Statistical Modelling of Sediment Supply in Torrent Catchments of the Northern French Alps

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Abstract. The ability to understand and predict sediment transport in torrent catchments is a key element for the protection and prevention against the associated hazards. In this study, we collected data describing sediment supply at 100 torrential catchments in the Northern French Alps. These catchments have long records of past events and sediment supply due to debris deposition basin management enabling estimation of sediment supply frequency. The mean annual, the 10-year return period and the reference volume (i.e. the 100-year return level or the largest observed volume) of sediment supply were derived for studied torrents. We examined the relationships between sediment supply volumes and several explanatory variables using multivariate statistical analyses. Several predictive models were developed in order to estimate the sediment supply in torrents that are not equipped with sedimentation structures.

1 Introduction

In mountain areas, the knowledge of the mean annual and event-driven sediment supply potential is important for the assessment of torrential hazards and the management of torrent catchments. Empirical methods, relating volume to descriptive catchment characteristics (for example, [1-3]), are a relatively simple approach to estimate the material supply of a torrent and are commonly used in engineering projects.

These approaches have generally been calibrated on a limited number of torrents and/or with short observation periods. Some of these approaches are specifically focused on debris flows and/or have been calibrated on "specific" torrents, i.e. particular, very active torrents producing large amounts of sediment. Since most empirical equations were derived from samples of very active torrents, these equations may lead to overestimations when applied to catchments with few or small sediment sources. On the contrary, the less active, dormant torrents produce very erratically large amounts of sediment and their low background sediment production is usually unknown. Luckily, some of these rarely active catchments in the French Alps were also equipped with debris deposition basins.

This study aims to present a new prediction approach based on multivariate statistical models calibrated from an original dataset covering 100 torrents catchments in the Northern French Alps for which sediment supply records have been documented over a period of 5 to 40 years and have a wide spectrum of active erosion area and several order of magnitude of sediment specific yield.

2 Materials and method

In this study, we analysed 100 torrents with sediment supply data in the Northern French Alps (Fig. 1). The dataset is varied and includes debris-flow-prone, bedload-prone, and mixed torrents. For example, catchment areas range from 0.06 to 77.8 km² (median: 2.7 km²), the Melton index ranges from 0.09 to 2.8 (median: 0.77), and the ratio R_{zp} of connected eroding areas in the catchment defined as the ratio between the cumulated area of bare soil and rock connected with the torrent bed, divided by the catchment area ranges from 0.1% to 98% (median: 4%).

Data on sediment supply volumes were collected from the monitoring of debris deposition basin dredging and historical records from the catchment managers. For the studied torrents, the records on sediment supply covered periods ranging from 5 to 40 years (mean: 25 years).

These data were used to estimate the average annual volumes for all the torrents studied. For the torrents where long enough records were available, individual frequency analyses for each torrent were performed to estimate the quantile representing the sediment supply volume for a 10-year return period, as well as the reference volume, i.e. the 100-year return level or the largest observed volume (Fig. 2). The latter refers to the volume of the largest known and documented event or a theoretical 100-year return period event, if higher as was the case for 15 catchments. Generalized Pareto distribution GPD or exponential type adjustment were

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performed depending on the number of observations (GPD if n > 10 non-null observations were available).

