SUSCEPTIBILITY OF SMALL UPLAND CATCHMENTS TO DEBRIS-FLOW

Mélanie Bertrand[1], Frédéric Liébault[2], Hervé Piégay[3]

ABSTRACT

Over the last thirty years, morphometric indicators have been widely used to identify catchments prone to debris-flow. The most commonly used parameters are the Melton ruggedness index and the slope of the alluvial fan. We therefore compiled these two morphometric parameters and the observed response (fluvial vs. debris-flow catchments) for 620 alpine catchments.

We used this new database (compiled from the literature) to build a broader-scale statistical model for regional scale debris-flow prediction. Two multivariate statistical models were tested: linear discriminant analysis and logistic regression. After comparing the results between these two models we tested the influence of a balanced / unbalanced response variable. The logistic regression showed better results (median specificity around 0.9 and median sensitivity of 0.88) and has been chosen as the final model of discrimination.

Keywords: debris-flows, morphometric parameters, statistical model, fan slope, Melton ruggedness index

INTRODUCTION

Small torrents are known to be prone to flash floods and debris-flows. In order to limit vulnerability and take these extreme events into account in planning decisions we need to better predict the spatial occurrence of catchments prone to debris-flow and find potential points of debris-flows impact on infrastructures. For this purpose, we developped a simple methodology to discriminate the geomorphic response of catchments as a first step in debris-flow susceptibility characterization.

Several literature studies focused on morphometric indicators to roughly assess the dominant flow type on alluvial fans. Pioneer works were initiated in the 1960s (Melton, 1965), and some case studies were done in the 1980s. Kostachuk et al. (1986) and Jackson et al. (1987) tried to identify the debris-flow hazard on alluvial fans in the Canadian Rockies using catchment metrics. These early works have been followed up by an increasing number of studies in different alpine environments over the last 20 years (Marchi et al., 1993; Calvache et al., 1997, Sorriso-Valvo et al., 1998; De Scally and Owens, 2004; Rowbotham et al., 2005). These recent studies tried to integrate a large set of morphometric parameters into the modelling process, such as fan area (Ceriani et al., 2000), fan gradient (De Scally and Owens, 2004), stratigraphic data (Coe et al., 2003), or geological characteristics (D'Agostino and Marchi, 2001) but the improvement of the prediction is arguable.

To build a broader-scale statistical model for debris-flow prediction, we revisited these studies and compiled data from various alpine environments. Our objective was to test if a robust statistical model of discrimination between debris-flow and fluvial catchments could be obtained by using only the two most widely-used morphometric indicators for debris-flow susceptibility (Melton index and fan or channel slope). These two parameters present the advantage of being easily extracted from DEM or contour-level maps.

[1] PhD Mélanie Bertrand. Cemagref Grenoble, Unité de Recherche ETNA (Erosion Torrentielle, Neige et Avalanches), Domaine Universitaire, 2 rue de la Papeterie, BP76, F38402 Saint-Martin-d'Hères, France and ENS de Lyon, UMR 5600, CNRS, Lyon, France (e-mail: melanie.bertrand@cemagref.fr)

[2] Dr. Frédéric Liébault. Cemagref, UR ETNA, Saint-Martin-d'Hères, France

[3] Dr. Hervé Piégay. Université de Lyon, UMR 5600, CNRS, Lyon, France

We tested two multivariate statistical models: a linear discriminant analysis and a logistic regression. The results and the performance of these two models were compared. Here we present 1) the database compiled from literature, 2) the results from the two implemented statistical models.

MATERIAL AND METHODS

Database

A database of 620 small upland catchments was compiled from the alpine literature. For each catchment, we collected the Melton index, the slope of the alluvial fan (or channel slope at the catchment outlet), and the dominant geomorphic response at the catchment outlet (debris-flow vs. fluvial responses) (Tab. 1).

Tab. 1 Revisited studies of debris-flow susceptibility classified by alpine regions

Region	Number of catchments	Catchments with debris-flow response	Catchments with fluvial response	References
French Alps	83	64	19	Malet et al. (2004) Marchi & Brochot (2000) Remaître (2006) Thénard (2009)
Austrian Alps	31	16	15	Schraml et al (2007) in Scheidl & Rickenmann (2010)
Canadian Rockies	51	35	16	Jackson et al. (1987) Jordan (2007) Kostaschuk et al. (1986)
Italian Alps	229	201	28	D'Agostino and Marchi (2001) Ceriani et al. (2000) Lenzi (2000) Mambretti (2009) Marchi et al. (1993) Marchi & Cavalli (2007) Scheidl & Rickenmann (2010) Sorriso-Valvo et al. (1998)
Pyrenees	5	3	2	Gomez-Villar & Garcia-Ruiz (2000) Hürlimann et al. (2006)
Southern Alps (New Zealand)	118	73	45	De Scally & Owens (2004) De Scally et al. (2010)
Southern Pre-Alps (France)	51	0	51	Liébault (2003)
Switzerland	40	40	0	Bezzola & Hegg (2007), Rickenmann & Zimmermann (1993), Rickenmann et al. (2008a), Rickenmann et al. (2008b), Vaw (1992), In Scheidl & Rickenmann (2010)
Washington State (USA)	12	12	0	Kovanen & Slaymaker (2008)
Total	620	444	176	

