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

Maxime Morel[1,2], Guillaume Piton[1], Damien Kuss[3,4], Guillaume Evin[1], and Caroline Le Bouteiller[1]

[1]Univ. Grenoble Alpes, INRAE, CNRS, IRD, Grenoble INP, IGE, 38000 Grenoble, France

[2]Office National des Forêts - service de Restauration des Terrains en Montagne des Hautes-Alpes, 5 rue des Silos, 05000 Gap, France

[3]Office National des Forêts - Direction Forêt Risques Naturels, 9 quai Créqui, 38000 Grenoble, France

[4]Syndicat Mixte des Bassins Hydrauliques de l'Isère, 9 rue Jean Bocq, 38022 Grenoble, France

Correspondence: Guillaume PITON (guillaume.piton@inrae.fr)

Abstract.

The ability to understand and predict coarse 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 99 torrential catchments in the Northern French Alps. The sample covers a wide range of geomorphic activity: from torrents experiencing debris flows every few years to fully forested catchments exporting small bedload volumes every decade. These catchments have long records of past events and sediment supply to debris basins. 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 specific sediment supply volumes and many explanatory variables using linear regression and random forest approaches. Results showed that the ratio of sediment contributing area (bare soil) to catchment area is the most important predictor of the sediment production specific volumes (m^3/km^2). Others variables such as the Metlon index or the indices of sediment connectivity have also an influence. Several predictive models were developed in order to estimate the sediment supply in torrents that are not equipped with debris basins.

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. Four main groups of approaches are typically employed to predict the volumes produced by debris flows and/or floods: (1) empirical approaches relating volume to catchment descrip-

tive parameters (e.g. Takei, 1984; Marchi and D'Agostino, 2004); (2) hydrological approaches considering the link between volumes and water flows (Rickenmann and Koschni, 2010); (3) geomorphological approaches estimating volumes from on-site recognition of sediment sources located along the channel network (Hungr et al., 1984); and (4) historical approaches assessing

20   volumes from data observed during previous events (e.g. test pits, topographic surveys of the deposited volumes, dredging of debris basin - D'Agostino, 2013). If there is sufficient data, a frequency analysis can also be considered (Jakob and Friele, 2010).

Empirical methods are a relatively simple approach to estimate the material supply of a torrent and are commonly used in engineering projects (Jakob, 2021). Several relationships have been established in the literature (Table 1) involving only one

25   or multiple parameters with, for example, a surface area parameter (catchment area, sediment contributing area also called effective catchment area or contributive catchment area - Harvey, 2002; Fryirs, 2013), a slope parameter (stream slope, fan slope), a length parameter (length of the erodible channel) or a parameter relating to the geological/geomorphological context reflecting the potential for erodible materials. It is also worth noting that these relationships have been produced from regression (i.e. mean trends) or envelope curve models (i.e. maximum potential).

30   When sufficiently data are available, the 10- and 100-year volumes can be calculated using a frequency analysis similar to that used for instance in hydrology. D'Agostino and Marchi (2001) for instance proposed an envelope curve parametrized with the return period based on data coming from only three torrents. Time series of event magnitude are seldom available in torrent catchments. As can be seen Table 1, the existing relationships are mostly related to event-based data sets (where each event observation corresponds to a different catchment), and for which the prediction cannot be linked to any notion of return period.

35   Furthermore, these relationships 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 overly conservative estimations when applied to less active catchments. Indeed, these less active, dormant torrents produce very erratically large amounts of sediment and their low back-

40   ground sediment production is usually unknown. Luckily, some of these rarely active catchments in the French Alps were also equipped with debris basins.

Why sediment export varies so much between mountain catchments remains a very active research topic. In addition to catchment size, slope, land cover and geology, the sediment connectivity is increasingly highlighted as a key driving factor (Heckmann et al., 2018; Altmann et al., 2021; Arabkhedri et al., 2021). Recently, the concept of (sediment) connectivity has

45   been introduced to describe the efficiency of sediment transfer from its sources to the river system and the links between sources and sinks of sediment such as lakes in the upstream areas of catchments (Fryirs, 2013). The connectivity and disconnectivity of sediment sources to river systems within catchments are essential for sediment fluxes and thus for sediment export at catchment outlets. Several indices have been developed to quantify this phenomenon in the catchments (Heckmann et al., 2018). In particular, the index of connectivity (IC) (Borselli et al., 2008; Cavalli et al., 2013) has been widely used in torrential

50   catchment studies (e.g. Micheletti and Lane, 2016; Blanpied et al., 2018; Schopper et al., 2019).

Table 1: Summary of the main empirical methods for predicting sediment production volumes of Envelope Curve type (EC) or regression equation (RE). See definition of the parameters in notation list in the appendix.

Reference	Equation	Type	Description
Zeller (1976)	$V_{100} = 755.1 \cdot \chi_1 \cdot A^{0,782}$	?	Equation based on a sample of 16 events that occurred in Uri region (Switzerland). Area of catchments between 1 ha and 10 km^2. Values of coefficient χ_1 for a "100-year" event between 6 and 20
Takei (1984)	$V = 13,600 \cdot \chi_2 \cdot A^{0.61}$	RE	Equations based on 551 events in Japan between 1972 and 1977. $\chi_2 = 1.0$ correspond to a median regression, other values can be considered to get higher estimates, e.g. $\chi_2 = 5.22$ or 8.38 correspond to an envelop curve of 90% and 95% of data, respectively
Kronfellner-Kraus (1984)	$V = 100 \cdot \chi_3 \cdot A \cdot S$	?	The author specifies that this formula gives the order of magnitude of the volume during extreme events. Relationship established using a sample of 1420 cases in the Austrian Alps. χ_3 varies between 250 and 1750 for low to very active catchments
D'Agostino et al. (1996)	$V = 29,100 \cdot A^{0.67}$ $V = 84,000 \cdot A \cdot S^{1.3}$ $V = 45,000 \cdot A^{0.9} \cdot S^{1.5} \cdot GI$ $V = 39,000 \cdot A \cdot S^{1.5} \cdot GI \cdot \chi_4^{-0.3}$	RE	Equations based on 62 events that occurred in Italy (Trentino). $\chi_4 = 3$ for debris flows, 2 for debris floods and 1 for floods
Rickenmann (1997)	$V = \chi_5 \cdot A^{0.78}$ (a) $V = (640 \cdot S_C - 23) \cdot L$ (b) $V = (110 - 250 \cdot S_C) \cdot L$ (c)	?	Equations given in the case of a very high solid transport. (a) : χ_5 range from 17,000 to 27,000. It is considered here that the relation with a coefficient of 27 000 is an envelope curve. (b) : if 0.07 m/m $\leq S_C \leq$ 0.15 m/m. (c) : if 0.15 m/m $\leq S_C \leq$ 0.40 m/m
D'Agostino and Marchi (2001)	$V = 70,000 \cdot A$	EC	Relationship established on a sample of 84 cases in the upper part of the Adige basin (province of Bolzano, Italy).
	$V = 25,415 \cdot A \cdot S^{1.28} \cdot GI$	RE	The sample includes very diverse data with volumes ranging from 700 m^3 to 950,000 m^3
	$V_T = (14,500 \cdot (-\log(-\log(1-1/T)) - 3,500) \cdot A$	EC	Envelope curve built from an analysis on 3 Italian catchments: Moscardo torrent (4.1 km^2, 9 years of data), Rio Bianco torrent (0.88 km^2, 20 years of data) and Rio Inferno torrent (0.69 km^2, 46 years of data)

Table 1 – continued from previous page

Reference	Equation	Type	Description
Franzi and Bianco (2001)	$V = 8,959 \cdot A^{0.7652}$	RE	Equation based on a sample of 201 data from the Swiss, Italian and French Alps
Marchi and D'Agostino (2004)	$V = 65,000 \cdot A^{1.35} \cdot S^{1.7}$ $V = 18,000 \cdot A^{1.16} \cdot S^{1.3} \cdot GI$	RE	Same approach as that undertaken in the work of D'Agostino et al. (1996) with a larger sample: 125 events in Italy in the eastern part of the Italian Alps, a doubling of the sample compared to 1996. But the statistical analysis that led to the relationships was performed on 86 cases where $V/A > 2,500$ m^3/km^2 and $V/L > 2,1$ m^3/ml
Peteuil et al. (2012)	$V = 25,000 \cdot A$ $V = 120,000 \cdot (A \cdot R_{zp})^{0.6}$	EC	Relationships resulting from a sample of 72 torrential catchments mainly located in the french northern Alps

This study aims to present a new prediction approach overcoming the several limitations pointed above. It is based on multivariate statistical models calibrated from an original data set covering 99 torrent catchments in the Northern French Alps. These catchments have a wide spectrum of sediment contributing area and several order of magnitude of sediment specific yield, and their sediment supply records have been documented for years to decades. From these records we were able to estimate statistically the mean annual, 10-year return period, and reference volume. Then we examined the relation between theses volumes and several explanatory variables such as geomorphological, hydro-climatic, geological or sediment connectivity indicators. Statistical approaches (random forest and power law regressions) were used for a simple use based on the most significant indicators. The paper presents the data set used and explain how can be extracted the explanatory variables. It then explores the correlation between catchment scale parameter and exported sediment volumes. The accuracy, application domain and limitations of the method developed are finally discussed.

