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Landslides
Journal of the International
Consortium on Landslides

ISSN 1612-510X

Landslides
DOI 10.1007/
s10346-011-0282-8

Landslides
DOI 10.1007/s10346-011-0282-8
Received: 30 June 2010
Accepted: 12 July 2011

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Abstract Engineered (structural) debris-flow mitigation for all creeks with elements at risk and subject to debris flows is often outside of the financial capability of the regulating government, and heavy task-specific taxation may be politically undesirable. Structural debris-flow mitigation may only be achieved over long (decadal scale) time periods. Where immediate structural mitigation is cost-prohibitive, an interim solution can be identified to manage residual risk. This can be achieved by implementing a debris-flow warning system that enables residents to reduce their personal risk for loss of life through timely evacuation. This paper describes Canada's first real-time debris-flow warning system which has been operated for 2 years for the District of North Vancouver. The system was developed based on discriminant function analyses of 20 hydrometric input variables consisting of antecedent rainfall and storm rainfall intensities for a total of 63 storms. Of these 27 resulted in shallow landslides and subsequent debris flows, while 36 storms were sampled that did not reportedly result in debris flows. The discriminant function analysis identified as the three most significant variables: the 4-week antecedent rainfall, the 2-day antecedent rainfall, and the 48-h rainfall intensity during the landslide-triggering storm. Discriminant functions were developed and tested for robustness against a nearby rain gauge dataset. The resulting classification functions provide a measure for the likelihood of debris-flow initiation. Several system complexities were added to render the classification functions into a usable and defensible warning system. This involved the addition of various functionality criteria such as not skipping warning levels, providing sufficient warning time before debris flows would occur, and hourly adjustment of actual rainfall vs. predicted rainfall since predicted rainfall is not error-free. After numerous iterations that involved warning threshold and cancelation refinements and further model calibrations, an optimal solution was found that best matches the actual debris-flow data record. Back-calculation of the model's 21-year record confirmed that 76% of all debris flows would have occurred during warning or severe warning levels. Adding the past 2 years of system operation, this percentage increases marginally to 77%. With respect to the District of North Vancouver boundaries, all debris flows occur during Warning and Severe Warnings emphasizing the validity of the system to the area for which it was intended. To operate the system, real-time rainfall data are obtained from a rain gauge in the District of North Vancouver. Antecedent rainfall is automatically calculated as a sliding time window for the 4-week and 2-day periods every hour. The predicted 48-h storm rainfall data are provided by the Geophysical Disaster Computational Fluid Dynamics Centre at the Earth and Ocean Science Department at the University of British Columbia and is updated every hour as rainfall is recorded during a given storm. The warning system differentiates five different stages: no watch, watch level 1 (the warning level is unlikely to be reached), watch level 2 (the warning level is likely to be reached), warning, and severe warning. The debris-flow warning system has operated from October 1, 2009 to April 30, 2010 and October 1, 2010 and April 30, 2011. Fortunately, we were able to evaluate model performance because the exact times of debris flows during November 2009 and January 2010 were recorded. In both cases, the debris flows did not only occur during the warning level but coincided with peaks in the warning graphs. Furthermore, four debris flows occurred during a warning period in November 2009 in the Metro Vancouver watershed though their exact time of day is unknown. The warning level was reached 13 times, and in four of these cases, debris flows were recorded in the study area. One debris flow was recorded during watch II level. There was no severe warning during the 2 years of operation. The current warning level during the wet season (October to April) is accessible via District of North Vancouver's homepage (www.dnv.org) and by automated telephone message during the rainy season.

Keywords Rainfall-induced landslides · Debris flows · Warning system

Introduction

Landslides worldwide result in thousands of deaths and several billion dollars in damage. In the USA, landslides are responsible for an estimated 25 to 50 deaths and direct damages to the economy of approximately $3 billion annually (Schuster and Highland 2001). While the number of deaths pales in comparison with other fatal causes, the costs to the economy are significant.

In Canada, an estimated 200 people have lost their lives due to landslides between 1880 and 2007, resulting in an average of two persons per year (Hungr 2004). This compares, for example, to some 550 murders or approximately 3,000 deaths by vehicle accidents annually. Estimated annualized economic losses in western Canada alone range between $28 and $64 million and landslide prevention between $26 and $71 million, for a total of $54 to $97 million (Hungr 2004). Per capita loss due to landslides in British Columbia has been estimated by Hungr (2004) at $7 to $33, or an equivalent to 0.2% GNP. While these numbers are relatively low compared to many other hazards that any given individual faces daily, landslide hazards are significant, particularly in densely developed urban environments. The extreme media hype that followed the January 2005 fatal landslide in North Vancouver demonstrated that a simple quantification of landslide hazard and risk by comparative statistics does not do justice to the social response to landslides in urban environments.

Of all landslide types, debris flows are the most hazardous due to their long travel distances, the impossibility of forecasting their exact timing and location, and relatively frequent occurrence in mountainous terrain. Within the District of North Vancouver (DNV), debris flows have been identified as a significant hazard because several communities are located on colluvial fans, landforms that have been created by debris flows over time. Fortunately, nobody has yet been killed by debris flows in the district; however, due to population pressures, urbanization continues to penetrate into increasingly marginal lands including areas subject to landslide hazards. In many instances, the hazard had not been recognized during earlier development phases, and hazard avoidance is no longer an option for those lands.

Kerr Wood Leidal Associates (KWL) (2003a) identified a large number of potential debris-flow creeks. These creeks were prioritized based on consequence and detailed studies were carried out for the 10 highest priority creeks. Debris-flow hazard maps were generated based on modeling and detailed field work (Kerr Wood Leidal Associates (KWL) (2003b)). BGC Engineering Inc (2009) conducted a quantitative risk analysis for the ten high-risk debris-flow sites.

The 2003 KWL report proposed conceptual designs for debris-flow mitigation at the ten highest priority creeks that amounted to a total of $ 27 million (2003 dollars). Given the approximate 30% increase in construction costs that have taken place since the 2003 report was issued plus inflation, the total will likely have increased beyond some $ 40 million by 2011. This capital expenditure is well above the district's budget for hazard mitigation in any given year. In addition, a recent web-based poll administered by the district showed that most residents oppose geohazard expenditures in excess of $1 million per year (note, this includes all geohazards including liquefaction, wind hazards, wild fire hazards, tsunamis, and all landslide types). This prompted the district to examine an alternative to structural measures, which, in the case of debris flows, could partially be achieved by a warning system until such time as structural measures can be implemented.

In the last 5 years, southern British Columbia has seen an unprecedented development boom that continues despite the global financial crisis in 2008/2009 and the associated weak US housing market unabated at the time of publication of this paper. Given the topographic constraint of the mountainous region to the north of Vancouver and the ocean to the west and expansive floodplains of Fraser River threatened by river and sea-born floods, land suitable for residential development and free from geohazards is scarce (Fig. 1). The North Shore Mountains rise quickly from the Fraser lowlands and are characterized by numerous steep channels incised in bedrock and glacial drift. Many of these channels are capable of producing debris flows that can travel up to several kilometers downslope and affect infrastructure and urban development along their flow path and runout area.

Many debris-flow prone areas have been developed prior to recognition of the debris-flow hazard and due to the extremely high property prices; acquisition of those properties subject to debris-flow hazard exceeds the cost of structural mitigation measures. Several consulting reports, however, have identified and at least partially quantified hazard and risk on debris-flow prone streams with homes at risk. Therefore, ignoring the hazard is not considered an option by the District of North Vancouver, which has developed the most