The Melton index (or Melton's ruggedness number) is an index of the ruggedness of the catchment (Melton, 1965) and is calculated as the ratio of the basin relief (vertical difference between the maximal elevation of the basin and fan apex) and the square root of the catchment area measured at the fan apex. The slope of the fan is given in degrees. From the 620 catchments censed in the database, 176 have a fluvial response and 444 a debris-flow response. The catchments are located in 9 different alpine regions of the world.

Preliminary statistical test

We chose to only identify two groups of catchments: (i) those that are known to produce debris-flows as attested by field surveys and/or historical documents, and (ii) those that never produce debris-flow. In the literature, other groups may be proposed, for example hyperconcentrated flows (Costa, 1988) or debris flood (Ceriani et al., 2000; Marchi and Dalla Fontana, 2005) or mudflow or debris avalanches (Jakob and Hungr, 2005). We considered that these distinctions may be ambiguous and difficult to determine in the field or by using historical archives, so we decided to adopt a more objective binary classification.

To explore the variability of the morphometric indicators between the two response groups, we considered all the catchments together, whatever their region, and tried to highlight correlations between the two indicators and the geomorphic response observed in order to define a statistical model of discrimination. This was done applying an ANOVA test.

Description of discriminating models

Two discriminant statistical models were tested: the linear discriminant analysis and the logistic regression.

The linear discriminant analysis classifies objects according to their distance to the centroïds of the response groups. Here, the response is a categorical dependent variable (a qualitative variable which is expected to change depending on the explanatory variables). The variances between classes and within classes are calculated and kept constant. The calculated linear function is the one that maximizes classes' separability.

The logistic regression, a generalized linear model, calculates the probability of belonging to a group and is often used to predict or explain the occurrence of a phenomenon, considering explanatory variables. The response observed follows a Bernoulli law (i.e. it either takes value 0 for fluvial response or value 1 for debris-flow response). The parameter of interest is p, the probability of one response modality (0 or 1). Generalized linear models describe values of $f(p)$, where f is a non-linear function of p, through a linear combination of the two explanatory variables (log-transformed Melton ruggedness index and fan slope). In the case of the logistic regression, f is defined as a logit function: $\text{logit}(p)=\log(p/(1-p))$. The predicted values of $f(p)$ vary between $-\infty$ and $+\infty$ corresponding to values of p, the probability of debris-flow response, between 0 and 1.

These two kinds of multivariate statistical models were implemented in R software with the functions lda and glm.

Balanced versus unbalanced response parameter

The significantly different number of catchments in each response category (i.e. unbalanced response) has a great influence on the discriminant thresholds. When considering the entire dataset, the linear discriminant analysis shows a low predictive power for the debris-flow response. Indeed, the low number of fluvial response catchments tends to bring the center of gravity of the scatter plot of this category near the one of debris-flow catchments (reducing the variance between the two clouds), and to misclassify the catchments between the two centers of gravity as the discriminant line is closer to the center of gravity of the fluvial response cloud. The linear discriminant analysis model is sensitive to the equilibrium of the response parameter (the same number of catchments with debris-flow or fluvial response, i.e. balanced response) in the training set.

We therefore chose to constitute training sets (i.e. portions of the original dataset used to build up the statistical models) and target sets (i.e. portions of the original dataset used to test the efficiency of the statistical models) with balanced response groups by random sampling without replacement, then measure the predictive power of each model created.

We sampled 1000 times the training set (90% of the fluvial response catchments (=158) and the same number of debris-flow response catchments) and the target set (10% of the fluvial response catchments (=18) and the same number of debris-flow response catchments) with balanced groups and built up 1000 linear discriminant analysis and 1000 logistic regression models.

In the same way as the linear discriminant analysis, we also tested the effects of balanced and unbalanced response groups on the efficiency of the logistic regression. We sampled 1000 times the training set (90% of catchments in each category: 158 catchments with fluvial response and 400 catchments with debris-flow response) and the target set - used to validate the prediction power - (10% of catchments in each response group: 18 catchments with fluvial response and 44 catchments with debris-flow response).