2 Materials and methods

2.1 Sediment yield data

Data on sediment volumes were collected from the monitoring of debris basin dredging at the outlet of 120 investigated catchments. Those structures are managed by the french torrent control service ONF-RTM (*Office National des Forêts - Restauration des Terrains en Montagne*, n = 44 debris basins) or by local stakeholders such as river managers or municipalities (n = 76 debris basins) (Figure 1). Structures managed by ONF-RTM concern generally the most active catchments which were acquired by the French government during the late 19th and early 20th centuries to perform reforestation and torrent control masterplans (Piton et al., 2017). In these active catchments, debris basins were later built to protect various assets (e.g. roads, urbanized
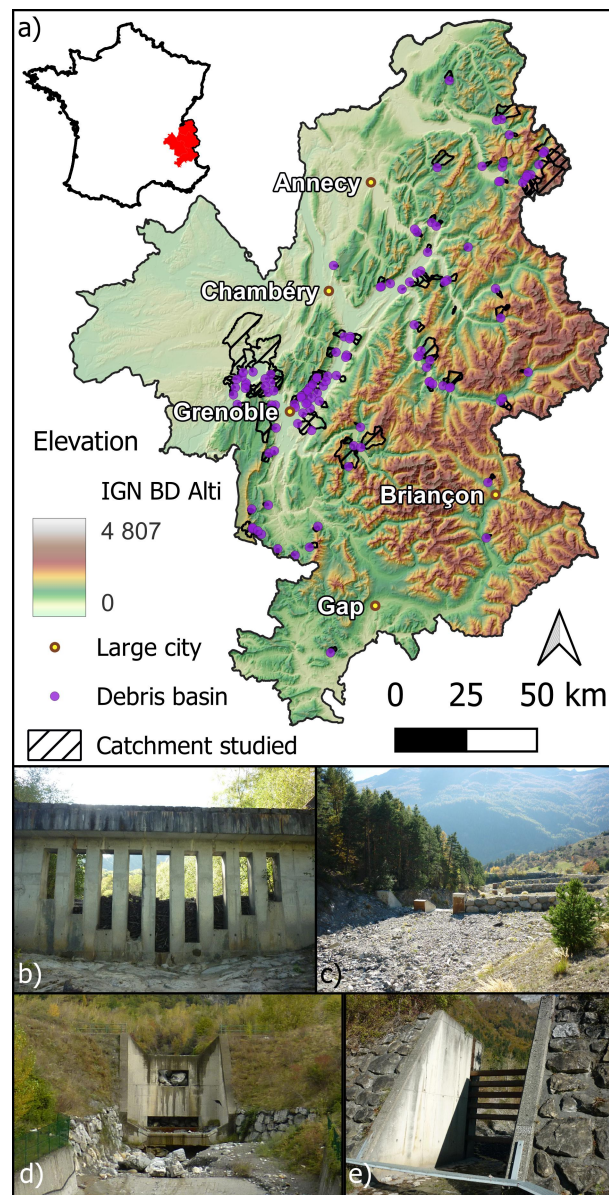
4

Figure 1. a) Spatial distribution of the studied sites (a link to access to maps of each catchment is provided at the end of the paper); examples of debris basin open check dams: b) Lavanchon torrent (Saint-Paul-de-Varces), c) Verdarel torrent (Saint-Chaffrey), d) Claret torrent (Saint-Julien-Mondenis) and e) Nant Croex (Ugine)

70   areas). Debris basins managed by local stakeholders concern mostly small and less productive catchments that nonetheless experience erratic intense bedload transport during strong floods. The types and shapes of the debris basin are heterogeneous (e.g. Figure 1b-e). The inventory of Carladous et al. (2022) showed that most of these structures, despite their variety, trap most of the coarse sediment supplied: their dredging is thus a relevant proxy of the catchment sediment yields. These structures are generally located near the apex of alluvial fan, but some of them are located in other parts of the catchment to protect specific

75   assets. Depending on the activity of the catchment, dredging was carried out several times a year or as soon as the structure was partially filled. The dredging operations were mainly carried out using mechanical excavators and trucks. Estimates of volumes were generally made by counting the trucks evacuating the sediment and at lesser times by comparing topographic surveys. It is noteworthy that these measurements have uncertainties that are difficult to quantify, but that we assume to be $\pm$ 25%. Due to the regular dredging of the debris basins, data could be collected continuously for each studied catchment, dredging operation

80   covered periods ranging from 5 to 40 years (mean = 25 years). A total of 797 dredging operations were recorded (with a mean number per catchment mean of 7, and a range of 1 to 28).

In addition, another source of sediment supply data in the 120 basins comes from the national database on torrential events (BD-RTM; https://bdrtm.onf.fr). Briefly, this database provides information on past events that have been recorded in the catchments, giving details of any causes, process type (i.e. debris flows or flood), damage and estimated volumes of sediment

85   transported. This database is complementary to the debris basin dredging data as it provides data on sediment supply that occurred before the structures were built. Moreover, the event volumes are sometimes more reliable in cases where the sediment volume is higher than the capacity of the structure, since they include an estimation of all the deposits. The BD-RTM provided details on 348 events in the studied catchments. The number of events per catchment varies from 0 to 19. Similarly to dredging volumes, estimates of these volumes are subject to uncertainties that are difficult to quantify.

90   A check of the input data was applied especially when an event occurred in the same year as a dredging operation. In the case of inconsistent estimated volumes from both events and dredging, we made a correction by retaining the largest volume. This ensures a safe estimate of sediment production in the catchment.

2.2   Estimation of sediment yield characteristics

Average annual sediment yields were estimated by analyzing the sediment supply data within a temporal window corresponding

95   to the period of monitoring of the debris basin dredging (i.e., from the year of the structure construction to the most recent year for which the managers provided dredging operation information). We estimated the mean annual production V_m by taking into account the volumes of events and dredging volumes (data from the managers of the structure and the BD-RTM). The data check identified several suspicious structures with clear change in dredging frequency suggesting a change in the function of the structure (e.g., when cleaning is abandoned, the structure tends to maintain a sediment regulation zone where flow

100   spread freely and pseudo-cycles of erosion and deposition occurs freely). These structures can lead to an incorrect estimation of average volumes and were excluded from the data set. In the end, 99 structures were retained for the analysis.

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 V_{10}, as well as the reference volume
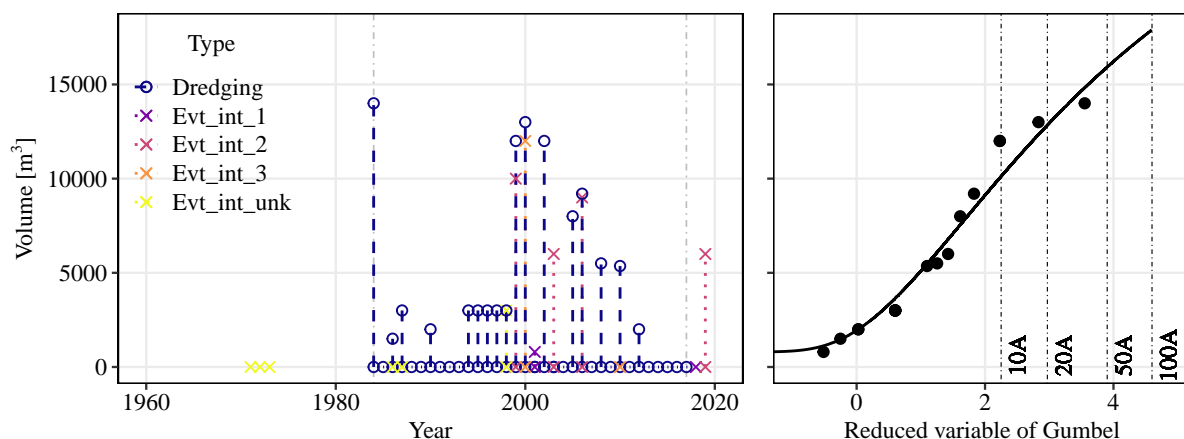
Figure 2. Example of a reconstructed sediment yield time series: case of the Arches torrent (Isère, France). The left panel represents the amount of solid input volume and the years of occurrence of these inputs. The types of dots and lines differentiate the type of input data (i.e., dredging data or historical event). The color of the dots and lines informs the intensity associated with the historical event ("Evt_int_1", "Evt_int_2", "Evt_int_3", "Evt_int_unk" refer to minor, moderate, high and unknown intensity, respectively). The two vertical dashed lines in grey delineate the monitoring period. The right panel shows the adjustment performed from the observations to estimate the volumes. The monitoring period covers 35 years and presents 19 years with non-null observations. A GPD distribution was adjusted.

V_{ref} (Fig. 2). The latter refers to the volume of the largest known and documented event or a theoretical 100-year return period
105   event, if higher as was the case for 15 catchments. Generalized Pareto distribution (GPD) or exponential type adjustments were performed depending on the number of observations (Coles, 2001). The data set was separated into three sub-samples based on the number of non-null and unique observations of sediment volume n : (1) if $n \leq 5$ (50 % of the cases), we computed the mean annual production but avoid extrapolation. These watersheds were therefore not used to estimate V_{10} and V_{100}; (2) if $5 \leq n < 10$ (25 % of the cases), an exponential distribution was adjusted ; (3) if $n \geq 10$ observations (25 % of the cases), a
110   GPD distribution was adjusted. Finally, we estimated V_{10} and V_{ref} for 69 catchments. The plots of the reconstructed sediment yield time series and the statistical adjustments are presented for the individual catchments in the Figure SM1.

The volumes were also normalized by the watershed area A to work with specific sediment yields (V_m/A, V_{10}/A and V_{ref}/A) expressed in m³/km² that can more easily be cross-compared between catchments.

