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A new hierarchical Bayesian approach to analyse environmental and climatic influences on debris flow occurrence

Vincent Jomelli [a,*], Irina Pavlova [a], Nicolas Eckert [b], Delphine Grancher [a], Daniel Brunstein [a]

[a] Laboratoire de Géographie Physique, CNRS, place Aristide Briand, FR-92195 Meudon, France
[b] UR ETGR, IRSTEA/Université Grenoble Alpes, BP 76, 38 402 Saint Martin d'Hères, France

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ABSTRACT

How can debris flow occurrences be modelled at regional scale and take both environmental and climatic conditions into account? And, of the two, which has the most influence on debris flow activity? In this paper, we try to answer these questions with an innovative Bayesian hierarchical probabilistic model that simultaneously accounts for how debris flows respond to environmental and climatic variables. In it, full decomposition of space and time effects in occurrence probabilities is assumed, revealing an environmental and a climatic trend shared by all years/catchments, respectively, clearly distinguished from residual "random" effects. The resulting regional and annual occurrence probabilities evaluated as functions of the covariates make it possible to weight the respective contribution of the different terms and, more generally, to check the model performances at different spatio-temporal scales. After suitable validation, the model can be used to make predictions at undocumented sites and could be used in further studies for predictions under future climate conditions. Also, the Bayesian paradigm easily copes with missing data, thus making it possible to account for events that may have been missed during surveys.

As a case study, we extract 124 debris flow event triggered between 1970 and 2005 in 27 catchments located in the French Alps from the French national natural hazard survey and model their variability of occurrence considering environmental and climatic predictors at the same time. We document the environmental characteristics of each debris flow catchment (morphometry, lithology, land cover, and the presence of permafrost). We also compute 15 climate variables including mean temperature and precipitation between May and October and the number of rainy days with daily cumulative rainfall greater than 10/15/20/25/30/40 mm day^{-1}. Application of our model shows that the combination of environmental and climatic predictors explained 77% of the overall variability of debris flow occurrences in this data set. Occurrence probabilities depend mainly on climatic variables, which explain 44% of the overall variability through the number of rainy days and maximum daily temperature. This important time component in the variability of overall debris flow occurrence is shown to be responsible for a significant increase in debris flow activity between 1970 and 2005 at regional scale. Environmental variables, which account for 33% of the overall variability, includes mostly the morphometric variables of the debris flow catchments.

1. Introduction

Debris flows (DFs) are rapid, surging flows of water heavily charged with rock sediments in a steep channel. This mass movement occurs frequently in mountain areas all over the world and represents a significant natural hazard (Hungr, 2005). Debris flows result from complex interactions between two groups of factors. The first group corresponds to environmental variables like local topography or sediment properties which depend on the lithology, the type of soil, or the vegetation cover. The second group corresponds to climate/weather variables. Hence, to better understand the occurrence of debris flows, analyses should take both environmental and climatic variables into account, but treating them simultaneously in modelling approaches is difficult irrespective of the type of physical or statistical model chosen. For that reason, explanatory climatic and environmental variables of debris flow occurrence are usually analysed separately. However, simultaneous analysis of environmental and climatological predictors makes it possible to investigate their respective roles and to determine which has the most influence on debris flow activity.

Some deterministic models can simultaneously account for environmental and climatic variables in the assessment of debris flow activity. For instance, slope stability models use geotechnical variables to define debris flow susceptibility related to specific rainfall events (Borga et al., 2002; Fiorillo and Wilson, 2004; Gomes et al., 2008; Tarolli et al., 2011). However, these models are generally applied to catchments with

* Corresponding author.
E-mail address: vincent.jomelli@lgp.cnrs.fr (V. Jomelli).

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homogeneous environmental characteristics located in the same climate zone, so as to enable the definition of all the required input conditions. In other words, when using such models, the number of environmental and climatic explanatory variables of debris flow activity is limited, to reduce the difficulty of modelling.

Statistical analyses that search for variables which explain debris flow occurrence generally use a debris flow dataset covering a large territory involving high environmental and climatic variability. So, to reduce the complexity, most studies consider environmental and climatic predictors separately. Lorente et al. (2002), Griffiths et al. (2004), Chen et al. (2009), Blahut et al. (2010), Kapusta et al. (2010), and Tien Bui et al. (2012a) used multivariate and fuzzy logic analyses to isolate specific environmental predictors responsible for changes in debris flow activity over a period of several decades. In these studies, temporal and spatial variations in the climatic component were not included in the analysis. Other authors focused on the climatic component responsible for triggered debris flows either at a local scale or over a large territory (Jomelli et al., 2004; Guzzetti et al., 2006; Magliulo et al., 2008; Sepulveda and Padilla, 2008; Pavlova et al., 2014), but in these studies, the environmental context was implicitly considered to be homogeneous.

A number of authors aimed to combine the two groups of variables, but their analyses did not focus on an accurate quantification and hierarchization of the role of climate versus environment in the triggering of the events (Jomelli et al., 2003, 2007; Chang and Chao, 2006; Xu et al., 2013) with a clear distinction between effects related to the climate and effects related to the environmental conditions. For instance, Bayesian neuronal network approaches have been applied for evaluating landslide susceptibility (Tien Bui et al., 2012b). Logistic regressions were also used by Jomelli et al. (2009) to identify environmental variables responsible for debris flow occurrence including lithology or altitude, and climatic variables including extreme precipitation and the number of days of frost, but the predictor with the most influence on debris flow activity was not identified.