Efficiency of the models

We compared the results of the two models with balanced and unbalanced response groups with sensitivity and specificity indicators. These are calculated from confusion matrices (Tab. 2) and are not dependent on prevalence (the proportion of fluvial and debris-flow catchments is a priori not known). The sensitivity is the proportion of positive cases correctly predicted, and the specificity is the proportion of negative cases correctly predicted. Here, we considered that the positive case is the debris-flow response and the negative case the fluvial response. As the logistic regression models give a probability of debris-flow response, we use a median probability threshold to establish in which category the response is predicted. It means that catchments with a probability of debris-flow response higher than the median probability have a predicted debris-flow response and catchments with a probability to debris-flow response lower than the median probability have a predicted fluvial response.

Tab. 2 Confusion matrix adapted from Begueria (2006): a, true positives; b, false positives; c, false negatives; d, true negatives.

	Observed	
Predicted	Debris-flow response	Fluvial response
Debris-flow response	a	b
Fluvial response	c	d

We compared the median value and the dispersion of sensitivity and specificity indicators for both kinds of model with balanced response groups. We then compared the results for the logistic regression model with balanced and unbalanced response groups. Finally we chose the more efficient model to predict the geomorphic processes occurring at the outlets.

RESULTS

We plotted the Melton index versus fan or channel slope (Fig. 1). Each variable was log-transformed to obtain normal distributions.

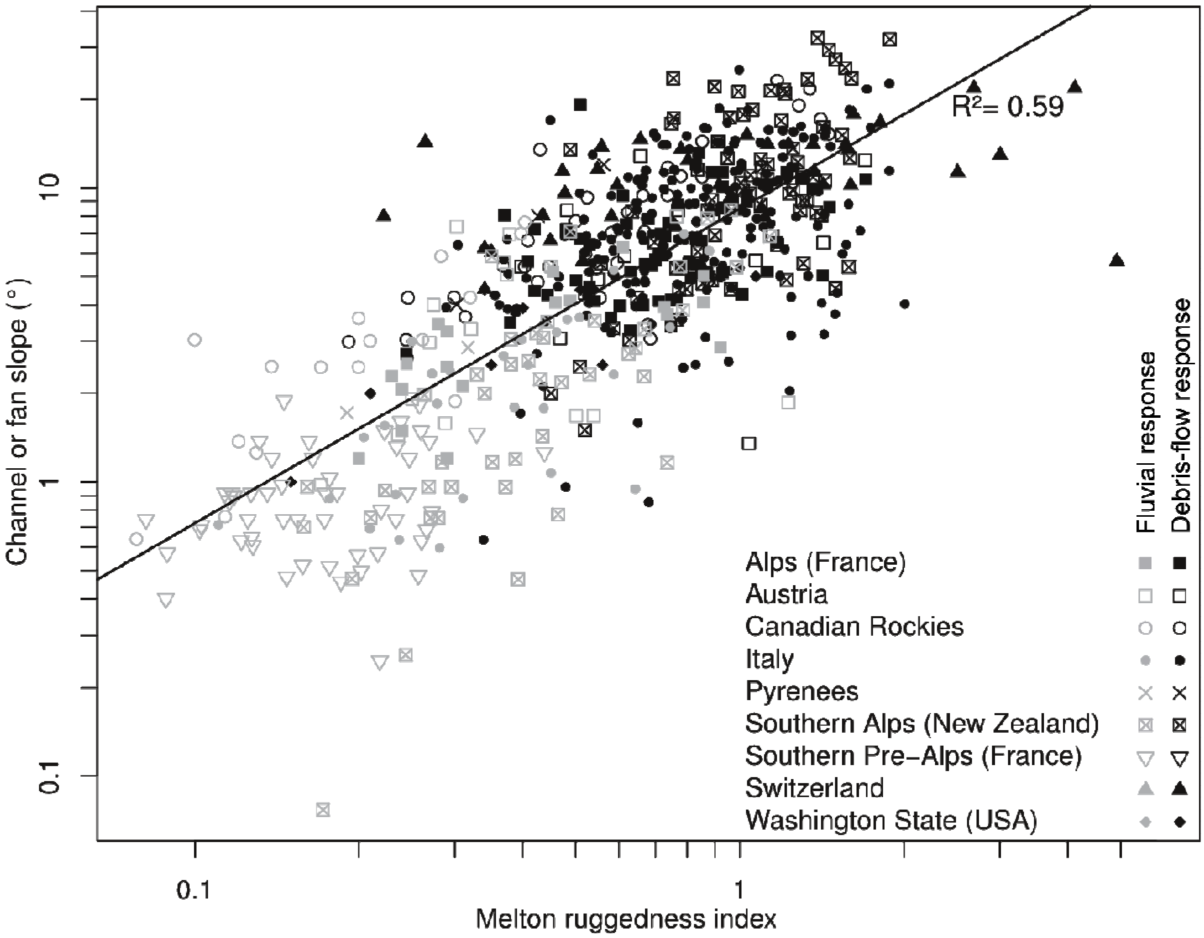

Fig. 1 Morphometric parameters of catchments, data extracted from literature. Logarithmic scale The two log-transformed variables showed a strong linear correlation (R^2= 0.59).