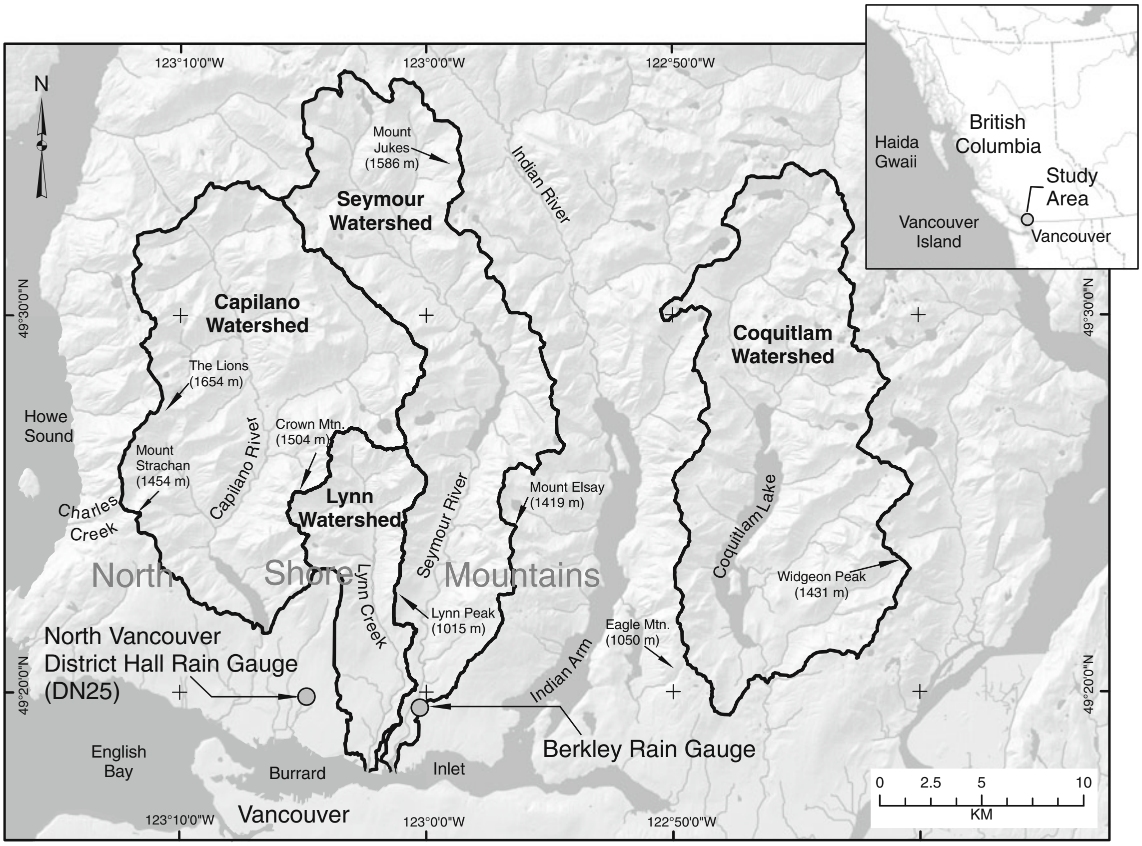

Fig. 1 Study area map showing the locations mentioned in this paper

comprehensive geohazard and risk assessment process fully accessible to the public of any municipality in Canada.

Reliable prediction of landsliding occurrence based on climatic thresholds has been accomplished in numerous countries and has been described in many publications that have been discussed, for example, in Wieczorek and Glade (2005) and Guzzetti et al. (2007, 2008). A large number of researchers have used rainfall intensity–duration curves and plotted rainfall data from landslide-producing and non-producing storms. Envelopes or separating lines were drawn to extract the intensity–duration data that allows classification of a storm to be either debris-flow producing or not. This particular method does not lend itself to application for a real-time debris-flow warning system in North Vancouver because the thresholds for debris-flow initiation would occur numerous times per year. During the rainy season (October to April) of the 10-year period 2000 through 2009, rainfall intensities of greater than 5 mm/h the lower envelope of debris-flow initiating rainfall intensity at the one hour duration occurred 228 times. This would result in an annual average of 23 warnings per year. Furthermore, debris-flow triggering landslides and non-debris-flow triggering storms plot on top of each other and are thus not suited to discriminate one group from the other (Fig. 2).

The principal objectives of creating a real-time debris-flow warning system were:

- Create several progressive levels of warning that can be understood by the public.
- Provide sufficient time for residents who wish to evacuate between the warning level and the likely time of debris flows.
- Minimize the likelihood of debris flows during the watch and no watch levels so that residents who evacuated could safely return to their homes.
- Allow real-time access via the internet and telephone.
- Minimize the risk of system outage, particularly during severe events.

It is important to realize that a real-time debris-flow warning system is thus different from a debris-flow prediction system in that the exact time of debris-flow occurrence is not the driving variable. Rather, a time period during which debris flows are likely needs to be identified with a high degree of confidence.

Landslide and debris-flow warning systems

Several landslide and debris-flow warning systems have been designed and implemented worldwide. Table 1 summarizes a selection of those systems and provides some commentary.

Study area

The study area encompasses the North Shore Mountains of Vancouver including Indian Arm, the eastern slopes of Howe Sound, and the watersheds of Capilano River, Seymour River, Lynn Creek, and Coquitlam River (Fig. 1). The North Shore Mountains are typical of the Coast Mountains of mainland British Columbia. Elevations range between sea level and 1,500 m. Because of a strong orographic effect, annual precipitation is extremely variable and ranges from about 1,300 mm/year near the ocean to over 4,000 mm/year at summit elevations. Slopes typically are overlain by shallow (<2 m thick) morainal and colluvial blankets that are prone to landsliding during the fall and winter when Pacific cyclones cause prolonged and orographically enhanced precipitation. These storms can last for several days and are often the cause of flooding in SW British Columbia. The associated landslide potential can be exacerbated by rapid rises in freezing level associated with warm fronts from the central Pacific. This scenario, where rain falls on wet autumn snow, usually occurs in November and December before the snowpack is of sufficient thickness to absorb much rainfall before releasing it to the underlying ground. Variation in mean daily discharge for Mackay Creek, a small watershed (2 km^2) located between Capilano River and Lynn Creek, is typical for small watersheds in coastal British Columbia. Discharge decreases from January to July followed by a sharp rise beginning in October. The highest discharges are observed during late October through late December, which coincides with the highest precipitation. Other peak discharges, observed during May and August, are often associated with isolated convective cells embedded in low pressure systems.

Methods

Data selection

The key to any successful debris-flow warning system are the adequacy and appropriateness of data on debris-flow occurrence

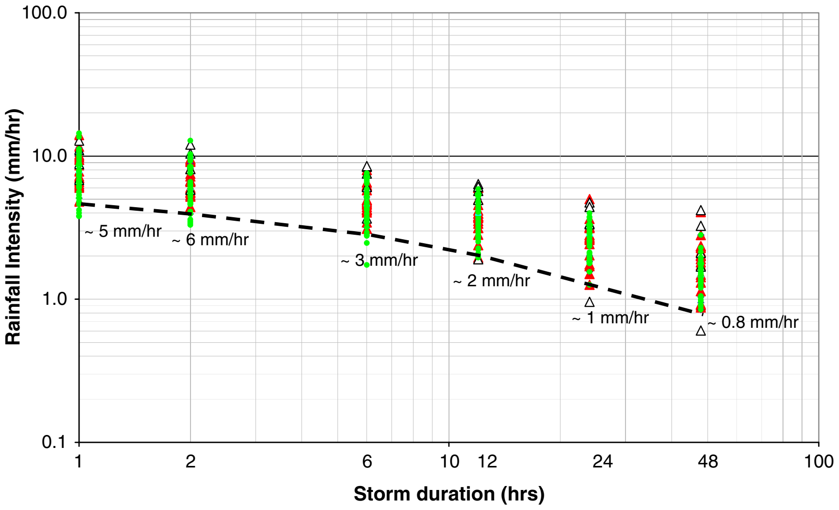

Fig. 2 Storm intensity–duration threshold for shallow landslides in the North Vancouver Mountains. The lower threshold is fitted by hand. *Red symbols* indicate storms that triggered landslides. *Green symbols* indicate storms that did not trigger landslides

