restriction imposed by these studies was the consideration only of events that did not end in streams. Present research enhanced these results by including events that both ended and did not end in streams, and found that, when events that did not stopped on the hillside are

incorporated in the analysis, there was no correlation between volume at the initiation point and debris flow –debris slide travel distance. For 55% of the events that started on the lower part of slope, the initial volume was greater than 40% of the volume of the whole event. Events that started on the lower part of slope had a short length, as the termination point (in some cases the stream) was usually close to the point of initiation. Regardless of the movement type (i.e., slide or flow) and position on the slope, events that involved a large part of their volume in the first reach generally did not have a long path.

Subsurface water flow tends to vary according to slope position: the closer to the top of the slope, the smaller the quantity of water moving through the soil (Viessman & Lewis 1996). In the Arrow Forest District, this is not always the case, as there could be significant water flow seeping from shallow slopes above the main valley. This has been identified as a management problem, especially where road construction has concentrated the subsurface flow (Jordan 2002). Increased water flow through the undisturbed soil increases the pore water pressure and therefore the effective stress is reduced (Terzaghi 1943, Kenney 1984, Powrie 1997). However, there was no correlation between the debris flow – debris slide initiation point on the slope and debris flow travel distance (Table 2), as a significant number of short events initiated mid-slope, as well as 67% of the mid-slope events were less than 100 m long.

Terrain curvature influences the local hydrological conditions (Viessman & Lewis 1996). As the index of terrain curvature that was used in this study only characterized the first two reaches, it was unlikely that any correlation with the debris slide-flow travel distance would be significant (Table 2). However, the interaction between plane and profile curvature was significantly correlated with debris flow travel distance, suggesting that in combination with the variable describing hillside variability the local curvature of the first two reaches significantly influenced travel distance.

The vegetation plays an important role in the occurrence of the mass failure. However, the data does not support a similar conclusion for the travel distance, as no correlation was observed between stand parameters (i.e., diameter at breast height or average height of the dominant/co-dominant trees) and debris flow – debris slide travel distance. Stand characteristics likely have a reduced impact on event dynamics once a failure occurred, which does not contradict the findings of other studies that found that these characteristics can influence the probability of terrain failure (Traci 1985, Watson et al. 1994).

Rheological studies have stressed the importance of soil granulometric properties on terrain stability (Terzaghi 1943, Innes 1983, Hungr et al. 1984, Takahashi 1991, Iverson 1997). The dataset presented a relatively constant particle size distribution along path of the event, regardless the position of the soil profile used to represent local granulometry in respect with the event (i.e., inside or outside), mainly sand, sand-gravel or gravel. The results show that the type and grading of particle size distribution did not have a significant influence on the debris flow travel distance (Table 2). However, soil fine particle percentage had a significant influence on event travel distance ($\alpha = 1$), which is in agreement with theoretical soil mechanics studies (Iverson 1997, Powrie 1997).

Logging activities could have a significant impact on debris flow – debris slide initiation and travel distance (Fannin et al. 1996, Sidle & Wu 1997). The dataset used to build this model contained only events that passed through unharvested stands, with the exception of the first reach. For these events, the forestry related activities in the first reach seems to have little influence on debris flow – debris slide travel distance (Table 2). This is consistent with the idea that logging activities (such as clearcutting or roads) influence the initiation of the

mass movements, but do not have a significant influence on the travel distance of the event over un-logged terrain.

The tests used to identify and assess outliers revealed that four events within estimation dataset are influential outliers. Further investigation showed that they did not fulfill the reach definition and they were eliminated from analysis. Consequently, the model was built using 26 events. The regression equation supplied by backward selection procedure was:

$$L = -140.35 + 257.42 \times \log(\sqrt{path} + 1)^{1.2} + 0.03 \times \left(\frac{h+1}{10}\right)^{5} \times (1 + \sin(slope)) + 43.65 \times \cos(azimuth)^{5} + curvature + e \quad (2)$$

$$Curvature = 0.34 \times cvcv + 0.21 \times cvcx - 8.47 \times cvp + 212.1 \times cxcv - 42.63 \times cxcx + 11.75 \times cxp + 0.68 \times pcv + 20.52 \times pcx \quad (2')$$

where L is the slope length of the event and e is the residual.

The regression model fulfilled all the assumptions and requirements needed for prediction. The forward and stepwise selection procedures supplied similarly results, as all predictor variables identified by backward procedure as significant were selected, but the interaction between slope and stand's height. However, the models identified by the forward and stepwise procedures were not considered because the final equations did not fulfill all the regression assumptions (i.e. normality), regardless the variable selection method. The model (2) predicted seven of the eight events correctly, within the established confidence limits (Table 4). The regression was also tested on the four events eliminated as outliers and influential cases, and predicted one of them correctly.