We plotted histograms of the Melton index and fan or channel slope. An ANOVA analysis was used to test the significance of the differences between the two response groups with a p-value <0.0001 for both Melton index and fan slope. Mean values of log-transformed Melton index were -0.23 and -1.25 for debris-flow and fluvial responses, respectively (Fig. 2(A)), and mean values of log-transformed fan or channel slope were 2.01 and 0.50 for debris-flow and fluvial groups, respectively (Fig. 2(B)).

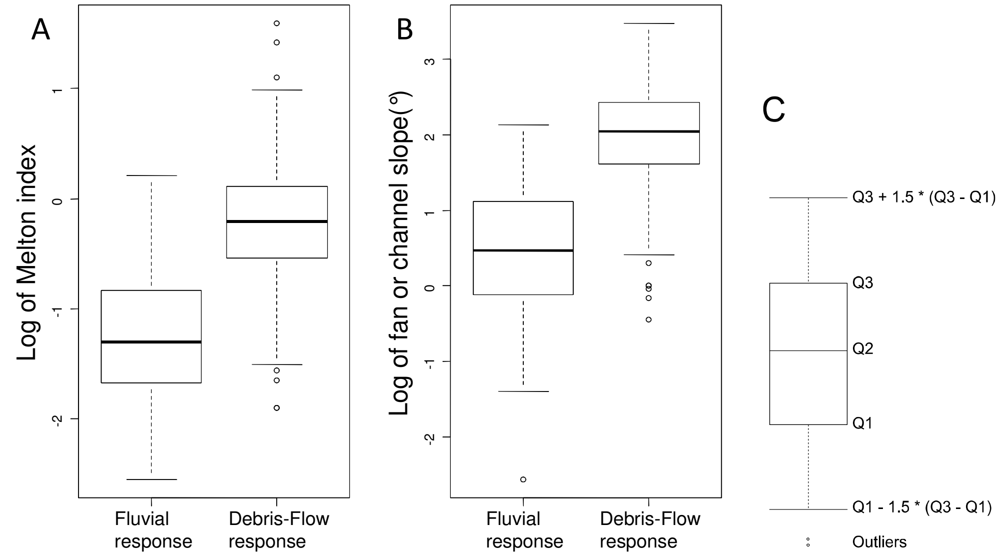

Fig. 2 Comparison of (A) log Melton index and (B) log fan or channel slope distributions for each response group. (C) Values represented by the box plot.

The linear discriminant analysis showed a great variability of results. Depending on the catchments sampled at each iterance, the discriminant line is more or less attracted to one or other response group cloud. The results of an example of sampling are shown in Fig. 3. The quantile of slope and intercept values are shown with lines: for each line we take the value of slope and intercept of the same quantile. This example shows a very good sensitivity (0.94) but a slightly lower value of specificity (0.67).