2.3   Explanatory variables of sediment yield

115   Inspired by our expert knowledge, by previous works cited in Table 1 and by the literature on sediment connectivity, we did our best to estimate simple proxies of potential drivers of the sediment production: rainfall, relief, geology, land use, connectivity indexes and process type. More sophisticated indicators and models certainly exist but using them on a sample of about one hundred catchments was out of the scope of this work which was to develop a method simple to use even if crude in its result.

2.3.1 Precipitations

120 An analysis of the rainfall chronicles was carried out for each catchment in order to obtain rainfall quantile values. For this purpose, the rainfall data from the COMEPHORE reanalyses were used (©Météo France, see https://radarsmf.aeris-data.fr/). These data provide precipitation values at an hourly time interval, on a 1 km² resolution grid and over the period 1997-2017. To have a single hourly value in each catchment, weighted average of the set of COMEPHORE grid cells included in the catchment extent were computed. The three annual maximum rainfall events of 1 h, 6 h and 24 h duration were extracted

125 from the time series and their empirical probability of occurrence was estimated using the Weibull formula (Coles, 2001). The 10-year return period values of each rainfall duration was then computed ($P1h_{10}$, $P6h_{10}$, and $P24h_{10}$, respectively).

2.3.2 Morphometric parameters

The Melton index M is an index of the ruggedness of the catchment (Melton, 1965) and is calculated as the ratio of the catchment relief (difference between the catchment maximal elevation and the elevation of the debris basin) by the square root

130 of the catchment area measured at the debris basin. It is a normalized index of the gravitational energy of the catchment.

The mean stream slope S_{CE} and the fan slope S_C were calculated. The first refers to the mean slope of the reach located upstream of the debris basin and controlling the sediment transport, i.e. the reach with the mildest slope. The latter refers to the mean slope of the reach at the fan apex measured on with a length equal to $10-20$ channel widths (Bertrand et al., 2013).

All variables were calculated using the 25 m resolution national DTM covering the entire study area (BD Alti ®, see details

135 in https://geoservices.ign.fr/bdalti and Discussion about the related uncertainties).

2.3.3 Sediment transport processes

Several studies revealed that it is possible to discriminate catchments depending on the dominant sediment transport process using geomorphic characteristics (although these methods cannot be very accurate, they provide a first approximation, see Church and Jakob, 2020). Wilford et al. (2004) developed a method using the stream length combined with the Melton index

140 to differentiate between debris-flow-prone, debris flood-prone and flood-prone catchments. Bertrand et al. (2013) developed a model to discriminate debris-flow- and flood-prone torrents using Melton index and fan slope. Examination of the watershed classes according to the two methodologies shows that the method of Bertrand et al. (2013) tends to merge debris flows and debris floods in the same pool (Figure 3). This may be due to the estimation of the fan slope which can be uncertain because of the coarse resolution of the DTM and because some catchments do not have a clearly defined fan. For these reasons, we

145 adopted the method of Wilford et al. (2004) for the study.

2.3.4 Sediment contributing area: connected eroding areas

We delineated the sediment contributing area using the French GIS database of the forest inventory as a mask (BD Forêt® V2, mapping vegetation units of surface > 5000 m², see https://geoservices.ign.fr/bdforet). This database provides an accurate digitization of the different natural vegetation covers (with information of the vegetation type, e.g. moorland, herbaceous for-
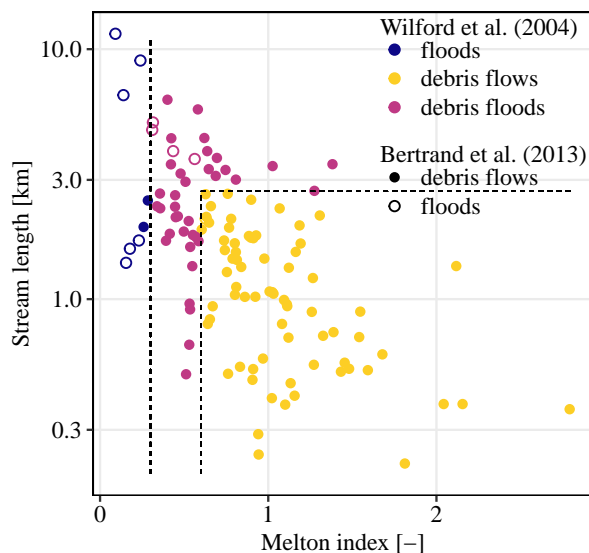
Figure 3. Catchment classifications based on the dominant sediment transport process. The color of the points indicates the classification according to Wilford et al. (2004). The dashed lines indicate the discriminating limits of the different categories according to this method. The type of dot indicates the classification according to Bertrand et al. (2013).

150   mations, deciduous forest, coniferous forests). Land without vegetation cover can correspond to agricultural areas, to artificial areas (e.g. urban, road) or to bare soil, often located in the headwaters. Here, geometries with bare soil were considered as potentially sediment contributing area (the definition is thus not exactly the same than that used by Haas et al., 2011; Altmann et al., 2021, but goes essentially in the same spirit). To some extent, vegetated geometries considered as moorland may sometimes be potentially sediment-producing diffuse gullying areas. These geometries were included or excluded from the

155   potential sediment contributing area after a quick visual assessment of each geometry. We then characterized if these areas were connected to the channel network (Figure 4). For this purpose, following Peteuil and Liébault (2011), an area of bare soil was considered connected and thus part of the sediment contributing area if (i) continuous bare soil was visible between the hillslope and the channel on the orthophotos, or (ii) a permanent or ephemeral watercourse draining this area was present in the BD TOPO® database (base of detailed hiking maps usable down to a scale of 1:2000, see https://geoservices.ign.fr/bdtopo).

160   The data processing allowed us to calculate the connected sediment contributing area for each catchment (A_{ZP}). We are thereafter interested in the proportion of sediment contributing area to catchment area $R_{ZP} = A_{ZP}/A$.

We identified 37 catchments for which no bare soil area was delineated with our protocol. Having catchments with null value as sediment contributing area would be an issue for the statistical method used. After analysis of aerial images, these catchments do not have clearly visible sediment contributing areas, except for two watersheds for which the BD Forêt® does

165   not detect small bare soil zones. For these catchments, we assumed that the very small sources of sediment are essentially remobilization of sediment from the stream bed. We approximated the channel widths from hydraulic geometry relationships that relate the bankfull width to the catchment area. Hydraulic geometry models have been recently developed in France on a
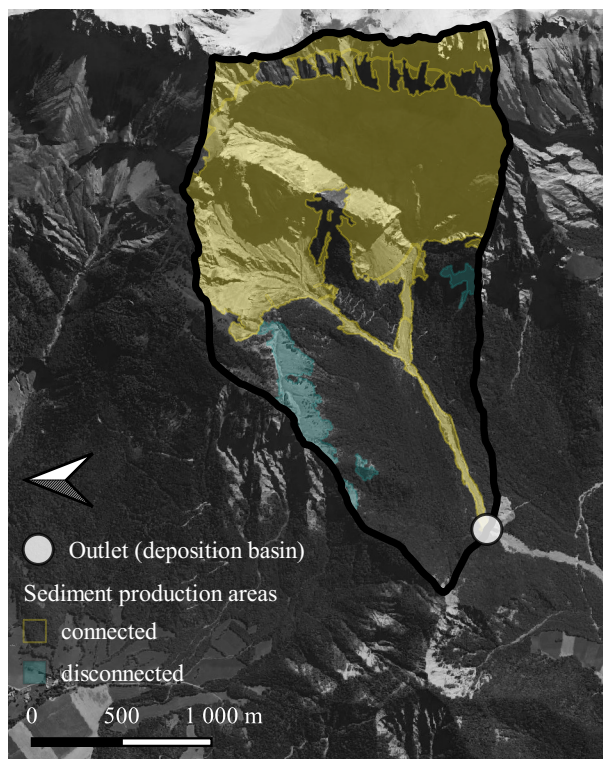
Figure 4. Delineation of sediment contributing area, example of the Ebron torrent catchment (Isère, France). Most of the bare soil is connected (yellow polygon) but two disconnected talus slopes without vegetation can be seen on each side of the main channel (green polygons) and are not considered in the computation of the sediment contributing area (background image source: IGN BD ortho).

national and regional scale (Gob et al., 2014). In our case, we estimated the bankfull width W_{bf} for all study sites using the regional hydraulic geometry model built from observations in the inner French Alps: $W_{bf} = 5.06 \cdot A^{0.27}$. Channel bed area was

170 estimated by the product $W_{pb} \cdot L_{CE}$, where L_{CE} is the length of the main stream in the catchment. This channel bed area was added to the value of sediment contributing area previously estimated in each basin.

2.3.5 Geological index

A geological index GI was calculated on the sediment contributing areas following the methodology proposed by D'Agostino and Marchi (2001). Its value is computed by weighting the score associated to each lithological class (e.g. 5 for Quaternary

175 deposits, 3 for marls and 0.5 for granits) in proportion to the area covered by this lithology in the studied area, here the sediment contributing area. This parameter is a proxy of the relative erodibility of the lithology of the sediment contributing area. The definition of the lithological classes was performed mainly on the basis of national geological maps (BD Charm-50 ©BRGM, see https://www.geocatalogue.fr/Detail.do?id=4156).

