Relating sediment supply to the morphological and hydro-meteorological characteristics of torrent catchments

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UNION EUROPÉENNE Fonds Européen de Développement Régional
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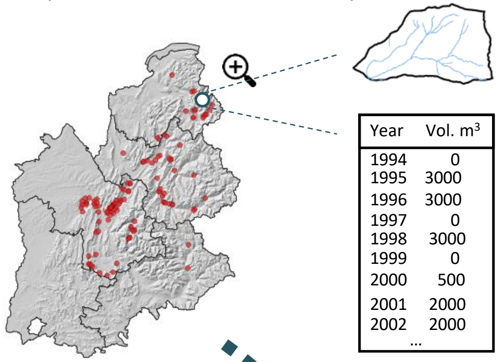
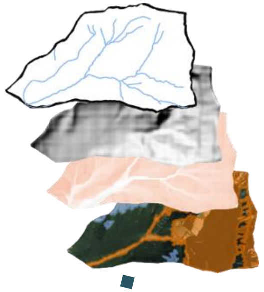
METHODOLOGY

Collection of sediment supply data (n = 120 catchments)

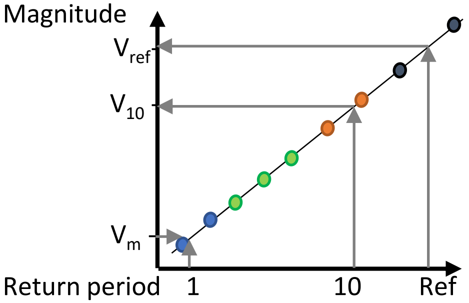


Year	Vol. m^3
1994	0
1995	3000
1996	3000
1997	0
1998	3000
1999	0
2000	500
2001	2000
2002	2000
…	

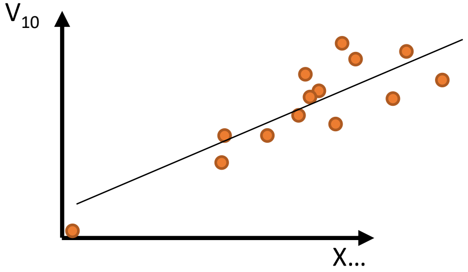
Geomorphological and hydro-climatic characterization of the catchments



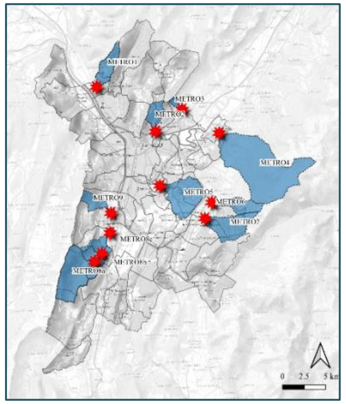
Estimation of sediment supply for each catchment



Statistical modelling
Volume = f(parameters)