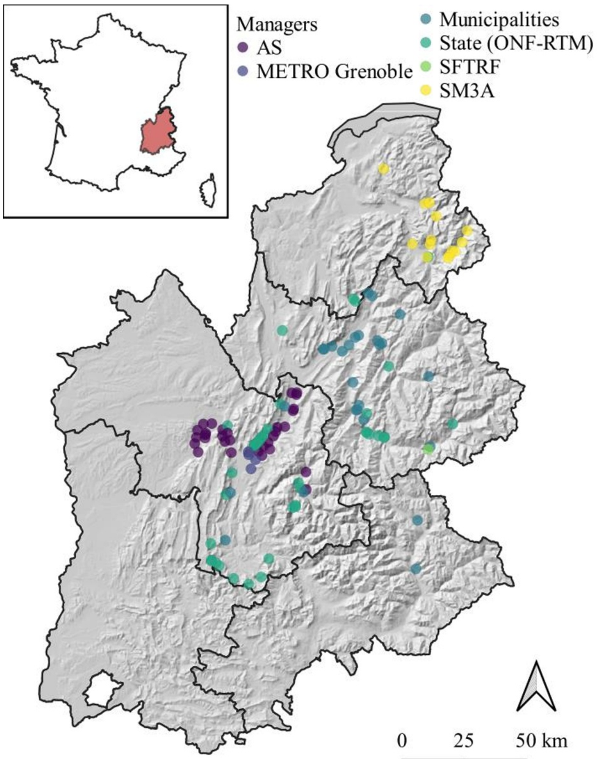

Fig. 1. Spatial distribution of the studied sites. The colours represent the different data providers (State (ONF-RTM): state torrent control service; AS: Isère river tributaries manager in Isère department; METRO Grenoble: intercommunality of Grenoble; SFTRF: Fréjus tunnel motorway manager; SM3A: Arve river catchment manager).

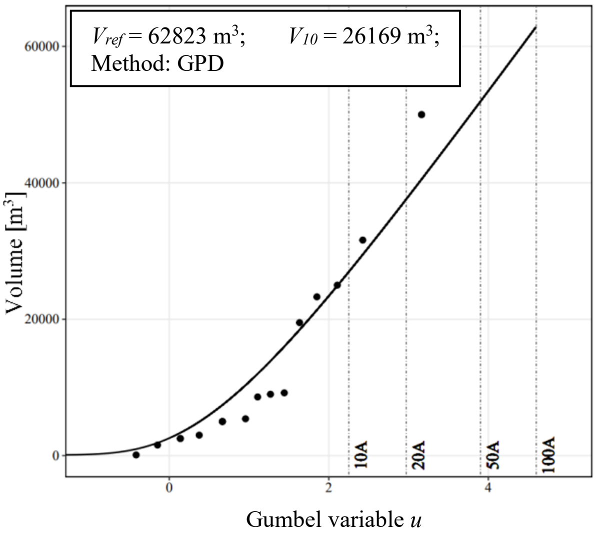

Fig. 2. Statistical adjustment performed from the observations to estimate the volumes: example on the Ebron torrent (Isère, France). The monitoring period covers 35 years and presents 19 years with non-null observations. A GPD distribution was adjusted.

On the studied catchments, several morphological and hydrometeorological characteristics were determined (for example, sediment connectivity indices [4], proportion of connected eroded areas in the catchment, Melton index, alluvial fan slope, etc.). Fig. 3 shows the distribution of some of the calculated explanatory variables.

Based on this database, multivariate statistical analyses using Random Forests (RF) and multiple linear regression (LR) were performed to relate the explanatory variables to the sediment supply variables of the studied torrents.