The main goal of this paper is to present a new methodological approach which makes it possible to analyse the main environmental and climatic drivers of debris flow occurrence simultaneously, so as to quantify their respective influence at a regional scale. To reach this goal, an innovative hierarchical Bayesian statistical approach was developed to analyse the debris flow database and identify links between debris flow and environmental and climatic variables. Using probabilistic analysis, it was possible to determine the respective roles of climatic and environmental parameters in debris flow activity, and to link the main changes in debris flows with significant fluctuations in the predominant drivers (climate, environment), with a clear distinction drawn between structured patterns of geophysical meaning and "random" noise. The model can also cope with events that may have been missed during surveys, thus expanding its ability to infer significant links with covariates. As a case study, we chose a large territory where debris flow events were triggered in contrasted environmental conditions and a long enough period to account for the possible effects of climate change.

2. Study area

27 catchments located in Savoie region in the northern French Alps were selected for this study (Fig. 1). Most of these catchments are tributaries of Arc and Isère rivers which both are oriented NW–SE and constitute natural borders of the Vanoise National Park and the Grandes Rousses massif. Many summits exceed 3000 m in altitude with the highest summit Grande Casse peak at 3855 m above sea level. The altitudinal gradient exceeding 1000 m between the upper part of debris flow catchments and the valley bottom and slopes steeper than 30° promote high debris flow activity in this region. Geologically, the catchments belong to the outer and inner crystalline zones. The SE part of this region including the upper part of the valley d'Arc mainly consists of schist, while the central part of the Vanoise National Park is a crystalline outbreak and the lowest NW part is covered by sedimentary rocks. Quaternary deposits are widespread throughout the valleys. These consist of glacial and fluvio-glacial deposits, scree, landslide accumulations and alluvial fans. Arc and Isere valley catchments are exposed to the influence of the Atlantic Ocean macro-circulation, and receive a large amount of precipitation. The mean annual precipitation sum at an elevation of 1000 m a.s.l. is about 1000 mm/year with relatively low variability from one year to another. However valleys N-S parallel to the Alpine structure located in the eastern part of the studied region is characterised by relative drier conditions (about 1400 mm on the western part of the valley and 960 mm on the eastern part). Seasonal distribution of precipitation shows high summer (about 1/4 of the annual amount) and autumn maxima (about 1/3 of the annual amount). The number of rainy days during these periods is about 8 and 11 days per month respectively. Maximum daily precipitation frequently exceeds 15 mm in summer. Mean regional maximum annual temperatures stay close to 10 °C with maxima reaching 30 °C in summer. The 0 °C isotherm is about 2300 m in altitude with variations according to the slope aspect. The tree line limits are at a height of 2300–2400 m a.s.l.

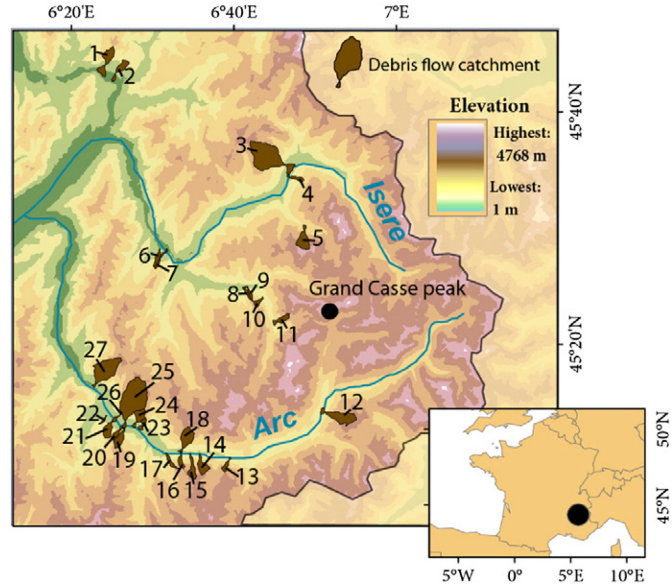

Fig. 1. Location of debris flow catchments in the study area (the French Alps). The numbers correspond to the catchment ID in Table 1.

3. Data sources

3.1. Debris flow data and related environmental variables

A total of 124 debris flow events triggered between May and October were dated daily in the 27 active catchments with more than three debris flow events per catchment between 1970 and 2005 (Fig. 1, Table 1). 17 catchments (60%) showed a moderate frequency with less than five events over the study period, and only six catchments had more than five events during the study period. The highest debris flow frequency per catchment was recorded in Torrent du Poucet with 13 events, and in Torrent du Rieubel and Ruisseau de Cleret with 8 events each.

These events were extracted from a national survey conducted by the 'Restoration of Mountain Land' (*Restauration des Terrains de Montagne*; RTM). This database is a compilation of all possible kinds of historical archives such as monographs by local publishers, technical reports, unpublished documents in the archives of local authorities and state agencies as well as observed data collected by RTM state agencies (Besson, 1985). In the database, a clear distinction is made between debris flow phenomena and mudflows or sediment-laden floods.