Application of the method on several basins



INRAE

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HYDRODEMO

UNION EUROPÉENNE
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RÉGION SUD
PROVENCE ALPES CÔTE D'AZUR

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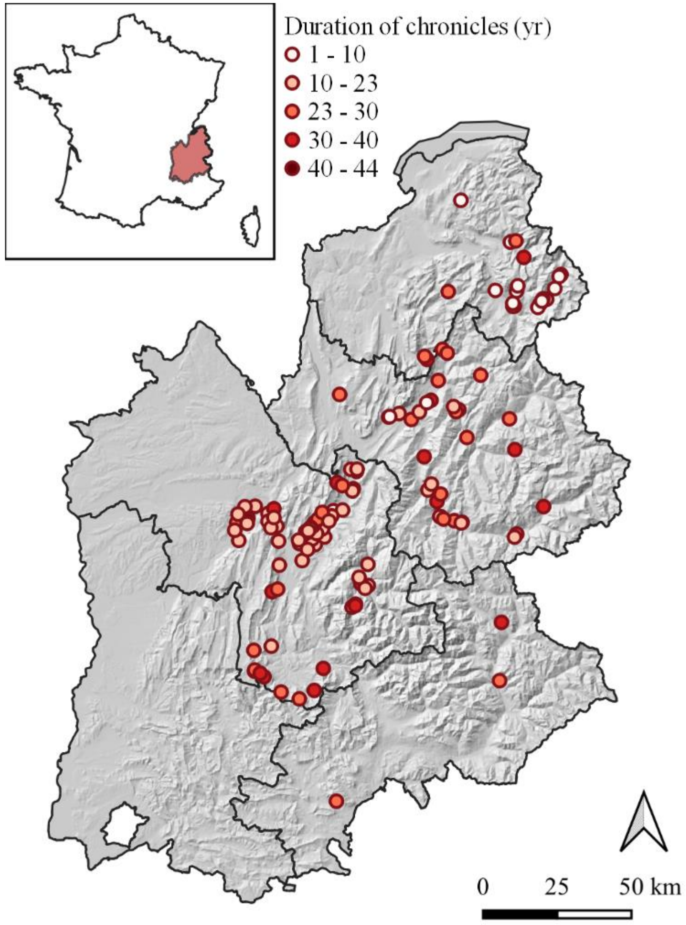
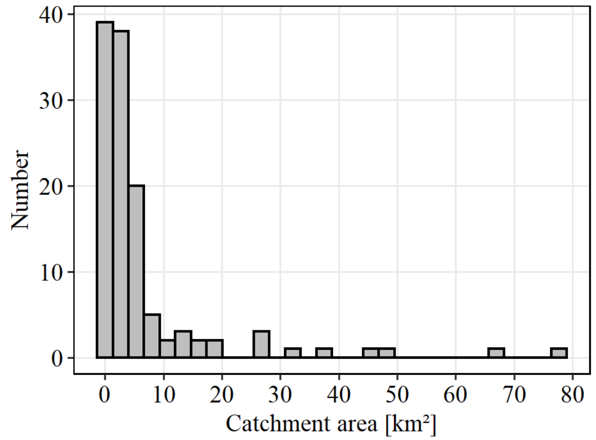
EN PARTENARIAT AVEC LA RÉGION AUVERGNE-RHÔNE-ALPES

Data collection

- We selected 120 catchment in the French Northern Alps.
- They are small torrential catchments (area ± 5 km²)
- The catchments have sediment retention basins managed by State (torrent control service) or municipalities.
- Sediment retention basins dredging registries provide data on sediment yield for each catchment.
- Registries provide observations on ± 25 years
- Data coming from : ONF-RTM (French torrent control service), basin agency (SM3A), local communities and stream managers.



Location of the sediment retention basins and duration of the dredging chronicles

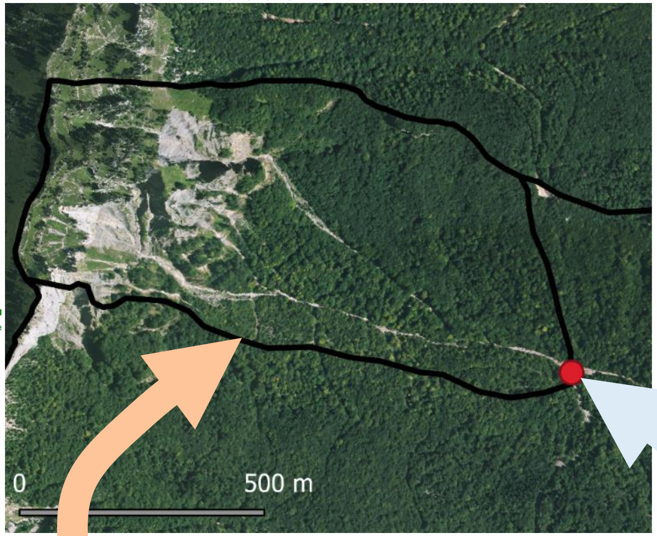


Distribution of the studied catchment areas

Data collection

- Two sources of sediment supply
  - Historical archives of the RTM database (informs about important past torrential events)
  - Sediment retention basins registry
- Creation of sediment supply time series for each catchment
- Possibility of estimating production volumes
  - Mean annual volumes
  - Extreme volumes