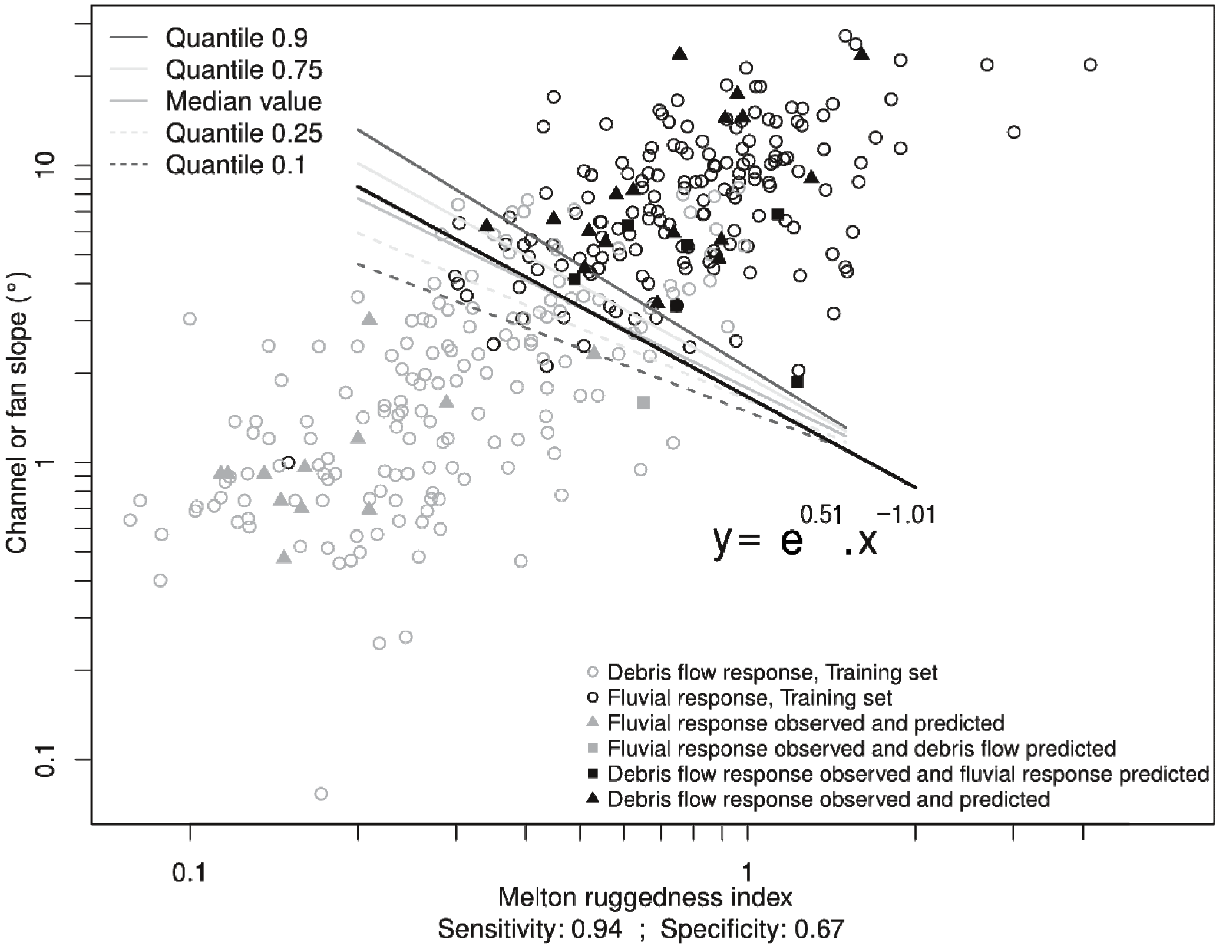

Fig. 3 Linear discriminant analysis for a set of sampled catchments. Quantile values of slope and intercept of 1000 discriminant analysis iterations

Fig. 4 shows an example of catchments sampling and the results of a logistic regression model. As we choose to define the response given by the model from a median threshold on the fitted probability (not taking into account the 0.5 probability value), we have the same number of catchments in each response category. Consequently, the sensitivity and specificity indicators are identical and show here a good result (0.87).