Table 1 Select summary of debris-flow warning systems worldwide

Agency	Location	Model Type	Additional Information	References
NOAA-USGS	Southern California	System relied on forecasts and measurements of precipitation linked to empirical precipitation thresholds to predict onset of rainfall-triggered debris flows	Several debris-flow fatalities occurred which prompted NOAA and the USGS to collaborate in the development of a national debris-flow warning system that could issue timely warnings of potential debris flows to the affected population and civil authorities. The system is limited to rainfall-induced debris flows and flash floods in areas that have burned less than 2 years ago	NOAA-USGS Debris-Flow Task Force (2005)
State of Oregon, Department of Forestry, Department of Geology and Mineral Industries, National Weather Service, Oregon Department of Transportation, Oregon Emergency Management	Oregon	Empirical combination of antecedent moisture (since 2007) and rainfall intensities. Includes allowance for snow accumulation. Region-specific variances	ODF monitors rainfall and provides weather forecasts, consults with ODF specialists, and issues warnings when appropriate. debris-flow warnings are issued at the time of, or between 3 and 48 h prior to the anticipated arrival of precipitation significant enough to trigger debris flows. During the warning period, people in vulnerable locations are asked to take immediate precautionary actions. Warnings will be issued on a more conservative basis when the anticipated threshold exceedence occurs during darkness	Wiley (2000) Hinkle (personal communication, 2008)
USGS	Seattle	Predictive thresholds are based on cumulative 3-day and previous 15-day rainfall and a rainfall intensity threshold. System consists of real-time rainfall monitoring, soil moisture and pore pressure measurements, NWS quantitative precipitation forecasts, tracking of rainfall relative to the cumulative rainfall thresholds and a decision tree that guides the use of the thresholds to guide the warning levels	4 landslide warning levels. Null is defined by landslides being very unlikely; isolated slides may occur even during dry weather. An outlook is issued when cumulative threshold exceeded or forecast amounts of rainfall and estimated snowmelt are expected to exceed cumulative rainfall thresholds. A watch is issued when the probability of landslides has increased significantly because the thresholds have been exceeded and the ground is sufficiently wet to produce landslides with additional heavy rainfall. Isolated landslides may occur even without additional rainfall. Warning is issued when rainfall intensity–duration thresholds and antecedent water indices are exceeded and widespread, shallow landslides are occurring or have a very high probability of occurring	Baum and Godt (2010) Chleborad (2003) Chleborad et al. (2008) Godt et al. (2006)
Hong Kong Geotechnical Office	Hong Kong	Based on rolling (sliding time window) 24-h rainfall and corresponding frequency of landslides	Warning system was established in 1977. Statistical model based on the Poisson frequency distribution was chosen to correlate storms with spatially normalized landslides. This system assigns a predicted number of landslides per unit area for a given 24-h rainfall event	Chan et al. (2003)
Rio de Janeiro (Alerta Rio System)	Rio de Janeiro	Based on a combination of antecedent rainfall and rainfall intensities The daily rainfall then declines asymptotically for a 4-day cumulative rainfall	System consist of a network of 30 telemetered rain gauges and weather radar that are used to operation forecaster to issue warnings for landslides and flash flooding to government agencies and the public during severe rainstorms	D'Orsi et al. (1997) Ortigao et al. (2001)
Taiwanese Soil and Water Conservation Bureau of the Council of Agriculture	Taiwan	Based on a rainfall triggering index which is defined as a product of on the rainfall intensity and the effective accumulated rainfall, used to evaluate the debris-flow occurrence potential	System consists of a linked network of real-time reporting rain gauges, a series of flow detection devices and cameras. Every debris-flow hazard area has their own lower and upper warning envelopes that are defined by historic rainfall event data for the area	Jan and Lee (2004) Jan et al. (2007)

and rainfall. The fundamental problems that arise with debris flow are that it is rarely known when exactly debris flows occurred. In the North Shore Mountains and adjacent mountain terrain that constitutes part of Vancouver's drinking watershed, Metro Vancouver maintains a robust landslide documentation system for the Seymour River, Capilano River, and Coquitlam River watersheds. After significant storms, the watersheds are patrolled by vehicle and sometimes by helicopter, and all notable occurrences including snow avalanches and landslides are entered into a detailed database. The minimum size of a landslide thus detected is approximately 25×25 m in size. Metro Vancouver provides BGC with those data upon request.

Twenty-seven landslide dates were selected for analysis. Discriminant function analysis mandates that at least two groups are selected on which the discrimination can be conducted and so non-landslide-triggering storms had to be selected. A total of 36 non-landslide-triggering storms were chosen for discrimination. These were based on a minimum of approximately 40 mm of rain in a given storm, which is considered the lowermost value above which debris flows can occur if sufficient antecedent moisture is available. We attempted to sample summer (ten storms) and winter storms (26 storms) alike to extract the importance of antecedent moisture conditions. However, winter storms were purposely over-represented since almost all debris flows occur in the period between October 1 and March 31.

Landslides that occurred in recently (last 15 years) clearcut areas or those that originated from roads (road fill failures or failures associated with redirected drainage) as well as slopes ending in reservoirs that may be associated with rapid drawdown failure were excluded from the analysis to avoid bias (e.g., Reichenbach et al. 1998). This procedure was justified because the watersheds in question have minimal human disturbance. A real-time debris-flow warning system for disturbed areas would need to be calibrated separately and would likely result in lower thresholds.

The data gathered for integration in the debris-flow warning system had to be (a) continuously recorded for the duration for which landslide data exist and (b) suitable for predictive purposes in terms of frequency of updates and resolution to a small area.

Hydroclimatic data

Hourly precipitation was recorded at the North Vancouver District Hall (DN25) tipping-bucket rain gauge. DN25 was selected because it provides the most continuous and longest record available on the North Shore. However, its post-1994 data required comparison with the nearby City of North Vancouver (CNV) rain gauge because in 1994, the DN25 gauge had been relocated adjacent to cooling towers on the District Hall roof top. Water vapor from the towers is believed to have condensed in the gauge, artificially increasing precipitation totals (Jakob et al. 2003). This condensation is believed to have led to a distinct positive trend, particularly in short-duration rainfall,

An additional tipping-bucket rain gauge (DNV) was installed on the District Hall roof top in July, 2006. The two gauges are vertically separated by two floors, and therefore, it was assumed that DNV is not affected by the cooling tower. To investigate whether DN25 data were adjusted to account for the condensation effect of the cooling towers, the data were compared with CNV and DNV records.

Discriminant function analysis

Hydrometric data were chosen over a variety of time scales exemplifying antecedent moisture conditions and rainfall intensity (Table S1). It would be meaningless to include all of these variables in a statistical model, especially since there are likely to be many redundancies in the analysis. Therefore, a discriminant function analysis was conducted to identify the variables that provide the best discriminatory power and variance.

Discriminant function analysis (DFA) seeks to classify data into mutually exclusive groups on the basis of a set of variables. The analysis proceeds by finding a linear function that maximizes the ratio of between-group to within-group variability within multidimensional space. Many statistical textbooks provide information on the use of this method (i.e., Dillon and Goldstein 1984). For this study, two groups of data (landslide-triggering storms and non-landslide-triggering storms) were used for analysis similar to the work conducted by Jakob and Weatherly (2003). However, the data record was complemented by new data that became available in the time period between the Jakob and Weatherly (2003) study and the present study.

The first step in DFA is to extract a function that minimizes misclassification of storms with regard to landslide versus non-landslide triggering. Stepwise DFA selects variables for inclusion based on the magnitude of their additional, or partial, contributions to the discrimination process. The choice of the variable is based on the highest *F* value, computed from the ratio of between-group to within-group variance of discriminant scopes at each step in the analysis. The *F* value for a variable indicates its statistical significance in the discrimination between groups and is thus a convenient measure of the extent to which a variable contributes to the prediction of a group membership. Variables are then discarded from the model if the computed *F* value is less than the user-specified *F*-to-remove value.

In the stepwise DFA chosen for this analysis, the program will terminate the procedure, when all variables have been entered or removed or the maximum number of steps has been reached as specified, or when no other variable in the model has an *F* value smaller than the *F*-to-remove in this dialog or any variable after the next step has a tolerance value smaller than the specified.

Multivariate analyses mandate the examination of inter-variable correlations that allow the detection of heavily inter-correlated variables that would induce redundancy in the statistical model. The correlation matrix shows that the antecedent and intensity variables are highly intercorrelated, suggesting that multiples ought to be avoided in the final statistical model. It also demonstrates good correlations of the total storm precipitation with rainfall intensities of 12 to 48 h that suggests that these are typical storm durations. Similarly, the 1-m^3 exceedence time variable ($Q_{1\ \mathrm{h}}$) is well correlated with longer rainfall intensities (12 to 48 h) but also correlates well with a range of antecedent rainfall. This result suggests that the streamflow at Mackay Creek is a good combined surrogate for antecedent rainfall as well as longer rainfall intensities.

Arithmetic means were compared for the landslide-triggering (LS) and non-landslide-triggering (NLS) groups (Table S1). This comparison showed that all antecedent variables for the LS group are significantly higher than those for the NLS group, while the statistical difference for the rainfall intensities is relatively minor. The $Q_{1\ \mathrm{h}}$ variable, which is the number of hours a discharge of

1 m^3/s is exceeded, is also significantly different for the LS group compared to the NLS group. This observation indicates that antecedent conditions are of higher significance in discriminating between the two groups. In practical terms, this implies that a high-intensity summer storm following a long period of drought is very unlikely to produce shallow landslides and that the rainfall intensities necessary for landslide initiation are reached much more often than landslides actually occur. This empirical observation is supported by principles of soil mechanics that suggest that soil suction must be overcome in dry soils, followed by a slow increase in the water table, to achieve partial or full saturation and thus a coincident lowering of the factor of safety of a slope against landsliding.