Example of sediment supply data for the Bresson torrent



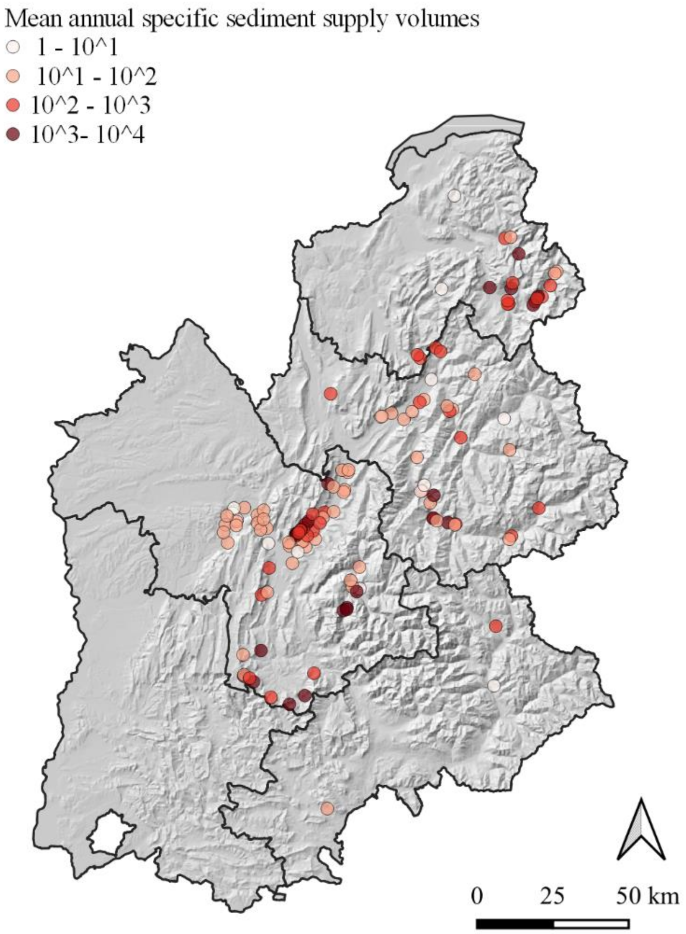
Historical archives

Date	Vol. m^3	Intensité
16/06/1819	?	3
…		
02/07/1987	700	2
…		
30/06/1990	1000	2
…		
03/08/1998	?	1
…		
10/08/2002	?	2
…		
10/08/2004	?	2
…		
01/06/2008	1500	2
…		
01/07/2016	?	2
…		

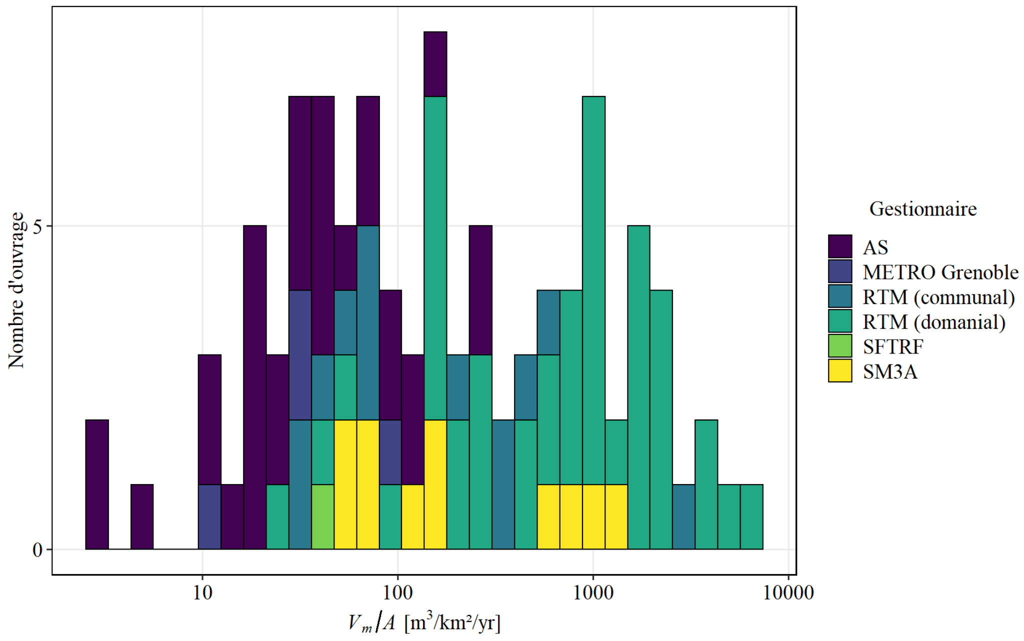
Dredging registry

Année	Volume m^3
1987	5700
…	
1994	1500
…	
1998	3000
1999	3000
…	
2002	2000
…	
2004	800
2005	3000
…	
2008	1500
…	
2015	700
…	