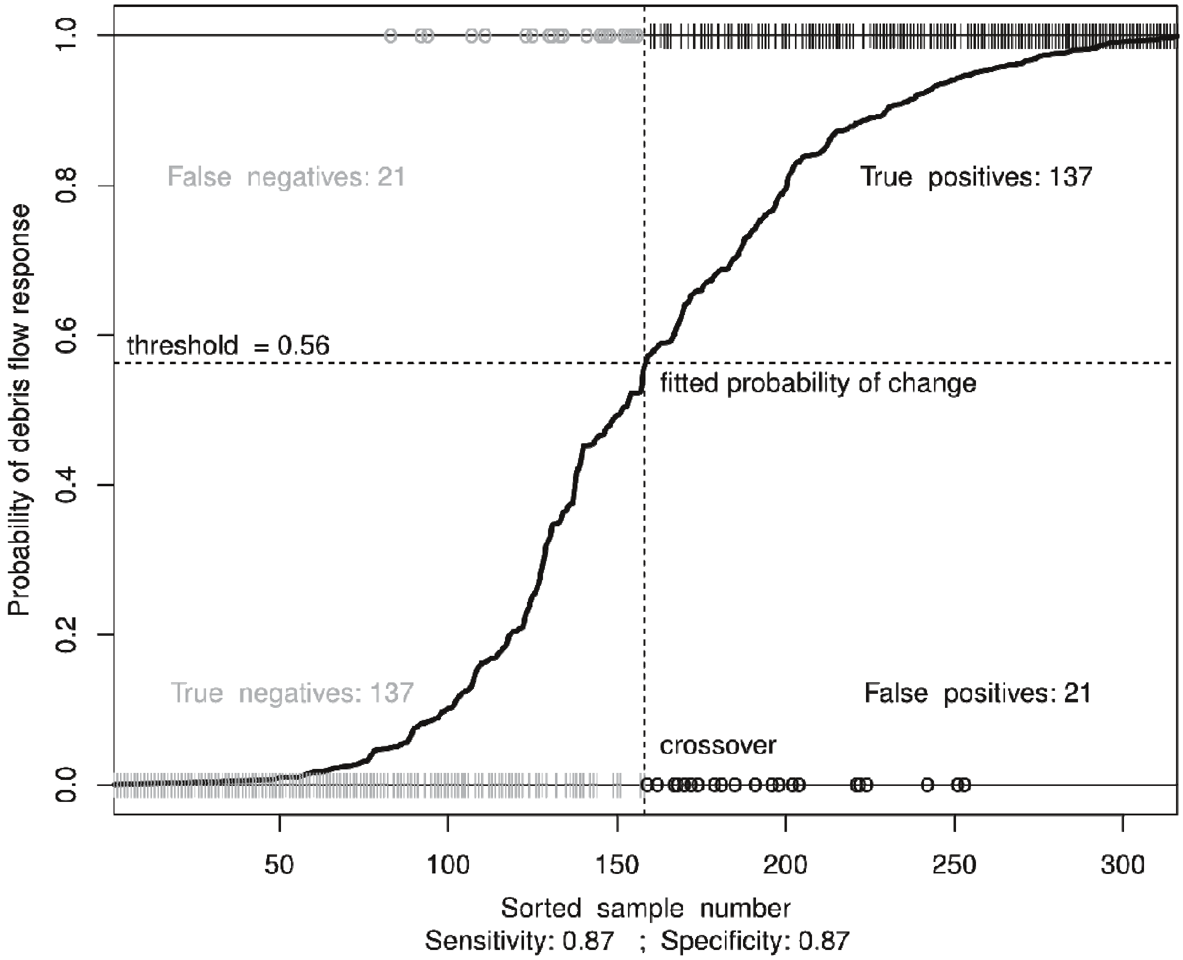

Fig. 4 Logistic regression results for a set of sampled catchments

We compared the results of the two statistical models with sensitivity and specificity indicators calculated for each iterance of sampling (Fig. 5). The box plots showed a great variance of these two indicators depending on the sampled catchments. The logistic regression models showed a better specificity and a slightly worse sensitivity compared to the linear discriminant analysis models. The results of the logistic regression models were more stable with a median value of sensitivity and specificity around 0.87. On the contrary, median values were respectively 0.94 and 0.78 for the linear discriminant analysis models. Overall, the proportion of negative cases not correctly predicted was higher for this kind of model. This implies that the number of fluvial catchments predicted as debris-flow catchments is higher, even if the number of debris-flow catchments predicted as debris-flow catchments is higher than for the logistic regression model. Moreover, in a context of risk management, we need to know the probability of debris-flow response at the outlets of catchments in order to anticipate the organization of rescue (for example, closure the roads impacted by a debris-flow). These findings lead us to choose the logistic regression model which allows the probability of a debris-flow response to be calculated (as opposed to a simple binary response).

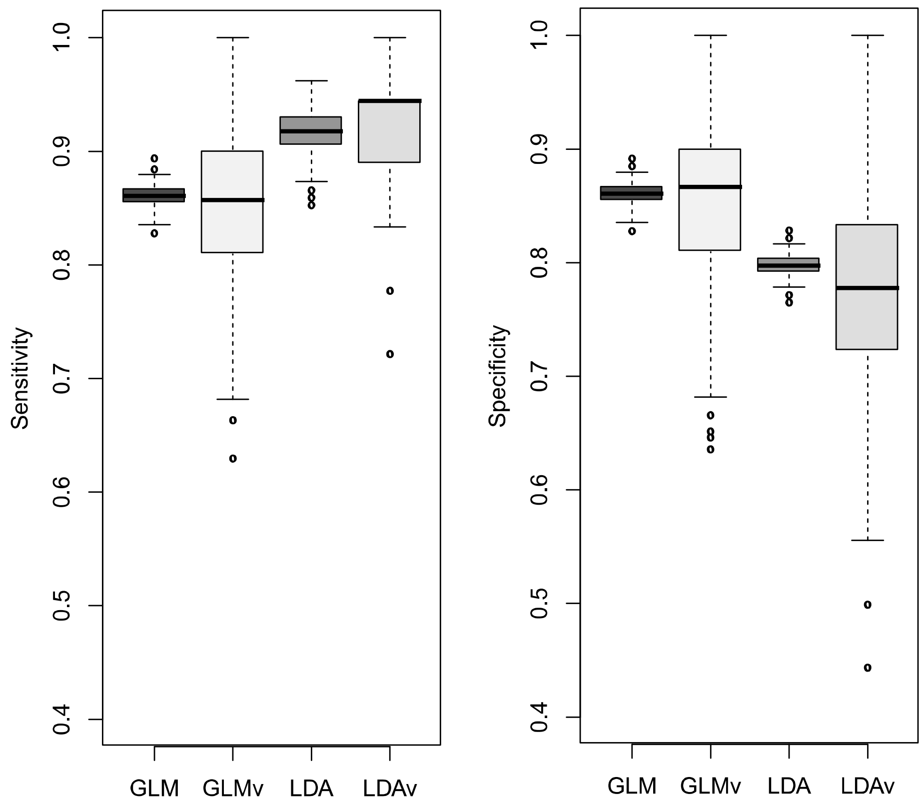

Fig. 5 Comparison of the sensitivity and specificity indicators of the two kinds of models, balanced response groups (GLM: Logistic regression, model dataset; GLMv: Logistic regression, validation dataset; LDA: Linear discriminant analysis, model dataset; LDAv: Linear discriminant analysis, validation dataset)