Test for normality

Violations of normality compromise the estimation of coefficients and the calculation of confidence intervals Lumley et al. (2002). Sometimes the error distribution is “skewed” by the presence of a few large outliers. Since parameter estimation is based on the minimization of *squared* error, a few extreme observations can exert a disproportionate influence on parameter estimates. Calculation of confidence intervals and various significance tests for coefficients are all based on the assumptions of normally distributed errors. If the error distribution is significantly non-normal, confidence intervals may be too wide or too narrow.

The best test for normally distributed errors is a normal probability plot of the residuals. This is a plot of the fractiles of error distribution versus the fractiles of a normal distribution having the same mean and variance. If the distribution is normal, the points on this plot should fall close to the diagonal line. A bow-shaped pattern of deviations from the diagonal indicates that the residuals have excessive skewness (i.e., they are not symmetrically distributed, with too many large errors in the same direction). An S-shaped pattern of deviations indicates that the residuals have excessive kurtosis—i.e., there are either too many or too few large errors in both directions.

Normal probability plots were generated for the three predictor variables. All three showed some deviations from the diagonal indicating some skewness and kurtosis. To further test violations in the normality assumption, the Shapiro–Wilks W test was performed (Shapiro et al. 1968). If the W value is statistically significant at 0.05, then the distribution is said to be non-normally distributed. The test suggested that some of the variables are non-normally distributed. A large number of transformation routines were attempted, but none succeeded in fully normalizing the distributions. However, a visual examination demonstrated that none of variables had a distinct bimodal distribution, and the variables were therefore left untransformed.

Results

Five steps were specified in the analysis as experience has shown that more steps will simply introduce redundant variables to the analysis. Initial results showed that the variables $Q_{1\ \mathrm{h}}$, 4 weeks, and 2 days function are good discriminators, followed by the variables 5 and 4 days. The correlations matrix demonstrates that the 5- and 4-day variables are highly correlated (r=0.91), suggestion redundancy. The 4-day variable was found to be 90% redundant (tolerance 0.10) and thus was deleted from the model.

To this point, the analysis demonstrated that the $Q_{1\ \mathrm{h}}$ (hours of Mackay Creek discharge exceeding 1 m^3/s) variable is a significant discriminator. Since real-time gauge metering and telemetry is costly and sometimes prone to failure, it was decided to test the analysis without this variable and examine if the loss in discriminatory power is too high to justify its exclusion.

Further simplification was achieved by dropping the 5-day variable, which is highly correlated to the 2-day variable. This step reduced the percentage of correctly predicted LS cases to 70% (from 75%), while the NLS case percentage remained constant at 90%. The results are summarized in Table 2. This table is interpreted as follows: Wilks’ lambda denotes the statistical significance of the discriminatory power of the current model. Its value ranges from 1 (no discriminatory power) to 0 (perfect discriminatory power). Redundancy is also highlighted by the tolerance column. A tolerance value of 0.01, for example, indicates that the variable is 99% redundant, while a high tolerance value indicates that the variable should remain in the model.

While it is desirable to maintain a high number of correctly classified cases, it is even more desirable to create a simple and robust model that allows replication of results. In the present model, a long-term antecedent variable, a short-term antecedent variable, and a rainfall intensity variable have been selected. The former two variables can easily be measured on a continuous basis, while the third variable would be forecasted by a rainfall forecasting model and can therefore be used to predict threshold exceedence.

Final model classification functions

Classification functions are computed for each group and can be used directly to classify cases. A given case is classified into either the LS or NLS group for which it has the highest classification score.

Based on the foregoing analysis, the two classification functions for LS and NLS are:

$$\mathrm{LS} = -11.85 + 0.031A_{4\ \mathrm{weeks}} + 0.116I_{48\ \mathrm{h}} + 0.081A_{2\ \mathrm{days}} \qquad (1)$$

$$\mathrm{NLS} = -4.58 + 0.017A_{4\ \mathrm{weeks}} + 0.081I_{48\ \mathrm{h}} + 0.025\mathrm{A}_{2\ \mathrm{days}} \qquad (2)$$

A priori classifications were not chosen because the number of LS and NLS were based on all LS storms for the time period and the NLS for all storms exceeding a threshold defined in Section 3.

Table 2 Discriminant analysis results of 64 rainstorms

	Wilks’ lambda	Partial lambda	F-remove	p level	Tolerance
Variables					
4 weeks	0.71	0.73	21.8	0.00001	0.96
48 h	0.61	0.85	10.4	0.002	0.97
2 days	0.58	0.90	6.9	0.011	0.99

Table 3 Misclassified landslide-triggering storms and possible reasons for misclassifications

Date of storm	Interpretation	Landslide
April 3–4, 1991	Likely associated with snowmelt	1 slump, 1 debris avalanche
November 28–30, 1994	Low 2-day (18 mm) antecedent rainfall	8 debris flows on different creeks, all in Seymour and Coquitlam watersheds
November 7–8, 1995	Low 2-day (1.8 mm) antecedent rainfall	7 mass movement events in Seymour, Capilano and Coquitlam watersheds
December 15–16, 2002	Low 2-day antecedent (21 mm) and 48-h (44 mm) rainfall intensity	
December 9–10, 2004	Low 2-day (21 mm) antecedent rainfall, low 48-h (29 mm) rainfall intensity	
November 10, 2005	Low 2-day (12 mm) antecedent rainfall	

Therefore, the probabilities of a case belonging to a respective group were based on group size ratio (LS=0.37/NLS=0.63).

Based on these functions, the statistics for correct prediction of storms are 70% of all landslide-generating storms and 90% of all non-landslide-generating storms (both group means: 83%). This implies that of seven of the 24 landslide-generating storms were misclassified as non-landslide-generating and only four of the 39 non-landslide-generating storms were classified incorrectly. While this result is encouraging, it does imply that storms will be misclassified if the function is used in its present form. However, it should be kept in mind that these classifications are largely a diagnostic tool for identifying areas of strengths and weaknesses in the current classification functions because these classifications are not a priori predictions but rather post hoc classifications. Only if one classifies new cases can one interpret this table in terms of predictive discriminatory power.

Subtracting the classification scores obtained from function 1 (Eq. 1) from those obtained from function 2 (Eq. 2) will yield a value termed "ΔCS" that can be interpreted as a reasonable proxy for the likelihood of debris flows because it surrogates the distance to the centroid of each data population.

To assure that this analysis is as realistic as possible, the misclassified cases were examined in detail. The misclassified dates of non-landslide-triggering storms are summarized in Table 4 including explanations for misclassification. This summary table indicates that an outlier of just one of the three classification variables can lead to a misclassification of storms. It is for this reason that a combination of meteorological forecasting with error margins and the observed rainfall intensity is chosen as a more robust debris-flow forecasting system.

One important outlier in Table 3 is the storm of December 9–10, 2004. It is noteworthy because this storm triggered a large number of debris flows in the Seymour and Coquitlam River watersheds and one debris flow on Indian Arm that destroyed a house at Jane Creek which lies outside the District of North Vancouver boundaries, but which is within the landslide calibration area. To examine why DN25 and VW14 stations recorded only moderate rainfall amounts, a series of 20 radar images were obtained from Environment Canada via the courtesy of Prof. Stull of UBC. These images show the 12-h precipitation in 1-h time steps for the duration of the storm. It appears that a relatively small storm on the 8th with southwesterly flow was followed by a strong storm that arrived on the 9th (approximately at 10 pm Pacific Standard Time). This storm had 12-h rainfall amounts of up to 100 mm with the maximum rainfall intensities witnessed at approximately 10 am to 2 pm on December 10th, which agrees well with the observed debris flow on December 10th on Indian Arm. Rainfall intensities measured at DN25 reached up to 7.2 mm/h at 8:30 am on the 10th, but then quickly subsided, while the highest rainfall occurred hours later in the upper watersheds of the North Shore Mountains. We hypothesize that the storm direction from the south with a southeasterly trajectory which bypassed North and West Vancouver was responsible for the debris flow and that the storm would not have triggered a debris-flow warning had the system been in place at this time. Similarly, we were

Table 4 Misclassified non-landslide-triggering storms and possible reasons for misclassifications

Date of storm	Interpretation
January 21–23, 2005	Very high 4-week (384 mm) antecedent rainfall, well above average (36 mm), 2-day rainfall
October 16–17, 2005	Except for the 48-h rainfall intensity all other variables plot well above the NLS means and even exceed some of the LS means. We speculate that this storm either trigger one or several landslides, or that rainfall intensities were not augmented by orographic uplift and were thus insufficient to reduce soil shear strength sufficiently to trigger failure.
January 9–10, 2006	Same explanation as October 16–17 storm
March 21–24, 2007	Same explanation as previous storm, except low (2 mm) 2-day antecedent precipitation. Very high 48-h rainfall (135 mm). Possible explanation is that much of the rain at higher elevation which is the typical elevations for debris-flow initiation was absorbed by a thick snowpack

interested why three of the NLS storms were counted as landslide triggering. Table 4 summarizes these storms and the likely reasons why the events would have been missed by the warning system.