Estimation of sediment supply : Mean annual sediment supply



Spatial distribution of mean annual specific sediment supply volumes (m³/km²/year)

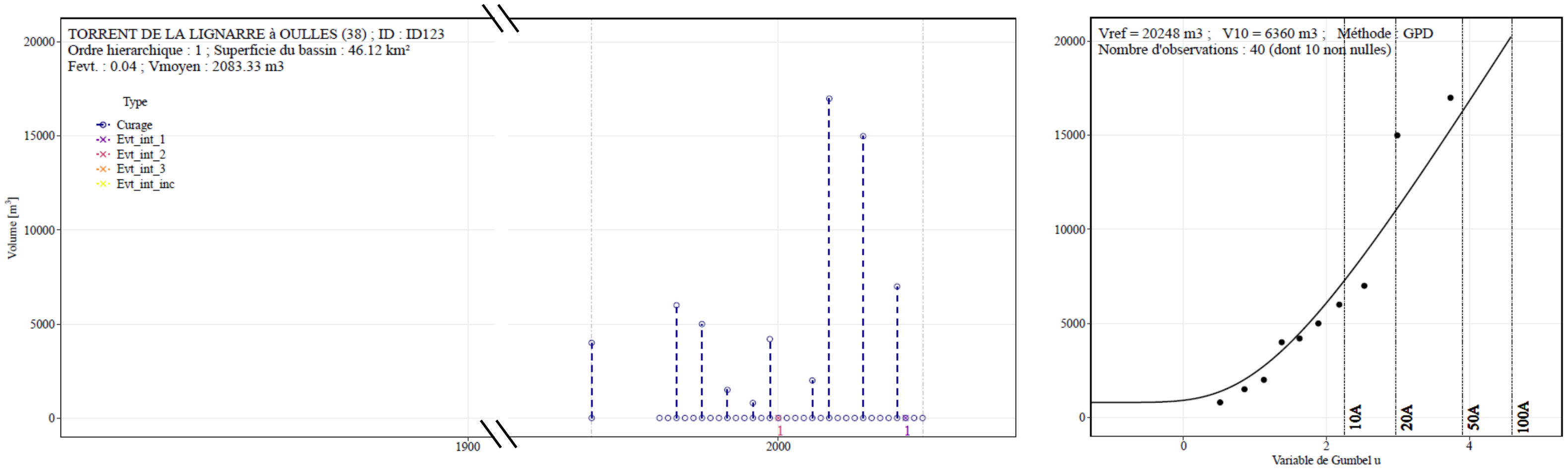


Distribution of mean annual specific sediment supply volumes (m³/km²/year)

- We estimated the the mean annual sediment supply
- Sediment supply volumes were scaled by catchment area for modelling
- The mean annual supply vary on several orders of magnitude

Estimation of sediment supply : Sediment supply for extreme floods

- Estimation for 10 yr return period flood (V10)
- Estimation for reference flood (100 yr recurrence or maximum observed)



Example of the Lignarre torrent; the figure on the left shows the history of sediment supply (volume); the figure on the right shows the statistical adjustment for estimating V_{10} and V_{100}

- Due to the relatively short duration of the exploited records and the limited number of observations, the estimate of production volume for a given return period is subject to uncertainties.
- The estimation of event production volumes was performed on 70 basins with sufficiently long chronicles.
- Exponential or GPD type adjustments were performed.

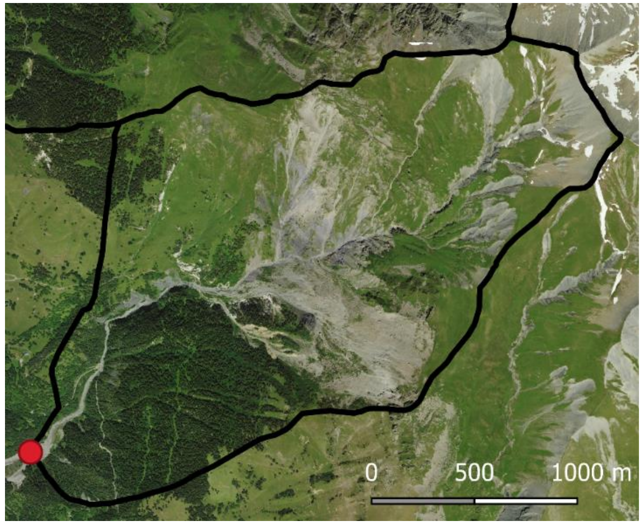
Descriptions of geomorphological characteristics of catchments