When we compared the sensitivity and specificity of the logistic regression by taking balanced and unbalanced response groups, the results were close (Fig. 6). However both sensitivity and specificity indicators were improved with unbalanced response, with a median value reached to 0.9 for sensitivity and a Q3 reached from 0.90 to 0.93 for specificity indicator. This comparison of balanced and unbalanced response models led us to choose an unbalanced response sampling to build up the logistic regression.

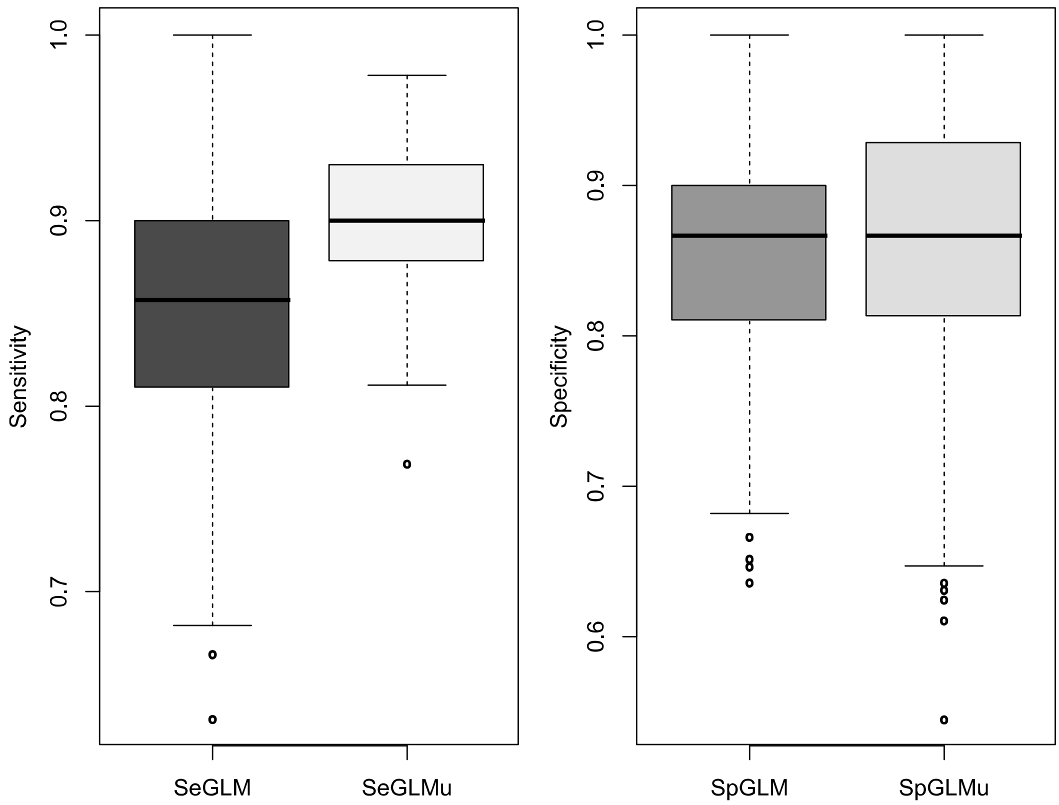

Fig. 6 Comparison of the sensitivity and specificity indicators of the logistic regression with balanced and unbalanced response groups (SeGLM: Sensitivity of the logistic regression model with balanced response variable; SeGLMu: Sensitivity of the logistic regression model with unbalanced response variable; SpGLM: Specificity of the logistic regression model with balanced response variable; SpGLMu: Specificity of the logistic regression model with unbalanced response variable)

An example of unbalanced sampling shows (Fig. 7) a good sensitivity (0.93) and a better specificity (0.93).