These examples emphasize that it is not possible to achieve a 100% certainty in the debris-flow warning system and that the system is only valid for the DNV boundaries for which the system is calibrated. Greater certainty could only be achieved if several rain gauges were interlinked and independently calibrated. This is currently not achievable because of the lack of rain gauges at key locations and the short record length of existing ones.

Model test

A statistical model can be tested by splitting the data record into two data populations, build the model on one data set, and then test it on the other. Another method is to repeat the analysis with a different data set of a rain gauge nearby. If similar variables and constants are chosen by the analysis, this procedure can also verify the model. Both model tests were chosen for this analysis because it was felt that the model has to be sufficiently stable to allow its use as a warning system.

Data splitting

A two-step process was followed to confirm that a model is valid. Step 1 builds a statistical model; step 2 validates it. To avoid bias, every other storm was separated from the chronologically ordered data set to generate the original model. The separated data formed the test dataset. While this treatment is intuitively correct, it has the disadvantage that with small datasets the total number of cases decreases and thus the number of variables that could be retained in the model. This, in turn, may decrease the robustness of the model.

The splitting of the dataset resulted in the following classification functions:

$$\mathrm{LS} = -14.05 + 0.098A_{2\ \mathrm{weeks}} + 0.129S \tag{3}$$

$$\mathrm{NLS} = -4.01 + 0.034A_{2\ \mathrm{weeks}} + 0.087S \tag{4}$$

with $A_{2\ \mathrm{weeks}}$ being the 2-week antecedent rainfall and S being the total storm precipitation. These equations were subsequently entered into a spreadsheet with the test dataset to calculate the respective classifications. The results from this exercise showed that of 12 of the test data set landslide-initiating storms, three were misclassified, and of the 20 non-landslide-initiating storms, three were also misclassified. We attribute the lack of complete fit to two factors: The first is the inherent bias in the dataset with the independent variable (LS, NLS) not being error-free. The second is that the decrease in cases caused by data splitting decreases the robustness of the model. Of note is that the variables depicted by the model are similar to those of the combined model. $A_{4\ \mathrm{weeks}}$ is an antecedent rainfall variable that is closely correlated to A4W (Eqs. 1 and 2). S as the total storm rainfall is highly correlated to the 48-h rainfall intensity because most landslide-triggering storms last for approximately 2 days.

Given that the data splitting provides reasonable predictive capability, it was decided to use the entire dataset that resulted in the classification functions 1 and 2. In addition, a separate analysis was run for a nearby station (West Vancouver, VW14) to examine the robustness of the original model from a spatial point of view. VW14 is located 8.6 km to the west of DN25.

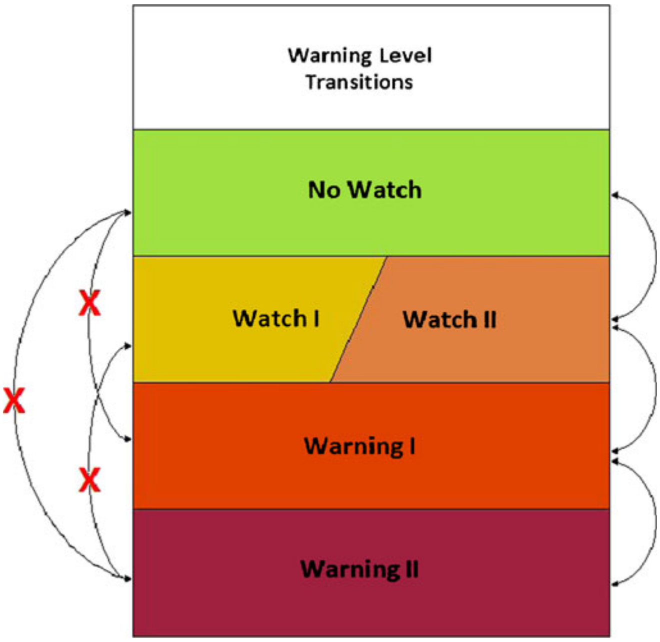

Fig. 3 Warning level transitions and switches that allow transitions from one warning level to another

Analysis of VW14 rain gauge data

Following the same steps as before, the following predictive equations were produced:

$$\mathrm{LS} = -6.43 + 0.05A_{4\ \mathrm{weeks}} + 0.28A_{1\ \mathrm{days}} - 0.033A_{5\ \mathrm{days}} \tag{5}$$

$$\mathrm{NLS} = -1.63 + 0.021A_{4\ \mathrm{weeks}} + 0.104A_{1\ \mathrm{days}} - 0.009A_{5\ \mathrm{days}} \tag{6}$$

Using this statistic, a total of 75% of all landslide-triggering storms and 87.5% non-landslide-triggering storms were correctly classified, which is close to the original result for DN25.

Notably, for both the DN25 and the VW14 gauges, the first and most significantly discriminatory variable was the 4-week antecedent rainfall. For VW14, the next most significant variable was the 1-day antecedent rainfall, which is highly correlated to the 2-day antecedent rainfall chosen by the analysis of the DN25 data. The 5-day antecedent rainfall is similar to the fourth most discriminatory variable chosen for the DN25 model that was discarded due to significant cross-correlation with the 2-day variable (r=0.56). In this case, however, the 1- and 5-day antecedent rainfall are not significantly correlated (r=0.10) and were therefore both retained in the analysis. A complete agreement in the variable selection and associated constants cannot be expected given the different storm characteristics over even short distances. However, the overlap of long-term antecedents (4 weeks) and short-term antecedents (1- and 2-day, respectively) demonstrates a reasonable consistency between the two different models.

Table 5 Five-fold debris-flow warning system and selection criteria used

Warning level	Message	Calculations	Cancelation	Override	Exc	$S>1$	*NDFs* (%)	*NDF*
No watch	Due to current and forecasted weather conditions, it is very unlikely that debris flows will occur in the North Shore Mountains	If ΔCS<−1	n/a	<6 h of no watch or watch >6 h and previous 6 h <4 mm/h and predicted 24 h ppt <1 mm/h	n/a		0	0
Watch level 1	Due to current and forecasted weather conditions, it is unlikely that debris flows will occur in the North Shore Mountains. It is unlikely that the warning level will be reached	If −1<ΔCS<2 for next 48 h	If ΔCS<−1	<6 h watch or warning >6 h and previous and forecast 6 h ppt <4 mm/h and <6 mm/6 h	449 x=14,299		0	0[a]
Watch level 2	Due to current and forecasted weather conditions, it is unlikely that debris flows will occur in the North Shore Mountain. It is likely that the warning level will be reached	If −1<ΔCS<2 for next 48 h and the next forecast change is to warning	If ΔCS<−1	<6 h watch or warning >6 h and previous and forecast 6 h ppt <4 mm/h and <6 mm/6 h			6 (2%)	30[a]
Warning	Due to current and forecasted weather conditions, it is likely that debris flows will occur in the North Shore Mountains	If ΔCS>2 for next 48 h	If ΔCS<2 and 6 h with <4 mm/h rain	<6 h of warning or severe warning >6 h and previous and forecast 6 h ppt <4 mm/h and <6 mm/6 h	121 x=3	66	15 (22.7%)	46
Severe warning	Due to current and forecasted weather conditions, it is very likely that debris flows will occur in the North Shore Mountains	If the predicted mean 48-h ppt ΔCS>2, and exceeded pred. mean or actual xrainfall of 18 mm/2 h during previous or forecast 6 h	If ΔCS<2 and 6 h <4 mm/h	<6 h of continuous severe warning	5 x=0.2	5	2 (40%)	51

Exc. the number of threshold exceedences for the calibration period for the respective warning level, $S \geq 1$ the number of storms reaching the respective warning level, N_{DFs} the number of debris-flow triggering storms and the percentage of all storms (n=21) that produced debris flows during the calibration period for the respective warning level, N_{DF} the total number of debris flows that occurred during the storms during the respective warning level as well as the percentage of storms that produced debris flows while at this warning level. Watch level I and watch level II share their statistics because they share a combined restriction of 6 h minimum