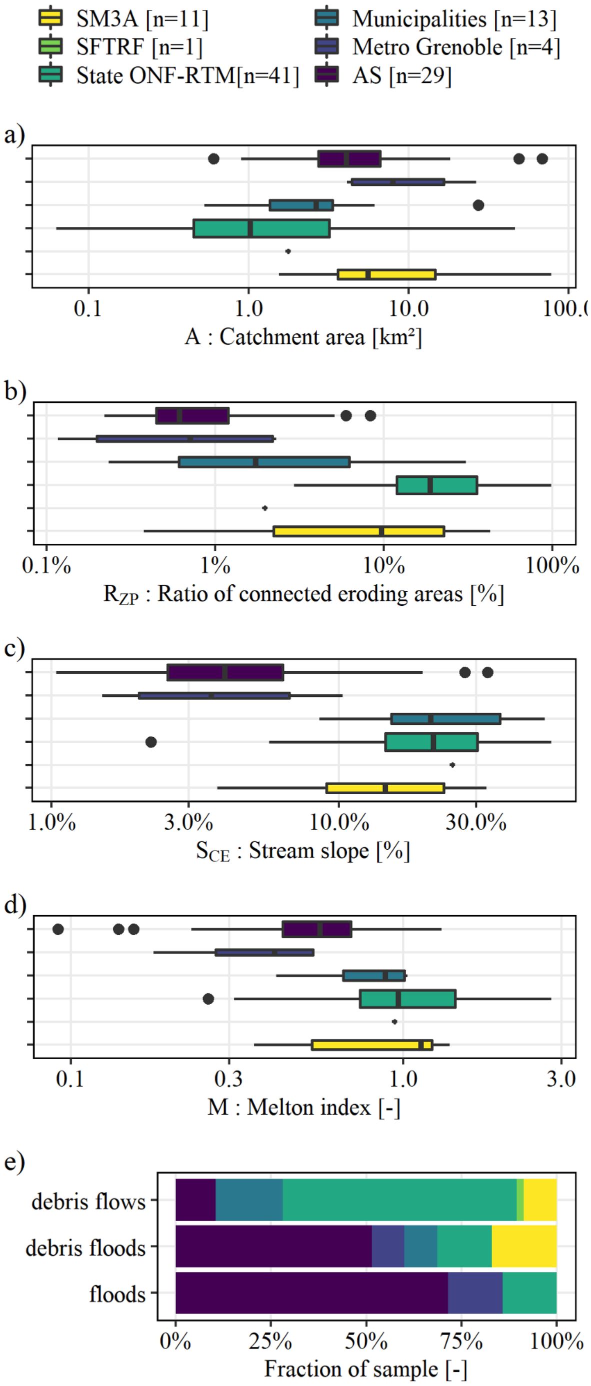

Fig. 3. Distributions of the main characteristics of the studied torrents: a) catchment area; b) ratio of connected areas; c) stream slope; d) Melton index; e) proportion of the of the sample classified according to [5] into debris flows, debris flood or floods. The colours represent the different data providers.

3 Results and concluding remarks

Multivariate statistical analyses were used to select the most relevant variables to predict the specific annual sediment yield (m^3/km²/year) and the event specific sediment yield (m^3/km²/event) for the 10-year return period and the reference event.

Results showed that the ratio R_{zp} of connected eroding areas was the most important predictor of the sediment production volumes (eg. Fig. 4). Other variables such as the Melton index or the indices of sediment connectivity have also an influence.

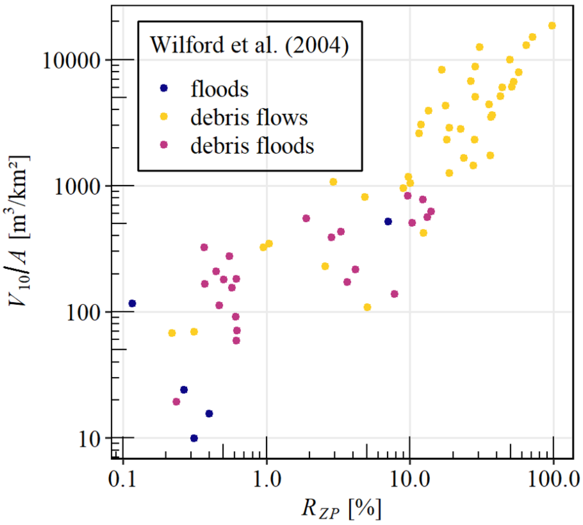

Fig. 4. Relationship between the specific sediment yield for the 10-year return period and the ratio of connected eroding areas; colours refer to the classification into debris flows, debris flood or floods according to [5].

Several statistical models were then calibrated based on several selected explanatory variables and their performance was then assessed. For example, Equations (1-3) show the most simple predictive models derived from the LR involving the catchment area and the ratio of connected eroding areas.

$$V_m/A=52\ R_{zp}^{0,81} \qquad (1)$$

$$V_{10}/A=168\ R_{zp}^{0,88} \qquad (2)$$

$$V_{ref}/A=475\ R_{zp}^{0,94} \qquad (3)$$

where V_m, V_{10} and V_{ref} are the mean annual volume, the 10-year return period volume and the reference volume (m^3), respectively; A is the catchment area (km²) and R_{zp} is the ratio of connected eroding areas in the catchment (%).