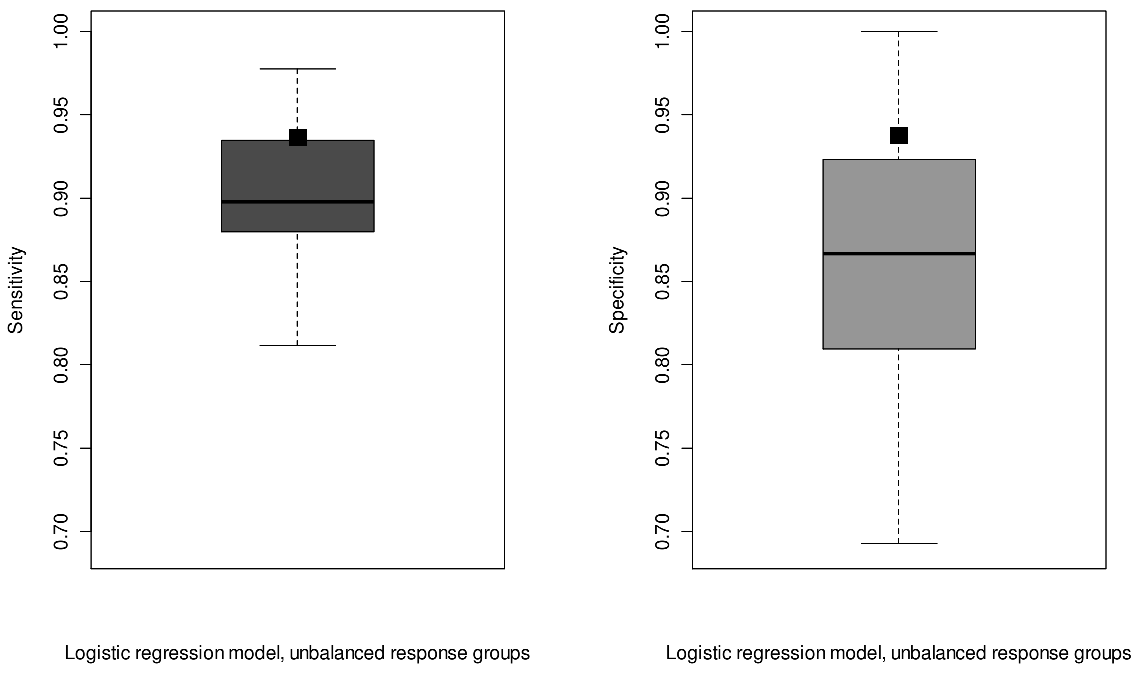

Fig. 7 Comparison of sensitivity and specificity results: unbalanced response variable (boxplot) and final model chosen (square)

Here, the final model is defined with the logit function as:

$$\log(\frac{p}{1-p}) = -0.71 + 1.58\log\left(\frac{H}{\sqrt{A_d}}\right) + 1.97\log s \qquad (1)$$

with log(p/(1-p)) the probability of debris-flow occurrence at point i along a channel, H, the difference between the maximum elevation of the catchment and the elevation of the point i, A_d, the drainage area at point i, and s the channel slope at point i.

DISCUSSION AND CONCLUSION

Data compilation from 620 upland catchments in various mountain ranges of the world under temperate climate provided the opportunity to test the performance of morphometric parameters for the identification of catchments prone to debris-flow. Linear discriminant analysis and logistic regression were used to discriminate fluvial and debris-flow processes. Both statistical models perform well, even if better predictions were obtained with logistic regression.

This study confirms that the Melton index and the fan or channel slope are very good predictors of the dominant sediment transport process of small upland catchments. Debris-flow prone catchments are characterized by steeper catchments and steeper channel slopes than those which only produce bedload transport, as already observed in many regional studies (Kostaschuk et al., 1986; Jackson et al., 1987; Marchi et al., 1993; Marchi and Brochot, 2000; De Scally and Owens, 2004; De Scally et al., 2010). Instead of providing a unique threshold value of the morphometric parameters above which debris-flow may occur, like most of the previous studies did, our large dataset revealed that the two parameters can be combined in a discriminant function showing a decrease of the channel slope threshold with increasing Melton index. This means that steep catchments are expected to produce debris-flows susceptible to stop at lower slopes and then to travel longer distances.

The morphometric approach of debris-flow susceptibility presents some limits. It is restricted to the characterization of the minimum gravitational energy required for debris-flows to propagate along the stream network. This gravitational energy can be quantified by morphometric parameters that can be easily constrained at regional scales from low resolution (~10-50 m) Digital Elevation Models. The statistical models derived from this study are very useful for regional scale mapping of debris-flow susceptibility along a stream network. Each segment of the stream network can be classified according to its probability to be travelled through by a debris-flow. But debris-flow occurrence is only partly explained by gravitational energy. The spatial variability of debris-flow occurrence along a stream network is also controlled by the magnitude and properties of the sediment supply. These sediment controls are very difficult to constrain at the regional scale, because they are closely linked with the geomorphic and geological variability of the landscape. We can argue that the morphometric approach provides a conservative assessment of debris-flow catchments, since the discriminant thresholds allow identifying all the catchments presenting enough gravitational energy to produce a debris-flow. Some of them will not produce debris-flow because sediment supply is insufficient or because the grain-size distribution of the sediment supply (which has an influence on the rheological properties of debris-flow) induces a lower than expected runout distance. Another limitation is that the morphometric approach ignores the conditions of sediment transfer in the catchment, which could be interrupted by sediment trap (i.e. glacial lakes).

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