[a] Debris flows likely occurred during watch level 2 but cannot be confirmed conclusively because this could only be calculated based on the modeled precipitation amounts which are only available for the last 2 years. All of these debris flows were triggered outside (east and north) of the District of North Vancouver and there has not been a single debris flow within the district boundaries in watch level 2

Model improvement

The following criteria were established to improve the functionality of the model as a warning system: In the original model, ΔCS was the only variable used to determine the warning level. Due to sudden transitions from one warning level to the next, new variables and criteria were introduced into the model to provide a consistent and smooth transition from one warning level to the next. The model has been designed to ensure that each warning level is preceded by the level that is higher or lower in the order of precedence without skipping a level, which would be undesirable from an operational point of view. The previous level must have been in place for six consecutive hours, and it must be followed by the next level in the hierarchy for 6 h before switching to the next level. Figure 3 illustrates all possible system transitions. If a warning level is not in place for six consecutive hours, an override is issued to avoid confusion to systems users. The system is equipped with a second type of override in which the current weather condition can be overridden to the next lower level in the hierarchy, whenever the conditions are met based on the current calculated and previous warning conditions. The following criteria were used to set each warning level (see Table 5 for a summary of calculation and override conditions for each warning level).

A no watch level is issued when it is considered very unlikely that debris flows will occur and is generated if ΔCS is less than -1 or when the watch level existed and there was less than 4 mm of rainfall for a period of 6 h and the predicted 24-h rainfall does not exceed 1 mm/h in any given hour. This was done to insure that that debris flows will not occur during no watch override. This also provides the system with the time required to recover from a state of no watch.

When debris flows are considered unlikely to occur, a watch level is issued. This warning level is issued when ΔCS greater than or equal to -1 and less than 2. The watch level has further been split into watch I and watch II to provide additional information as to the likelihood of reaching the warning level. The subcategory of watch is determined by the future values of ΔCS. If the next predicted change in ΔCS yields a warning level, then watch II is issued; otherwise, a watch I is issued.

When debris flows are considered likely by the system, warning I is issued. Warning I is generated when ΔCS is greater or equal to 2. A warning I will override warning II if the previous 6 h during warning II witnessed less than 4 mm of rainfall per hour in any hour for the previous and forecast 6 h and less than 1 mm of rainfall per hour on average for the previous and forecast 6 h. Again, this override was implemented to insure that the actual weather conditions are controlling the warning system when predictions are outdated.

The final warning level is warning II which is generated when debris-flow occurrence is considered very likely. The warning II

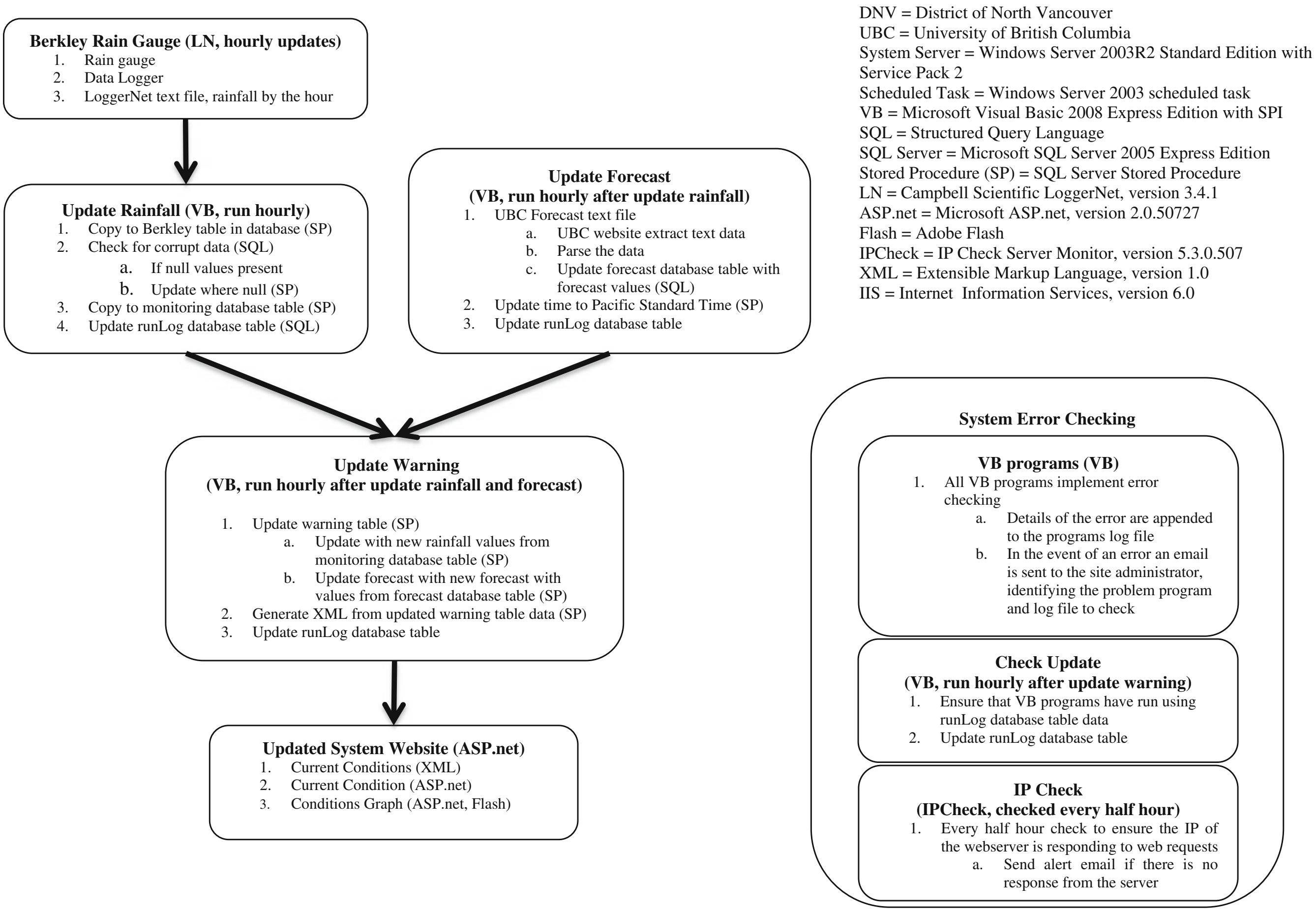

Fig. 4 Flow chart for development and operation of the debris-flow warning system. *Arrows* indicate the direction of data flow and graphic output