10

2.3.6 Index of connectivity IC

Calculation of the Index of connectivity IC was implemented thanks to the SedInConnect stand-alone software (Crema and Cavalli, 2018). It is based on a morphometric algorithm that computes the potential connectivity between hillslopes and a target area from a digital terrain model. Briefly, IC is defined as the logarithm of the ratio between an upslope- and a downslope-component expressing the potential for downwards routing of the sediment produced upslope and the sediment flux path length to the nearest sink along a flow line respectively for each grid-cell of catchment (Borselli et al., 2008; Cavalli et al., 2013). It can be expressed as follows:

$$IC_i = \log_{10}\left(\frac{\overline{W}_i \cdot \overline{S}_i \cdot \sqrt{A_i}}{\sum_i \frac{d_i}{W_i \cdot S_i}} \right) \tag{1}$$

where i is the index of the grid cell at which the computation is performed, A_i is the upslope area (km^2), d is the length of the steepest flow line between grid-cell i and the target area (m). $\overline{\chi}_i$ represents the average value of any parameter χ on the the upslope area of pixel i, e.g., of the slope $\overline{S}_i$ (m/m) or of the weighting factor $\overline{W}_i$. W is a weighting factor used to capture the spatial variability of some factor enhancing or damping the sediment transport process. Using the approach of Cavalli et al. (2013), especially suitable for torrents, W is computed from the standard deviation of the residual topography, i.e. difference between the point elevation and the mean average taken on a moving square window of side 5 pixels. A maximum absolute roughness is used to normalize this index. The maximum roughness measured on the Northern French Alps - 75.4 m - was used over all catchments to enable cross-comparison of values between catchments. The computation of the IC considers local obstructions to sediment transfer by providing sink polygons (lakes and glaciers in our analysis).

As output, SedInConnect computes IC values for each grid element. The IC is defined in the range of [-∞, +∞], the result is presented in terms of high or low index, where high values represent a better connectivity to the target. Here, the targets are the catchment outlets. The same DTM than previously was used. Its spatial resolution of 25 m was a bit coarse, 5 m for instance would have been better to capture the typical size of landforms relevant to debris flows and debris floods (Torresani et al., 2021), but such a detailed DTM was not available at the scale of the study.

The IC values being variable over the catchment of each debris basin, several statistical values were extracted as potential candidates to be relevant proxies of the catchment-scale connectivity. The mean, median and 95% quantile of the IC (ICm, $IC50$ and $IC95$, respectively) were extracted for each catchment. Most of the sediment being supplied by the sediment contributing areas, the median and 95% quantile of the IC were also extracted specifically on the grid elements included in the sediment contributing areas ($IC50_{ZP}$ and $IC95_{ZP}$, respectively).

For basins without delineated sediment contributing area, we assumed that sediment was supplied in a diffuse way throughout the catchment (the channel area was just a proxy of the sediment source area). Since no known source zone was mapped, we assumed the catchment mean IC value to be a relevant proxy of the sediment source IC. A lower envelope curve was defined from a scatter plot of $IC95_{ZP}$ versus ICm to verify this hypothesis on the catchments with known sediment contributing area (Fig. 5). The analysis shows that the ratio of $IC95_{ZP}$ to ICm is generally < 1 except in a few catchments where the ratio is
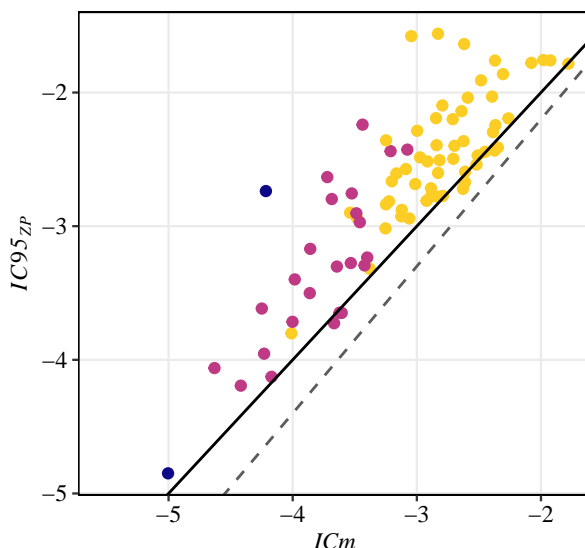
Figure 5. Relationship between $IC95_{ZP}$ and ICm of every catchments. The solid line indicates the line $1:1$. The grey dashed line indicates the line $1:1.1$. The color code corresponds to the dominant sediment transport process: yellow = debris flow, pink = debris flood and purple = bedload.

near 1.1. We arbitrarily assigned $IC95_{ZP} = 1.1 \cdot ICm$ to basins without mapped sediment contributing area. The underlying idea was to assign a value consistent with the distribution of the catchment IC but representative of the lowest connectivity in the data set studied.

Rather than absolute values of IC that must be interpreted with caution (Cavalli et al., 2013; Heckmann et al., 2018), we tested ratios of IC that could be somewhat normalized. The underlying assumption was that high catchment activity could be captured by relatively high connectivity of the sediment contributing area to the outlet as compared to the typical connectivity of the catchment. The ratios of the mean and 95% quantile value of IC computed in the sediment contributing area to the values sampled on the whole catchments were also computed (R_{ICm} and R_{IC95}, respectively).

2.4 Modelling approach

Random forests (RF) and linear regression (LR) techniques were applied to relate geomorphic and climatic characteristics to sediment yield volumes. Briefly, a RF model comprises an ensemble of individual classification and regression trees (a forest) from which a final prediction is based on the predictions averaged over all trees (Breiman, 2001). A RF model is created by drawing several bootstrap samples from the original training data and fitting a single classification tree to each sample. Independent predictions (i.e. independent of the model fitting procedure) are made for each tree from the observations that were excluded from the bootstrap sample (the out-of-bag samples OOB). These predictions are aggregated over all trees (the OOB predictions) and provide an estimate of the predictive performance of the model for new cases. RF models also produce measures of the importance of each predictor (Liaw and Wiener, 2002; Morel et al., 2020).

Table 2. Summary of the calculated variables. (-) indicates dimensionless variables.

Variable	Description	Unit	Min.	Median	Max.
$P1h_{10}$	1 hour rainfall for a 10 years return period	mm	11	21	31
$P6h_{10}$	6 hour rainfall for a 10 years return period	mm	32	51	75
$P24h_{10}$	24 hour rainfall for a 10 years return period	mm	58	81	120
A	Catchment area	km^2	0.06	2.7	77.8
L_{CE}	Stream length	km	0.22	1.7	11.5
S_{CE}	Mean channel slope	m/m	0.01	0.16	0.54
S_C	Fan slope	m/m	0.01	0.17	0.57
M	Melton index	-	0.09	0.77	2.8
R_{ZP}	Ratio of sediment contributing area to catchment area	%	0.1	4	98
IG_{ZP}	Geological index of the sediment production areas	-	0.5	3.1	5
ICm	Mean value of the connectivity index IC	-	-5.5	-3.1	-1.7
$IC50$	Median value of the IC	-	-5.5	-3.2	-1.9
$IC95$	Quantile 95 of the IC	-	-4.8	-2.4	-1.0
ICm_{ZP}	Mean value of the IC in sediment production areas	-	-7.2	-3.4	-2.0
$IC50_{ZP}$	Median value of the IC in sediment production areas	-	-7.2	-3.4	-1.9
$IC95_{ZP}$	Quantile 95 of the IC in sediment production areas	-	-6.0	-2.9	-1.5
R_{ICm}	Ratio of ICm_{ZP}/ICm	-	0.79	1.05	1.30
R_{IC95}	Ratio of $IC95_{ZP}/IC95$	-	0.65	1.24	1.91
V_m/A	mean annual sediment volume	m^3/km^2/year	10	330	13,530
V_{10}/A	10-years return period of sediment volume	m^3/km^2/event	80	1,450	42,610
V_{ref}/A	reference sediment volume	m^3/km^2/event	150	4,180	206,000

Importance analysis helps to select explanatory variables for model formulation. We implemented several prediction models (both RF and LR) based on one or more explanatory variables. This modelling strategy aims to assess the improvement of sophisticated models (i.e. multivariate random forests models) compared to parsimonious regressions. Statistical analyses were performed on R (R Core Team, 2020) and RFs were performed using the package "RandomForest" (Liaw and Wiener, 2002).

To assess the performance of the different models, we performed a leave-one-out (LOO) cross-validation procedure by leaving out each observation in turn, fitting a model with all remaining data, and then predicting the value of the left-out observation. This procedure provides an assessment of model performance for undocumented catchments. We quantified model predictive performance of our LOO predictions using three performance metrics. The coefficient of determination (R2) describes the proportion of the variance in the measured data that is explained by the model with R2=1 for perfect agreement. The percentage bias (pbias) measures the average tendency of simulated data to be overestimated (pbias<0 %) or underestimated (pbias>0 %) compared to their observed counterparts. As an error index, we used the RMSE-standard deviation ratio of observations (RSR) which standardizes the root mean square error (RMSE) using the standard deviation of the observations. Lower RSR values indicate better model performance, with zero indicating a perfect agreement. See Moriasi et al. (2007) for further details about calculation and complementarity of these metrics when comparing observed and predicted values.

3 Results

3.1 Variability of the parameters

The calculated sediment production and associated explanatory variables are summarised in Table 2. The whole data set and
245 the distributions and correlations between the explanatory variables are presented in the Table S1 and in the Figure S1. In brief,
the studied catchments experience specific sediment yield covering three order of magnitude with V_m/A, V_{10}/A and V_{ref}/A
ranging from 10 to 13,530 (m^3/km^2/year), 80 to 42,610 and 150 to 206,000 (m^3/km^2/event), respectively (Table 2).