Descriptions of catchment characteristics to explain sediment supply

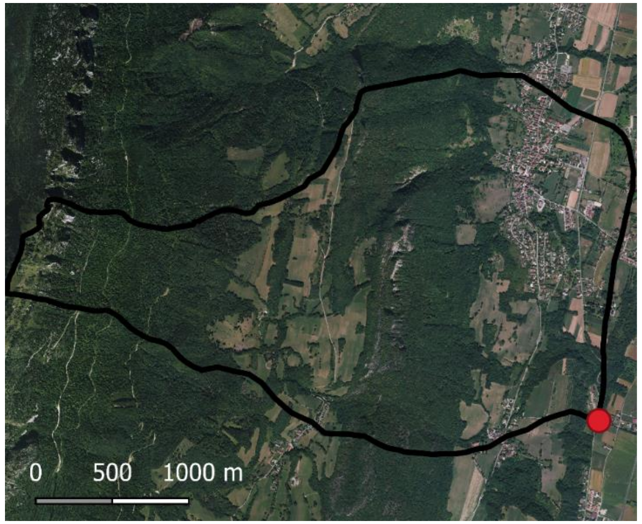
- **Proportion of eroding areas connected in the catchment area**
- Sediment connectivity index
- Channel mean slope
- Fan slope
- Melton index
- Geological index

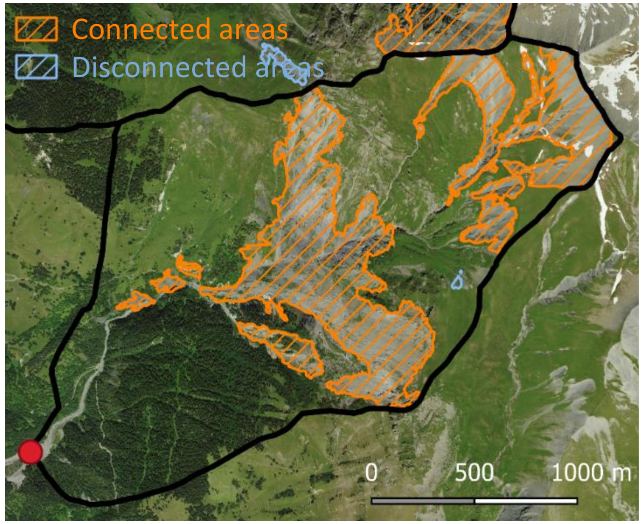
The delimitation of the sediment production areas was made from a GIS database (BD Forêt v2®)