Discussion

The positive coefficient of the variable expressing the interaction between slope and stand height at the first reach is consistent with the physics of mass movements: the increase in slope is reflected by an increase in travel distance (Newton et al. 2002). However, the positive correlation between debris flow – debris slide travel distance and stand height at the first reach indicated that the greater the stand height, the greater the travel distance. Where the initiation point was surrounded by forest cover (canopy closure greater than 0.5), the water quantity required to initiate mass movement is greater than if no vegetation was present (Selby 1993). Therefore, for the same event path, travel distance would be greater for debris slides-flows starting within a stand than for those starting in a clearcut, as initiation conditions are more difficult to be achieved in forested terrain than in clearcuts (Sidle et al. 1985, Greenway 1987), but once triggered, the movement would be faster as more water is stored within the soil matrix.

The positive coefficient for the variable expressing the aspect indicated that events with a northerly exposure had travel distances larger than those with a southerly exposure. Different water regime associated with the two exposures were probably responsible for the distinction in travel distance, as southerly faces have a more active evapotranspiration than northerly faces, therefore less water available.

There are two variables with negative coefficients, namely *cvp* and *cxcx*, which suggest that profile curvature controls the change in length of the event (i.e., increase or decrease), whereas the combination of profile and plan curvature controls the magnitude of the change (i.e., larger or smaller). This suggests that variation of the energy of an event is controlled by the profile curvature rather than the plan curvature, consistent with hydrology along the path as concave shapes have a wetter regime than plan or convex ones (Powrie 1997). This wet regime is a significant element in debris flow triggering as well as travel distance (Takahashi

Table 4 Confidence limits of predicted travel distance for the validation data set and the four outliers (the outliers are identified by the presence of the word "Outlier")

Lower confidence limit (m)	Predicted value (m)	Upper confidence limit (m)	Actual value (m)
131.6	267.3	403.1	1169.6 Outlier
1308.9	1554.7	1800.5	1341.7 Outlier
458.3	605.2	752.0	915.1 Outlier
161.2	283.2	405.3	91.6 Outlier
-58.8	61.5	181.9	115.0
39.8	149.4	259.0	98.7
-71.9	51.9	175.6	131.6
-63.4	31.7	126.9	102.9
-34.0	65.4	164.8	120.0
-63.7	32.3	128.4	135.0
-60.7	34.4	129.6	43.3
-16.7	148.7	314.0	116.0

1991, Selby 1993).

The variable quantifying the path of an event integrates the processes associated with the terrain mass movement with the hillside morphology. The significance of the hillside morphology on travel distance is reflected by the coefficient of correlation between the two variable ($r^2 = 0.36$), one order of magnitude larger than any other attribute, except terrain curvature (Table 2). Only one other variable has a coefficient of correlation larger than the one associated with the path variable, namely the terrain curvature ($r^2 = 0.45$), more specifically the interaction between the plane and profile curvature. Both path variable and terrain curvature describe the hillside morphology, which indicates that the most important attributes determining the length of a terrain mass movement is driven by the variation of the hillside rather than either detailed descriptors of the soil or vegetation, or general descriptor of the hillside (such as slope or azimuth). The importance of the variable describing the path in determining the travel distance was confirmed by the equation 2, who did not found as significant neither the average slope nor the initial volume, two of the mot used variables in predicting the length of the terrain mass failure. The findings of the present study indicate that the focus of the terrain failure investigations should be in identifying the initiation point and the hillside variability bellow the initiation point, as the magnitude of a landslide is determined by two sets of attributes, not necessarily related or overlapping; one associated with the initiation and one with the travel distance.

Conclusion

A travel distance model for debris flows and slides is presented, based on information collected in southeast British Columbia, Canada. The model incorporates a variable that represents terrain morphology by a single number, quantification made using a one-to-one correspondence between the binary and decimal numeration systems. The terrain morphology coding has a site-specific character, providing a process-based representation of local conditions. A newly-designed variable describing the event path enabled this model to include events ending in streams and those that did not. This created more flexibility, with two effects on travel distance prediction. Firstly, the model considered events that conformed to the real terrain variation and which did not impose any restriction based on the termination point. Secondly, examining both types of events simultaneously (i.e. events that ended in stream and

events that did not ended in stream) enabled the sample size of the estimation data set to be increased, and consequently the confidence interval of the predicted length was narrower.

Multiple regression analysis was used to assess the dependence of event travel distance on terrain morphology, slope, stand height, terrain curvature and canopy closure ($R^2 = 0.975$, $p < 0.001$). The model fulfills all the assumptions and requirements of regression analysis (i.e. normality, homoscedasticity, non-correlated errors, lack of colinearity or outliers). An independent data set was used to test the model. The model successfully predicted all but one of the test dataset events, and one of four outliers. The model consists of an equation that can be used in mass movement risk assessment associated with different forest activities (e.g. harvesting, road building).

The variable representing the terrain morphology by a single number allows integration of the hillside variability into computation in a similar manner to the most common attributes used to describe hillside, such as slope, exposition or vegetation size. The flexible character of the binary coding, determined by the processes characterizing local mass movements, captured the terrain variation for each specific site, which makes new variable describing the hillside variability suitable to any type of terrain variation.

The model for travel distance can be linked to suitable initiation models that can provide a better assessment of the risk associated with debris flow-debris slides. Quantification of the risk associated with terrain failure is an important part of the forest planning, as forest operations (e.g. road building, harvesting) are associated with risk of mass movements.

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