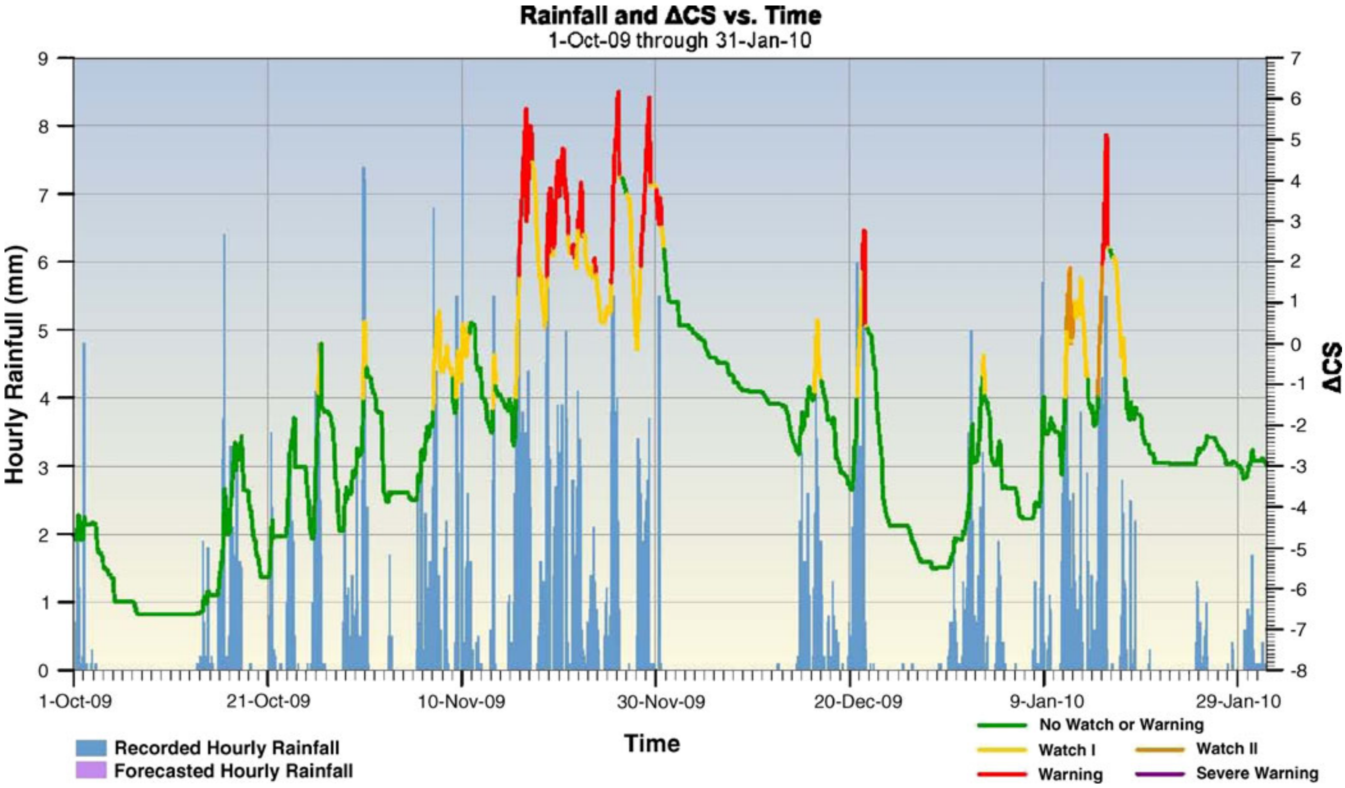

Fig. 5 Interactive real-time warning graph accessible only for BGC and DNV staff as it was found to be too complex to be accessible to the general public. Graph shows the time series of debris-flow warning for October 1, 2009 to January 31, 2010. A debris flow occurred on Charles Creek on November 19, 2009 while the system indicated a warning level. During operation that graph extends 24 h into the future and is updated hourly

criteria are that ΔCS is greater or equal to 2 and 18 mm of rainfall during a 2-h period during the previous or forecast 6 h. The system will only override to a warning II if the warning has not been in place for 6 h.

System implementation

The debris-flow warning system combines two sources of raw data: hourly rainfall data from the Berkley Escarpment rain gauge in North Vancouver (Fig. 1) and hourly rainfall forecast data from the Geophysical Disaster Computational Fluid Dynamics Centre at the University of British Columbia. Figure 4 illustrates the transfer of data through the system, from the data collection devices through to the final output over the web. Rainfall from the rain gauge is recorded to a datalogger at the Berkley Rain Gauge (Fig. 4). Raw data from the datalogger are broadcasted via cell modem to the systems Server. The system uses LoggerNet software to upload a text file from the datalogger. An SQL Server database is used to store and calculate all the systems information.

A scheduled task (Fig. 4 "update rainfall") has been implemented on the system's server that operates a Visual Basics (VB) program which updates the system's database with rainfall values from the datalogger text file. Rainfall data are imported into the database via a transfer procedure of all data in the datalogger text file to the database. In the next step, a VB program retrieves hourly forecast updates for the next 48 h from the UBC Weather Centre website (Fig. 4 "update forecast"). The program then parses the website text extracting each hour's average forecast rainfall value to update the database. The system then calculates the warning levels and hourly updates the warning table in the systems database (Fig. 4 "update warning") via another VB.Net program. Due to the real-time nature of the system, systems have been implemented that provide error alerts to the system's administrators (Fig. 4 "system error checking"). Once the data have been updated and processed, it is used by the debris-flow warning system web site. Implementation of the debris-flow warning system for the DNV required web server output that provides the DNV access to this XML (extensible markup language) file, which is used to display the current debris-flow

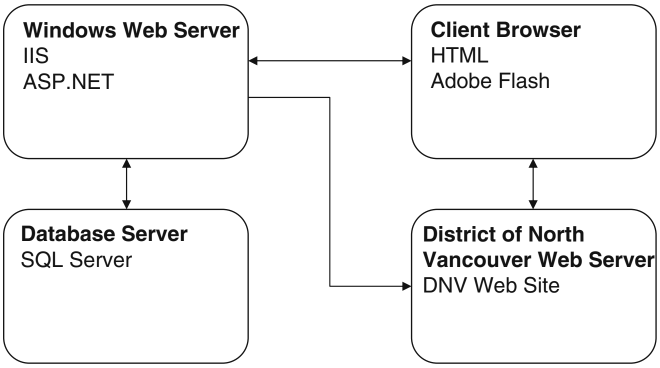

Fig. 6 Diagram showing the interaction between BGC's (windows web server and database server) and the server located at the District of North Vancouver

Table 6 Warning system performance rainy season of 2009/2010 and 2010/2011

Date of storm	Warning level	Duration (h)	Debris flow/location
November 15–17, 2009	Warning	32	2 (Metro Vancouver Seymour River)
November 18–21, 2009	Warning	54	6 (Metro Vancouver Capilano River)
November 22, 2009	Warning	12	1 (Howe Sound, Charles Creek)
November 23, 2009	Warning	5	
November 25–26, 2009	Warning	19	
November 28–29, 2009	Warning	26	
November 30, 2009	Warning	12	
December 20–21, 2009	Warning	9	1 (West Vancouver, Nelson Creek)
January 14–15, 2010	Warning	15	
November 29–30, 2010	Warning	6	
December 8–9, 2010	Warning	5	
December 11, 2010	Warning	6	
December 24–25, 2010	Watch II	26	1 (Metro Vancouver Seymour River)
January 5–6, 2011	Warning	8	

Note that there were no severe warnings between October 1, 2009 and April 30, 2011

warning level on the district's web site (Fig. 5) as well as on their automated phone system.

The web server not only provides the XML file but it also serves a password secured website that allows system managers and reviewers to obtain information about the current, previous, and forecasted system numerics which are not available to the general public. The web site application is a combination of ASP.net JavaScript (browser dependent version), XML, and Adobe Flash (browser dependent version) technologies on a Microsoft Windows Server 2003 operating system.

System performance

The debris-flow warning system has been operational between October 1, 2009 and April 30, 2010 and again between October 1, 2010 and April 30, 2011. During this time, a total of nine debris flows were documented during four storms when the warning level was reached and one storm when the watch II level was exceeded for 26 consecutive hours (Table 6). The warning level was reached 13 times during the 2-year test period. No debris flows were recorded during watch I or lower levels. The severe warning level was also not reached in the 2 years of system operation. In nine cases the warning level was reached but no debris flows documented. This number needs to be viewed with some caution as the weather, especially the cloud ceiling, immediately after a storm may not permit helicopter viewing of the entire watersheds potentially affected and thus some debris flows in remote areas could be missed. Irrespective of this limitation, the system operated as desired with more warning levels than actual debris flows while keeping the total number of warnings to a reasonable level (average of 6.5 warning level exceedences per year over a 2-year period).

Nothing is known as to the human response to this warning system. While the system and its functioning has been advertised in local media and public information session, as well as free information sheets available over the web and at the District Hall, neither the authors nor district staff knows how many people regularly monitor the debris-flow warning system. It is also unknown if people take precautionary measures when warning levels are reached or if anyone chooses to evacuate their homes.

Discussion

In this study, we report on the development and implementation of a real-time debris-flow warning system: the first in Canada. The model is not error-free and it is unlikely that such models can be established at a reasonable cost given the spatial and temporal variability of extreme rainfall particularly in mountainous terrain. The principal uncertainties that affect such system are twofold: One is that even though synoptic storms can reasonably well be predicted in terms of their timing and total rainfall amounts, the exact spatial distribution of rainfall and at different elevations is still problematic. High-intensity rainfall cells embedded in larger frontal system change their shape and directions through forced uplift and turbulence at time scales that cannot be captured by a warning system that requires sufficient time to allow evacuations. Some storm trajectories were such that while in the eastern sections of the North Shore Mountains, numerous debris flows were documented and none were recorded within the district boundaries. This emphasizes the spatial limitation of the system that cannot be transferred to even Port Coquitlam which is only some 20 km east of the district boundaries. These uncertainties could be diminished by installing a sophisticated rain gauge network that are telemetered and distributed at key locations and elevations in the various watersheds to be monitored. However, many years with a sufficient number of debris flows would need to pass until sufficient data are gathered in such system to calibrate it as has been done in this study.