This very strong variability of sediment production is directly related to the large variability of the ratio of sediment con-
tributing area to catchment size R_{ZP} ranging between 0.1% and 98% (median 4%), as well as the great variability of the
250 geological index GI which varies between sediment contributing area fully formed of erosion-sensitive material ($GI = 5$) and
in solid igneous or metamorphic rocks ($GI = 0.5$), with a median $GI = 3.1$. It may also be noted that that the complete data set
corresponds to generally small catchments (median $A \approx 3$ km^2), with short stream length (median $L_{CE} = 1.7$ km), where the
slopes are often steep (median $S_{CE} = 0.16$ m/m). The Melton index are relatively high (median $M = 0.77$) but values below
0.3, i.e. of basins prone to floods rather than debris floods or debris flow, are observed (Fig. 3). Although the absolute value
255 of the connectivity indexes are not easy to interpret, it can be seen that they vary over several units, e.g. from -6.0 to -1.5 for
$IC95_{ZP}$ meaning high variability of the connectivity of the sediment contributing area (recall that IC is a $\log_{10}$ parameter so
the upslope to downslope components vary over four to five order of magnitude between the catchments). The 10-year return
period rainfall ranges from 58 to 120 mm. In essence, the data set used in this analysis, although focusing on small mountainous
catchments located in a temperate climate, comprises a great variability of size, slope, relief, geology, land cover, connectivity
260 and rainfall intensity.

3.2 Relative importance of the parameters

The importance of the explanatory variables for predicting the different volumes is shown in Fig. 6. Results showed that the
ratio R_{zp} of sediment contributing area was by far the most important predictor of the sediment production volumes. This
relationship is presented in Fig. 4. In a lesser extent, the indices of sediment connectivity, especially $IC50_{ZP}$ and $IC95_{ZP}$,
265 have also an influence. Surprisingly, rainfall as well as geomorphic parameters such the Melton index, the fan or the stream
slopes showed low importance.

3.3 Building of prediction models

Based on the parameter importance, three different model formulations were tested for predicting the volume characteristics
V_m/A, V_{10}/A and V_{ref}/A. The ratio of sediment contributing area R_{ZP} is systematically included as input variable. The first
270 bi-variate equation was defined using also a proxy of the connectivity index, namely $IC95_{ZP}$, which proved to be statistically
also an important parameter. Figure 7 shows scatter plots of the sediment production versus R_{ZP} highlighting the strength
of this third parameter. Despite its relative low importance identified in Fig. 6, the Melton index was included in the second
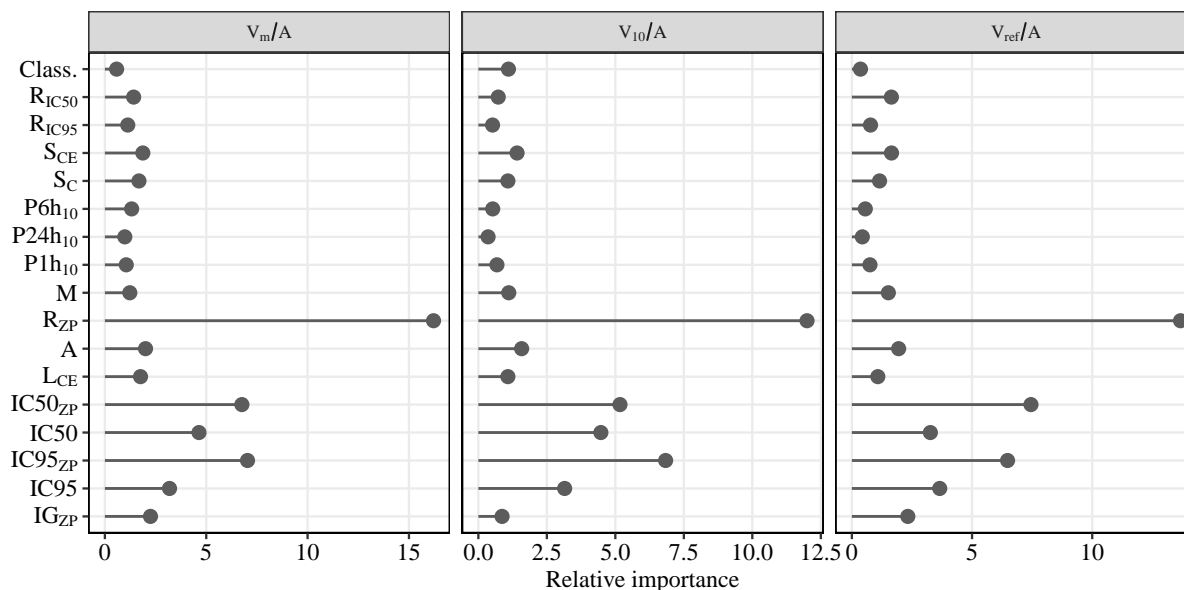
Figure 6. Index of importance of the parameters in the prediction of V_m/A, V_{10}/A and V_{ref}/A computed by the Random-Forest method.

bi-variate equation due to its simple calculation and common use in the literature. Formulations are shown in Table 3 and refer to mono-variate $V = f(R_{ZP})$ or bi-variate models $V = f(R_{ZP,M})$ or $V = f(R_{ZP}, IC95_{ZP})$. Other formulations were

275 explored by Morel et al. (2022), but we presented here only the most promising. We tested notably a RF accounting for all parameters and indeed the precision was marginally better than the three simple models we propose. All formulations were implemented using random forests and regressions separately. The $\log$ or $\log_{10}$ of the parameters was used to get distributions closer to Gaussian samples when needed. The equations were then rearranged to get direct estimates of the volumes. That is why power laws appear in the equations.

280 **3.4 Model performances**

Summary statistics describing the LOO cross-validation performance of the different methods for the three sediment production volumes V_m/A, V_{10}/A and V_{ref}/A are presented in Fig. 8. The comparison of the performances of the different model formulations shows in general comparable performances between the RF and LR models. Contrary to what was expected, the RF models do not bring improvements compared to the LR models. For example, for V_{10}/A models, R2 values range from

285 0.77 to 0.81 and from 0.77 to 0.80 for models using RF and LR, respectively. The errors are also smaller for the models using random forests (RSR indicator).

For all models, the percentage bias is negligible (on the order of 1 %). The performances are also evaluated in Figure 8 in terms of the proportions of the ratio of predicted divided by observed absolute values to be in the intervals $[1/2; 2]$ and $[1/5; 5]$. We notice that about 30 % of the predictions fall in the first interval, and about 50 % in the second. This gives a sense of
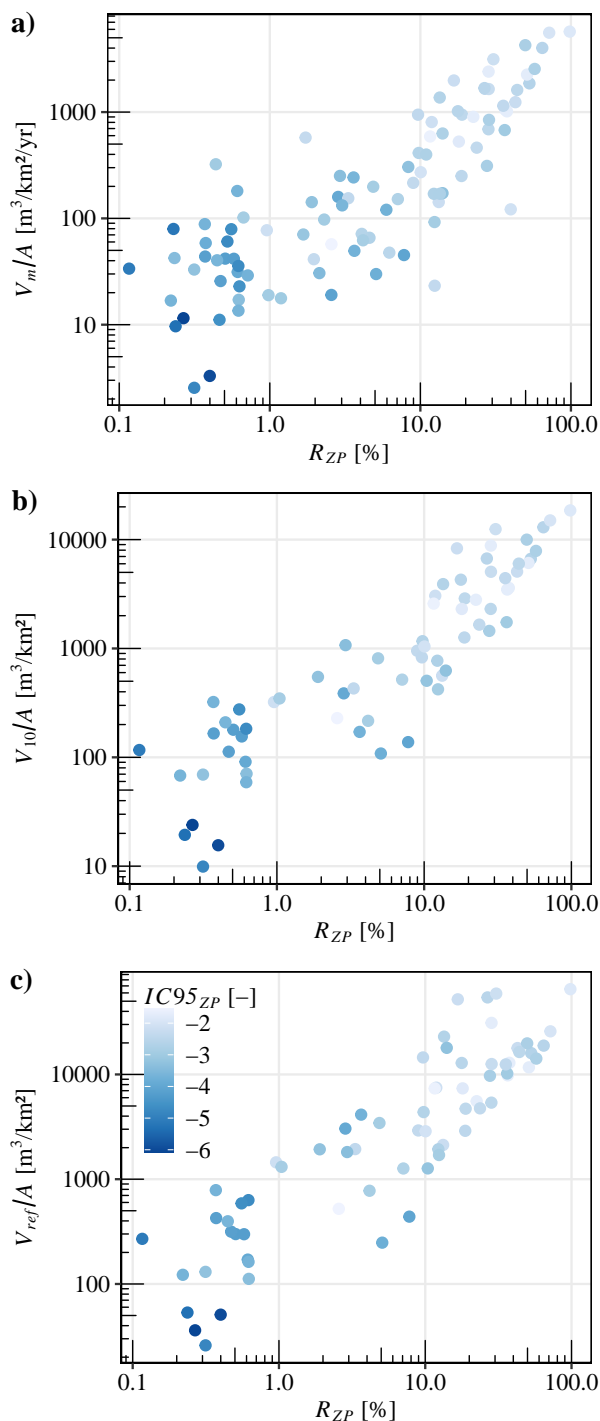
Figure 7. Relationships between volumes production variables (V_m/A, V_{10}/A and V_{ref}/A) and R_{ZP}. The color shade varies with $IC95_{ZP}$. It shows that strongly connected sediment contributing area, in light blue, are also preferably detected in catchments with high ratios of production zone R_{ZP}.