To assess the performance of the different models, we performed a leave-one-out cross-validation procedure, and we used several criteria: the coefficient of determination R2, the percentage bias, the RMSE-standard deviation ratio of observations. In general, the selected models predict satisfactory sediment supply volumes, even with very simple empirical equations such as Eq. (1-3). The predictive models lead to R2 coefficients ranging from 0.62 to 0.75. Contrary to what was expected, the RF models do not bring improvements compared to the LR models (e.g. Fig. 5). All the details regarding both the material and methods, and the results can be found in the research report of the project [6], as well as in a preprint paper [7] (including the full dataset).

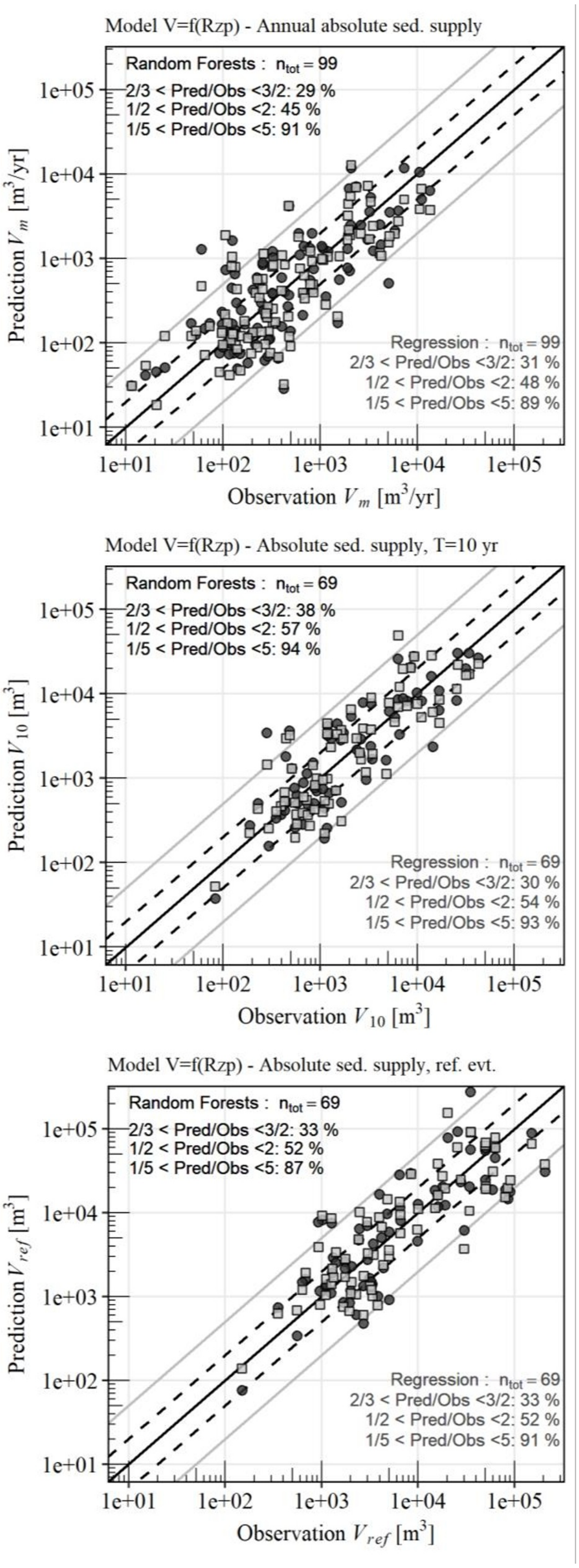

Fig. 5. Predicted against observed values of sediment supply for the V_m, V_{10} and V_{ref}. The grey squares et and dark circles represent the values predicted by LR (Eq. 1-3) and RF respectively. Solid black line refers to the perfect agreement. Dashed and grey lines refer to [$V_{pred.}$/2 ; 2$V_{pred.}$] and [$V_{pred.}$/5 ; 5$V_{pred.}$], respectively.

Performance was also assessed by measuring the proportions of the ratio of predicted to observed values within the intervals [2/3; 3/2]; [1/2; 2] and [1/5; 5]. We noticed that about 30 % of the predictions fall in the first interval, about 50 % in the second and a very high proportion in the third which is very large. This demonstrates the limitations of these methods that provide at most orders of magnitude of sediment supply.

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