The second uncertainty relates to geomorphology. Prior research has demonstrated that there are fundamentally two types of debris-flow systems: those that require channel recharge to produce flows at the crossing of hydroclimatic thresholds and those with abundant sediment that will always trigger a debris flow when a hydroclimatic threshold is exceeded (Jakob 1996; Bovis and Jakob 1999). For a regional debris-flow warning system, this differentiation is not as important because there will always be sufficient individual creeks of either type to warrant regional application. For specific creeks, however, the current recharge condition ought to be included in the warning to examine if debris flows can be triggered at all or if time needs to pass since the last event to accumulate sufficient removable material in the watershed. The sediment availability and runoff characteristics in a given basin can also be increased greatly through processes such as wildfires, insect infestations, mine development, forest road construction, or logging. Any process that can disturb vegetation on a regional scale will ultimately change runoff characteristics, lower root strength, and thus raise the susceptibility to shallow landsliding. Should any of these processes occur on a watershed or regional scale, the warning system that has been calibrated on undisturbed conditions need to be amended to account for such changes.

The debris-flow warning system is dependent on receiving regular hourly rainfall data updates, both current and forecasted. Since the data collection and reporting occurs through Internet and cellular connections, there is the possibility of occasional connection problems and data corruption. As discussed in the previous section, during each step of the data collection process, error checking takes place, and emails are automatically sent out to system administrators if a problem is encountered, so that the situation can be rectified. In order to minimize risks, the application is hosted by a major web hosting service provider that specializes in uninterrupted service and server redundancy.

Conclusion

As urban development continues to encroach in mountainous terrain and heavy rainfall events are becoming more frequent or more intense in many regions (Jakob and Lambert 2009), timely debris-flow warning is expected to become an increasingly desirable tool to reduce losses. Regional debris-flow warning systems can be applied to reduce residual risk particularly in areas where complete risk reduction by structural mitigation measures is considered unfeasible. Prior systems that are based on rainfall intensity and durations alone do not yield satisfactory results because warning thresholds would be exceeded too often to provide a believable system. A 21-year record of debris flows and hydroclimatic variables was used in a discriminant function framework to extract the most significant variables for a predictive system. The analysis extracted two variables for antecedent moisture conditions and one variable that reflect the rainfall intensity during a given storm. This variable combination is convenient because it allows continuous calculation of rainfall over a sliding window and allows integration of regularly issued weather forecasts in a predictive sense. The DFA provided functions whose difference can be interpreted as a proxy for debris-flow likelihood. Further calibration was achieved by qualitative designation of a series of criteria that match the observed record of debris flows. This yielded a real-time DFA-based continuously calculated prediction function. The function is run during the rainy season between October 1 and April 30 every year. It is linked automatically to the DNV's website where the warning level is displayed in real time on the district's website and a telephone message is automatically updated to provide information to those who do not have internet access. It is presently unknown how many, if any, residents respond to the warning system by evacuating their homes located on fans designated as being prone to debris flows. Irrespective, the system provides the possibility for residents to make informed decisions with regard to their own safety. Further system improvements can be made as more debris flows are recorded and can be added to the database and analyses. The system is applicable to the district boundaries only and cannot be transferred to other areas. Regional re-calibration with a representative rain gauge would have to be undertaken for those areas.

Acknowledgments

This work would not have been possible without the understanding of the intensive effort required for such study by the District of North Vancouver. We especially like to thank Jozsef Dioszeghy and Fiona Dercole for their continuing support. We acknowledge the excellent collaboration with the Geophysical Disaster Computational Fluid Dynamic Centre at the University of British Columbia. Neil Ripley drafted Fig. 1. Two anonymous reviewers provided useful comments and additional insights.

References

Baum RL, Godt JW (2010) Early warning of rainfall-induced shallow landslides and debris flows in the USA. Landslides 7:259–272

Bovis MJ, Jakob M (1999) The role of debris supply to determine debris flow activity in southwestern BC. Earth Surface Processes and Landforms 24:1039–1054

Chan RKS, Pang PLR, Pun WK (2003) Recent developments in the landslips warning system in Hong Kong. In: Ho KKS, Li KS (eds) Geotechnical engineering—meeting society's needs: proceedings of the 14th Southeast Asian Geotechnical Conference, Dec 10–14 (2001), Hong Kong. Balkema, Rotterdam, pp 219–224

Chleborad AF (2003) Preliminary evaluation of a precipitation threshold for anticipating the occurrence of landslides in the Seattle, Washington area. US Geological Survey Open-File Report 03-463

Chleborad AF, Baum RL, Godt JW (2008) A prototype system for forecasting landslides in the Seattle, Washington area. In: Baum RL, Godt JW, Highland LM (eds) Engineering geology and landslides of the Seattle, Washington area: Geological Society of America reviews in engineering geology, vol XX. Geological Society of America, Boulder, pp 103–120. doi:10.1120/2008.4020(06)

d'Orsi RN, Ortigao JAR, Dias A, Morales L, Santos MD (1997) Rio-Watch: the Rio de Janeiro landslide watch system. In: Proc. 2nd PSLPan-Am Symp. on Landslides, Rio de Janeiro, vol 1, pp 21–30

Dillon WR, Goldstein M (1984) Multivariate analysis—methods and application. Wiley, New York, 587p

BGC Engineering Inc (2009) North Vancouver debris flow and debris flood quantitative risk assessment: update. Accessible via www.dnv.org

Godt JW, Baum RL, Chleborad AF (2006) Rainfall characteristics for shallow landsliding in Seattle, Washington, USA. Earth Surface Processes and Landforms 31:97–110

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2007) Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorol Atmos Phys 98(3–4):239–267

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2008) The rainfall intensity–duration control of shallow landslides and debris flows: an update. Landslides 5:3–17

Hungr O (2004). Landslide hazards in British Columbia. Achieving balance in risk assessments. Innovation, April 2004, 12–16

Jakob M, Lambert S (2009). Climate change effects on landslides along the southwest coast of British Columbia. Geomorphology 107: 275–284

Jakob M (1996) Morphometric and geotechnical controls of debris flow frequency and magnitude in southwestern British Columbia. Unpublished Ph.D. thesis, University of British Columbia, Vancouver, 232pp

Jakob M, Weatherly H (2003) A hydroclimatic threshold for landslide initiation on the North Shore Mountains of Vancouver, British Columbia. Geomorphology 54:137–156

Jakob M, McKendry I, Lee R (2003) Changes in rainfall intensity in the Greater Vancouver Regional District, British Columbia. Can Water Resour J 28(4):587–604

Jan C-D, Lee M-H (2004) A debris-flow rainfall-based warning model. Chin J Soil Water Conserv 35(3):275–285

Jan C-D, Kuo FH, Lee MH (2007) A case study on debris-flow warning and evacuation during typhoon Haitang. In: 2nd International Conference on Urban Disaster Reduction, Taipei, Taiwan

Kerr Wood Leidal Associates (KWL) (2003a) Overview report on debris flow hazards. Submitted to the District of North Vancouver. Accessible via www.dnv.org

Kerr Wood Leidal Associates (KWL) (2003b) Reports on debris flow studies. Submitted to the District of North Vancouver

Lumley T, Diehr P, Emerson S, Chent L (2002) The importance of the normality assumption in large public hearth data. Annual Rev Public Health 23:151–169

NOAA-USGS Debris Flow Task Force (2005) Debris-flow warning system-final report. U.S. Geological Survey Circular 1283, 47pp

Ortigao JAR, Justi MG, D'Orsi R, Brito H (2001) Rio-Watch 2001: the Rio de Janeiro landslide alarm system. In: Ho KKS, Li KS (eds) Proc 14th Southeast Asian Geotechnical Conference, Hong Kong, vol 3. Balkema, Rotterdam, pp 237–241

Reichenbach P, Cardinali M, De Vita P, Guzzetti F (1998) Regional hydrological thresholds for landslides and floods in the Tiber River Basin (central Italy). Environ Geol 35(2–3):146–159

Schuster RL and Highland LM (2001) Socioeconomic and environmental impacts of landslides in the Western Hemisphere. US Geological Survey Open-file Report 01-0276

Shapiro SS, Wilk MB, Chen HJ (1968) A comparative study of various tests of normality. J Am Stat Assoc 63:1343–1372

Wieczorek GF, Glade T (2005) Climatic factors influencing occurrence of debris flow. In: Jakob M, Hungr O (eds) Debris-flow hazards and related phenomena. Springer-Praxis, Heidelberg, pp 325–352

Wiley TJ (2000) Relationship between rainfall and debris flows in western Oregon. Oregon Geol 62(2):27–43

Electronic supplementary material The online version of this article (doi:10.1007/s10346-011-0282-8) contains supplementary material, which is available to authorized users.

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