16

Table 3. Formulation for the different predictive models.

Model	V_m/A		V_{10}/A		V_{ref}/A	
$\#f(R_{ZP})$	$52 \cdot R_{ZP}^{0.81}$	(2)	$168 \cdot R_{ZP}^{0.88}$	(3)	$475 \cdot R_{ZP}^{0.94}$	(4)
$\#f(R_{ZP}, IC95_{ZP})$	$175 \cdot R_{ZP}^{0.67} \cdot 10^{0.14 \cdot IC95_{ZP}}$	(5)	$830 \cdot R_{ZP}^{0.70} \cdot 10^{0.18 \cdot IC95_{ZP}}$	(6)	$1982 \cdot R_{ZP}^{0.77} \cdot 10^{0.16 \cdot IC95_{ZP}}$	(7)
$\#f(R_{ZP}, M)$	$40 \cdot R_{ZP}^{0.75} \cdot M^{0.17}$	(8)	$125 \cdot R_{ZP}^{0.81} \cdot 10^{0.2 \cdot M}$	(9)	$363 \cdot R_{ZP}^{0.87} \cdot 10^{0.19 \cdot M}$	(10)
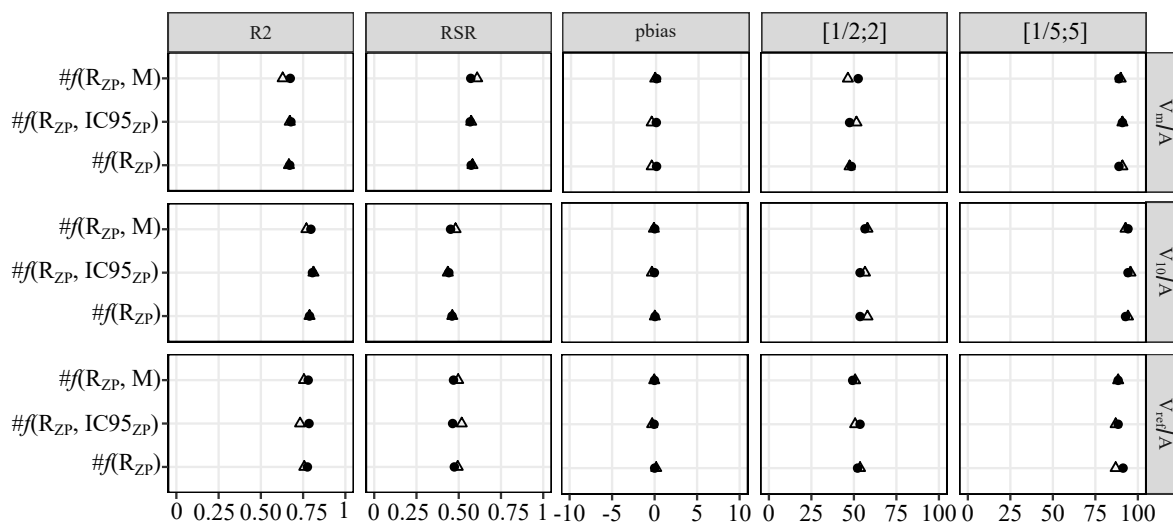
Figure 8. Efficiency criteria values obtained for leave-one-out cross validations of random forest and regressions model results. R2, RSR and pbias were evaluated on the specific volumes (i.e. V_m/A, V_{10}/A and V_{ref}/A). The analysis of the proportion of the predicted values to be included in the reference intervals were evaluated on the absolute volumes (i.e. V_m, V_{10} and V_{ref}).

the precision of such equations: they capture a relevant first approximation but cannot be very precise. Interestingly, bi-variate equations are only marginally more precise than the mono-variate equations, both using the simple Melton index M or the more sophisticated connectivity index $IC95_{ZP}$. Plots of the observed and predicted values, as in Fig. 9, are provided for each formulation in the Figures S2, S3 and S4.
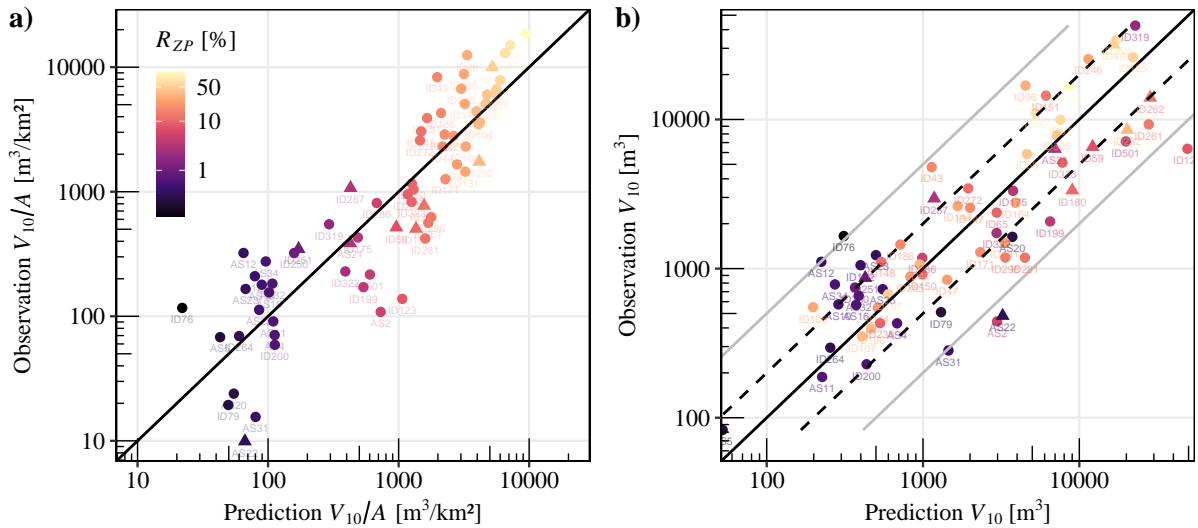
Figure 9. Exemple of observed against LOO predicted values for a) the specific volume V_{10}/A and b) the the absolute volume V_{10} (application of Equation 3). The black lines show perfect agreement between observed and predicted (i.e. $1:1$). The dotted line and the gray lines show, respectively, reference intervals $[1/2;2]$ and $[1/5;5]$. The code name of each catchment as provided in the full data set in sup is displayed near the dots.

4   Discussion

4.1   Input parameters

The key role of the sediment contributing area on the solid production of torrents was for instance stressed and studied by D'Agostino and Bertoldi (2014) who suggest an approach to prioritize the treatment of the various active areas. Alternatively, the present paper seeks to predict the sediment production volumes, and provides an original dimension by directly including this sediment contributing area, rather than the full catchment area, in the equations. Conceptually, this parameter captures most of the potential sediment supply of the catchment since sediment production is much higher on bare soils than under forest and vegetation cover (Cerda, 1999; Vanacker et al., 2007; de Vente et al., 2011; Mishra et al., 2019; Carriere et al., 2020). The strong correlation between sediment yield and erosive area has already been observed in the analyses conducted on a smaller data set comprising the most active catchments of the same region by Peteuil and Liébault (2011) regarding mean annual and event sediment production. Altmann et al. (2021) also proposed an automatic DEM analysis based on slopes and distance to drainage network to predict the sediment contributing area, which was well correlated to the mean annual sediment production. However, as shown in Table 1, this sediment contributing area did not appear until now in the other empirical equations proposed in the literature to predict event magnitude in mountain torrents.

The strong correlation with R_{ZP} shows that predictive models are well adapted to catchments where sediments mainly come from surface erosion (rill, sheet or gully erosion) but may significantly underestimate volumes in catchments where a significant proportion of inputs are from other, less visible sources (e.g. forested or vegetated landslides). If the sediment

18

sources of a catchment are of this type, our methods should be dismissed and a method which does not include an estimated sediment contributing area should be preferred. Using maps of landsliding areas as sediment contributing area could be an idea to test our method on such catchments but we suspect that the elementary sediment production, in term of m^3/km^2 of active area, is likely much higher for landslides than for gullies, bare soil and cliffs. This would be an interesting research question to explore.

The sediment production volumes did not exhibit strong relationships with the geological index. These results are consistent with the observation of Marchi and D'Agostino (2004) who showed the same result on their sample. It is also possible that this variable does not capture the complex interactions of geological, geomorphological and climatic conditions on sediment production. It must also be acknowledged that in most mountains of France, as well as, for instance, in Italy, Switzerland or Austria, torrent control works and reforestation master-plans were implemented in the past and a strong spontaneous reforestation occurred due to rural depopulation (Piton et al., 2017). Hence, the sediment contributing areas studied in this paper, i.e. areas where bare soil remains nowadays, are necessarily very erosive and active areas. The other areas that used to be active but that had geological features slightly less prone to erosion are most likely now stabilized and vegetated. It is also interesting to mention that we tested an extraction of the geological index at the scale of the catchments, rather than only on the sediment contributing areas. It proved useless and uncorrelated to the sediment production: many catchments have for instance a geology mostly composed of moraine, supposedly a lithology prone to erosion, but are fully vegetated by mature forest and thus do not produce much sediment.

The sediment production volume were also poorly correlated to the rainfall proxies. We assume that the temperate climate and associated meteorology of the studied region, the Northern French alps, does not vary enough to capture this possible effect and eventual feedback loop on the vegetation cover.

The results show that morphometric variables (M, S_{CE}, S_C) have a limited influence on sediment production. Precise topographic data were seldom available for the studied catchments and we made the choice to calculate the morphometric variables using a 25 m resolution DTM. This resolution is quite coarse, especially in the case of small steep watersheds. For a few catchments where more accurate DTM were available, we cross-compared these precise surveys with the values of slopes extracted in our study. The values were reasonably accurate for reaches flowing on large alluvial fans, well coupled with the upstream active basin (Harvey, 2002). Conversely, in narrow valleys or if the torrents were incised in the fans, the coarse DTM did not capture the actual channel profile which had a characteristic scale lower than the DTM resolution: incised channel bed and drops related to check dams were for instanced smoothed. In such case, the slopes were not accurately estimated. Repeating this analysis using more precise DTM would be interesting when such data will be available at a regional scale.

Another contribution of this work is the inclusion of a connectivity index, namely the quantile 95% of the IC extracted on the active erosion area, into the empirical equation. The analysis of the importance of the various explaining factor produced by the random forest analysis shows that the proxies associated to the IC are all of higher importance than any other variable except for the ratio of sediment contributing area R_{ZP} (Fig. 6). Indicators dedicated to the analysis of the sediment connectivity are numerous. As pointed out by the review of Heckmann et al. (2018), these indices, despite their high interest, are seldom used as input tool for simple predictive models of sediment delivery by catchment. Mapping IC is now simple and fast with

openly accessible tools (Crema and Cavalli, 2018; Martini et al., 2022). Such distributed information can be useful to shed a new light on the catchment morphology. With the Eqs. (5), (6) and (7), such indices are also reused to link this catchment features with their associated sediment export.

4.2 Discussion about the predictive models

350 The predictive models developed in this work provide an approximate assessment of sediment yield, and their use should be restricted to the physical context (geological, geomorphological, climatic) where they have been developed. However, the diversity of the torrents studied makes it worth testing their application in other regions. Including fully vegetated catchments with very small sediment production in our data set, and not only the most active torrents, is also a strength of our work: most mountain catchments in the Northern Alps, and in many other mountain ranges, are vegetated and poorly active. Nonethe-

355 less, some assets are located on their alluvial fans and practitioners need methods to study and predict their infrequent solid production. We believe that this contribution will help to address such weakly active hydrosystems.

The performance analysis shows that these equations provide at most a relevant order of magnitude of sediment production. In this paper, we reviewed some existing empirical equations used to estimate catchment solid production (Tab. 1) and propose new equations, basically three equations for each variable to predict (mean annual production or event magnitude). We are

360 regularly asked by practitioners which equation or method should be used. In practice, we apply all equations of Tab. 1 as well as the three new equations developed here. We know that none of them is very precise. Many underlying processes make the actual sediment production of mountain catchment very complex to predict. We do not think that using an equation with many input parameters would lead to a serious gain in precision: we tested a random forest model accounting for all parameters and indeed the precision was marginally better than the three simple models we propose. Each equation captures a given trend.

365 Collectively, these equations constitute a body of knowledge helping to bound the behaviour of mountain catchments. Using several equations rather than one provide multiple estimations. This also highlights the lack of precision of these equations. Using one, single equation could give a false sense of precision to inexperienced users. By using them regularly, and confronting them to other sources of information, users learn about the bias and behaviour of each equation or group of equations guiding them in one of the many educated guesses that any debris-flow or debris flood hazard assessment involves.

370 Such empirical equations are obviously only one type of tools between many others. debris-flow and debris flood hazard assessments require further *in situ* and historical analyses adapted to the stage of study (Jakob, 2021; Jakob et al., 2022).

5 Conclusion

Using a unique data set of sediment dredging in about one hundred debris basins and associated historical information, we estimated the mean annual and event-driven sediment production of torrents located in the Northern French Alps. Several

375 geomorphic indicators of their catchments were extracted including the catchment area, the sediment contributing area, the Melton index, as well as several statistical values of the index of connectivity IC computed on these catchments and other relief, lithological and rainfall indexes. We used these geomorphic parameters to try to predict the sediment supply of these

catchments using several statistical methods. Results showed that the ratio of connected eroding areas was the most important predictor of the sediment production volumes.

In line with the previous works synthesized in Table 1, this paper demonstrates that simple equations can predict sediment yield in torrent catchments with independent basin parameters that are simple and easy to determine. These simple equations are much faster and easier to use than sophisticated models as random forest methods, that surprisingly, did not lead to a better accuracy. Despite their limitations, predictive equations in Table 3 provide refined estimation methods of sediment production volumes. Because our models were built using a wide range of torrent types, they have the potential to be tested and applied in different regions.

These models complete the existing body of empirical methods that are used to assess debris-flow and debris flood hazard as well as to design protection measures. By including explicit mapping of the sediment contributing area and quantiles of the index of connectivity, our methods push the practitioners to focus on sediment sources and to analyse the sediment connectivity of the catchments: such analyses are not only useful to fuel our equations but will shed new light on the studied sites as compared to the classical analysis of slopes, relief and catchment size.

Appendix: Nomenclature

$\chi_{...}$ Generic parameter defined locally in the text

A   Catchment area [km^2]

GI   Geological Index of D'Agostino et al. (1996) [-]

IC...   Quantile of probability ...% of the Connectivity Index [-]

IC...$_{ZP}$ Quantile of probability ...% of the Connectivity Index extracted only on the sediment contributing area [-]

L   Length of the main river channel [km]

M   Melton index: catchment relief / $\sqrt{A}$ [-]

R$_{ZP}$ Ratio of sediment contributing area to catchment area [-]

S_C Slope of the alluvial fan [m/m]

S or S_{CE} Slope of the channel controlling the sediment transport [m/m]

T   Return period [year]

V   Solid volume associated to an event [m^3]

410 V_m Mean annual solid volume [m^3]

V_{ref} Solid volume with return period of 100 yrs or largest sediment volume observed if higher [m^3]

V_T Solid volume with return period of T yrs [m^3]

References

Altmann, M., Haas, F., Heckmann, T., Liébault, F., and Becht, M.: Modelling of sediment supply from torrent catchments in the Western Alps using the sediment contributing area (SCA) approach, Earth Surface Processes and Landforms, 46, 889–906, https://doi.org/10.1002/esp.5046, 2021.

Arabkhedri, M., Heidary, K., and Parsamehr, M.-R.: Relationship of sediment yield to connectivity index in small watersheds with similar erosion potentials, Journal of Soils and Sediments, 21, 2699–2708, https://doi.org/10.1007/s11368-021-02978-z, 2021.

Bertrand, M., Liébault, F., and Piégay, H.: Debris-flow susceptibility of upland catchments, Natural Hazards, 67, 497–511, https://doi.org/10.1007/s11069-013-0575-4, 2013.

Blanpied, J., Carozza, J.-M., and Antoine, J.-M.: La connectivité sédimentaire dans la haute chaîne pyrénéenne par l'analyse de la crue de juin 2013 : le rôle des formations superficielles, Géomorphologie : relief, processus, environnement, 24, 389–402, https://doi.org/10.4000/geomorphologie.12718, 2018.

Borselli, L., Cassi, P., and Torri, D.: Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment, CATENA, 75, 268–277, https://doi.org/10.1016/j.catena.2008.07.006, number: 3, 2008.

Breiman, L.: Random Forests, Machine Learning, 45, 5–32, https://doi.org/10.1023/A:1010933404324, number: 1, 2001.

Carladous, S., Piton, G., Kuss, D., Charvet, G., Paulhe, R., Morel, M., and Queffélan, Y.: Chap. 13: French Experience with Open Check Dams: Inventory and Lessons Learnt Through Adaptive Management, in: Check Dam Construction for Sustainable Watershed Management and Planning, pp. 247–266, Wiley Online Library, 2022.

Carriere, A., Le Bouteiller, C., Tucker, G. E., Klotz, S., and Naaim, M.: Impact of vegetation on erosion: Insights from the calibration and test of a landscape evolution model in alpine badland catchments, Earth Surface Processes and Landforms, 45, 1085–1099, https://doi.org/10.1002/esp.4741, 2020.

Cavalli, M., Trevisani, S., Comiti, F., and Marchi, L.: Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments, Geomorphology, 188, 31–41, https://doi.org/10.1016/j.geomorph.2012.05.007, 2013.

Cerda, A.: Parent material and vegetation affect soil erosion in eastern Spain, Soil Science Society of America Journal, 63, 362–368, https://doi.org/10.2136/sssaj1999.03615995006300020014x, 1999.

Church, M. and Jakob, M.: What Is a Debris Flood?, Water Resources Research, 56, e2020WR027144, https://doi.org/10.1029/2020WR027144, _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020WR027144, 2020.

Coles, S.: An introduction to statistical modeling of extreme values, vol. 208, Springer, 2001.

Crema, S. and Cavalli, M.: SedInConnect: a stand-alone, free and open source tool for the assessment of sediment connectivity, Computers & Geosciences, 111, 39–45, https://doi.org/10.1016/j.cageo.2017.10.009, 2018.

D'Agostino, V.: Assessment of past torrential events through historical sources, in: Dating Torrential Processes on Fans and Cones, edited by Schneuwly-Bollschweiler, M., Stoffel, M., and Rudolf-Miklau, F., vol. 47, chap. 8, pp. 131–146, Springer Netherlands, https://doi.org/10.1007/978-94-007-4336-6, 2013.

D'Agostino, V. and Bertoldi, G.: On the assessment of the management priority of sediment source areas in a debris-flow catchment: Management priority of sediment source areas in debris-flow catchment, Earth Surface Processes and Landforms, 39, 656–668, https://doi.org/10.1002/esp.3518, 2014.

D'Agostino, V. and Marchi, L.: Debris flow magnitude in the Eastern Italian Alps: data collection and analysis, Physics and Chemistry of the Earth, Part C: Solar, Terrestrial & Planetary Science, 26, 657–663, 2001.

de Vente, J., Verduyn, R., Verstraeten, G., Vanmaercke, M., and Poesen, J.: Factors controlling sediment yield at the catchment scale in NW
    Mediterranean geoecosystems, Journal of Soils and Sediments, 11, 690–707, https://doi.org/10.1007/s11368-011-0346-3, 2011.

D'Agostino, V., Cerato, M., and Coali, R.: Extreme events of sediment transport in the eastern Trentino torrents, in: Proceedings of the In-
460   ternational Symposium Interpraevent, pp. 377–386, http://www.interpraevent.at/palm-cms/upload_files/Publikationen/Tagungsbeitraege/
    1996_1_377.pdf, 1996.

Franzi, L. and Bianco, G.: A statistical method to predict debris flow deposited volumes on a debris fan, Physics and Chemistry of the Earth,
    Part C: Solar, Terrestrial & Planetary Science, 26, 683–688, 2001.

Fryirs, K. A.: (Dis)Connectivity in catchment sediment cascades: a fresh look at the sediment delivery problem, Earth Surface Processes and
465   Landforms, 38, 30–46, https://doi.org/10.1002/esp.3242, number: 1, 2013.

Gob, F., Bilodeau, C., Thommeret, N., Belliard, J., Albert, M.-B., Tamisier, V., Baudoin, J.-M., and Kreutzenberger, K.: A tool for the
    characterisation of the hydromorphology of rivers in line with the application of the European Water Framework Directive in France
    (CARHYCE), Géomorphologie : relief, processus, environnement, 20, 57–72, https://doi.org/10.4000/geomorphologie.10497, number: 1,
    2014.

470 Haas, F., Heckmann, T., Wichmann, V., and Becht, M.: Quantification and Modeling of Fluvial Bedload Discharge from Hillslope
    Channels in two Alpine Catchments (Bavarian Alps, Germany), Zeitschrift für Geomorphologie, Supplementary Issues, 55, 147–168,
    https://doi.org/10.1127/0372-8854/2011/0055S3-0056, 2011.

Harvey, A. M.: Effective timescales of coupling within fluvial systems, Geomorphology, 44, 175 – 201, https://doi.org/10.1016/S0169-
    555X(01)00174-X, geomorphology on Large Rivers, 2002.

475 Heckmann, T., Cavalli, M., Cerdan, O., Foerster, S., Javaux, M., Lode, E., Smetanová, A., Vericat, D., and Brardi-
    noni, F.: Indices of sediment connectivity: opportunities, challenges and limitations, Earth-Science Reviews, 187, 77–108,
    https://doi.org/10.1016/j.earscirev.2018.08.004, 2018.

Hungr, O., Morgan, G. C., and Kellerhals, R.: Quantitative analysis of debris torrent hazards for design of remedial measures, Canadian
    Geotechnical Journal, 21, 663–677, https://doi.org/10.1139/t84-073, 1984.

480 Jakob, M.: Debris-Flow Hazard Assessments: A Practitioner's View, Environmental and Engineering Geoscience, 27, 153–166,
    https://doi.org/10.2113/EEG-D-20-00110, 2021.

Jakob, M. and Friele, P.: Frequency and magnitude of debris flows on Cheekye River, British Columbia, Geomorphology, 114, 382–395,
    https://doi.org/10.1016/j.geomorph.2009.08.013, publisher: Elsevier BV, 2010.

Jakob, M., Davidson, S., Bullard, G., Busslinger, M., Collier-Pandya, B., Grover, P., and Lau, C.: Debris-Flood Hazard Assessments in Steep
485   Streams, Water Resources Research, 58, https://doi.org/10.1029/2021WR030907, 2022.

Kronfellner-Kraus, G.: Extreme Feststofffrachten und Grabenbildungen von Wildbächen, Internationales Symposion Interpraevent, pp. 109–
    118, 1984.

Liaw, A. and Wiener, M.: Classification and Regression by randomForest, R News, 2, 18–22, https://CRAN.R-project.org/doc/Rnews/, 2002.

Marchi, L. and D'Agostino, V.: Estimation of debris-flow magnitude in the Eastern Italian Alps, Earth Surface Processes and Landforms, 29,
490   207–220, https://doi.org/10.1002/esp.1027, 2004.

Martini, L., Baggio, T., Torresani, L., Crema, S., and Cavalli, M.: R_IC: A novel and versatile implementation of the index of connectivity
    in R, Environmental Modelling & Software, 155, 105 446, https://doi.org/10.1016/j.envsoft.2022.105446, 2022.

Melton, M. A.: The Geomorphic and Paleoclimatic Significance of Alluvial Deposits in Southern Arizona, The Journal of Geology, 73, 1–38,
    https://www.jstor.org/stable/30066379, publisher: The University of Chicago Press, 1965.

495 Micheletti, N. and Lane, S. N.: Water yield and sediment export in small, partially glaciated Alpine watersheds in a warming climate, Water Resources Research, 52, 4924–4943, https://doi.org/10.1002/2016WR018774, number: 6, 2016.

Mishra, A. K., Placzek, C., and Jones, R.: Coupled influence of precipitation and vegetation on millennial-scale erosion rates derived from 10Be, PLOS ONE, 14, 1–20, https://doi.org/10.1371/journal.pone.0211325, 2019.

Morel, M., Booker, D. J., Gob, F., and Lamouroux, N.: Intercontinental predictions of river hydraulic geometry from catchment physical
500 characteristics, Journal of Hydrology, 582, 124 292, https://doi.org/10.1016/j.jhydrol.2019.124292, 2020.

Morel, M., Piton, G., Evin, G., and Le Bouteiller, C.: Projet HYDRODEMO : Évaluation de l'aléa torrentiel dans les petits bassins versants des Alpes du Nord - Action 3 : Caractériser la production sédimentaire, Research Report, INRAE, https://hal.archives-ouvertes.fr/hal-03549827, 2022.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model Evaluation Guidelines for Systematic
505 Quantification of Accuracy in Watershed Simulations, Transactions of the ASABE, 50, 885–900, https://doi.org/10.13031/2013.23153, number: 3, 2007.

Peteuil, C. and Liébault, F.: ECSTReM, une méthode pratique pour prédire la production sédimentaire an-nuelle et événementielle des torrents à partir d'observations originales spécifiques aux Alpes françaises., p. 6, 2011.

Peteuil, C., Liébault, F., and Marco, O.: ECSTREM, une approche pratique pour prédire la production sédimentaire des torrents des Alpes
510 françaises, in: 12th Congress Interpraevent, pp. 293–304, 2012.

Piton, G., Carladous, S., Recking, A., Liebault, F., Tacnet, J., Kuss, D., Quefféléan, Y., and Marco, O.: Why do we build check dams in Alpine streams? An historical perspective from the French experience, Earth Surface Processes and Landforms, 42, 91–108, https://doi.org/10.1002/esp.3967, 2017.

R Core Team: R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria, https:
515 //www.R-project.org/, 2020.

Rickenmann, D.: Estimation des laves torrentielles, IAS–Ingenieurs et Architectes Suisses, 19, 386–392, 1997.

Rickenmann, D. and Koschni, A.: Sediment loads due to fluvial transport and debris flows during the 2005 flood events in Switzerland, Hydrological Processes, 24, 993–1007, https://doi.org/10.1002/hyp.7536, 2010.

Schopper, N., Mergili, M., Frigerio, S., Cavalli, M., and Poeppl, R.: Analysis of lateral sediment connectivity and its connection to debris
520 flow intensity patterns at different return periods in the Fella River system in northeastern Italy, Science of The Total Environment, 658, 1586–1600, https://doi.org/10.1016/j.scitotenv.2018.12.288, 2019.

Takei, A.: Interdependence of sediment budget between individual torrents and a river-system, in: International Symposium Interpraevent, pp. 35–48, Villach Austria, http://www.interpraevent.at/palm-cms/upload_files/Publikationen/Tagungsbeitraege/1984_2_35.pdf, 1984.

Torresani, L., D'Agostino, V., and Piton, G.: Deciphering sediment Connectivity Index and erosion pattern in a debris flow catchment, in:
525 Proc. 14th INTERPRAEVENT Congress, International Research Society INTERPRAEVENT, 2021.

Vanacker, V., von Blanckenburg, F., Govers, G., Molina, A., Poesen, J., Deckers, J., and Kubik, P.: Restoring dense vegetation can slow mountain erosion to near natural benchmark levels, Geology, 35, 303–306, https://doi.org/10.1130/G23109A.1, 2007.

Wilford, D. J., Sakals, M. E., Innes, J. L., Sidle, R. C., and Bergerud, W. A.: Recognition of debris flow, debris flood and flood hazard through watershed morphometrics, Landslides, 1, 61–66, https://doi.org/10.1007/s10346-003-0002-0, 2004.

530 Zeller, J.: Schutz vor Hochwasserschaden und Rutschungen im Gebirge, ein Uberblick, Berichte no 153, EAV Birmensdorf. Schweiz Z Forstwes, 1976.