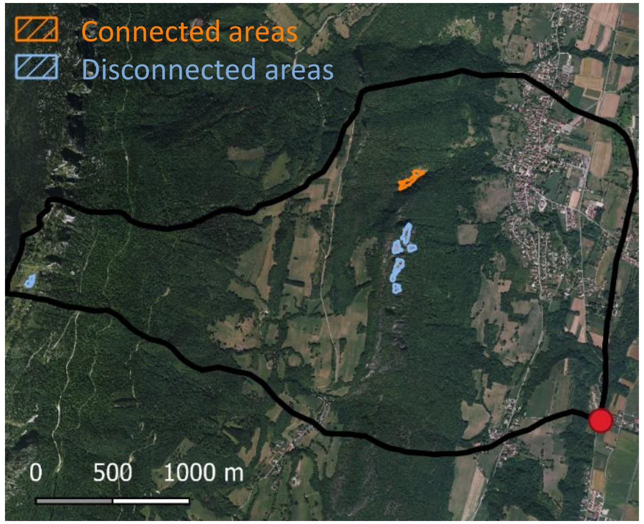
Torrent la Ravoire



Torrent la Maladière







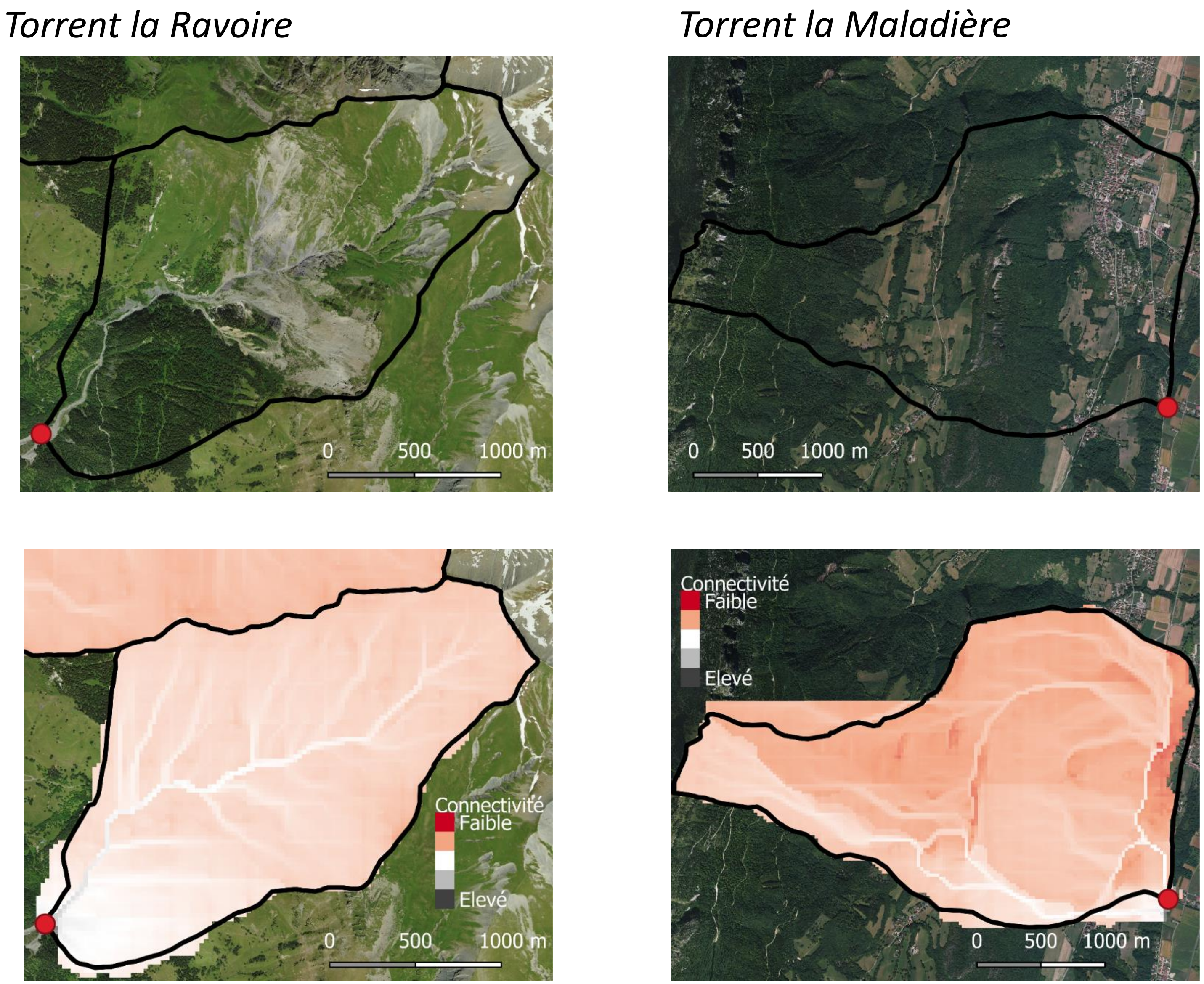
Delineation of erosion zones in catchment areas (blue = disconnected, orange = connected to river network). The red points indicate the location of the sediment retention basins (outlet).

Descriptions of geomorphological characteristics of catchments

Descriptions of catchment characteristics to explain sediment supply

- Proportion of eroding areas connected in the catchment area
- **Sediment connectivity index**
- Channel mean slope
- Fan slope
- Melton index
- Geological index

The connectivity index was calculated using the SedInConnect software (Crema & Cavalli, 2018, *Computers & Geosciences)*

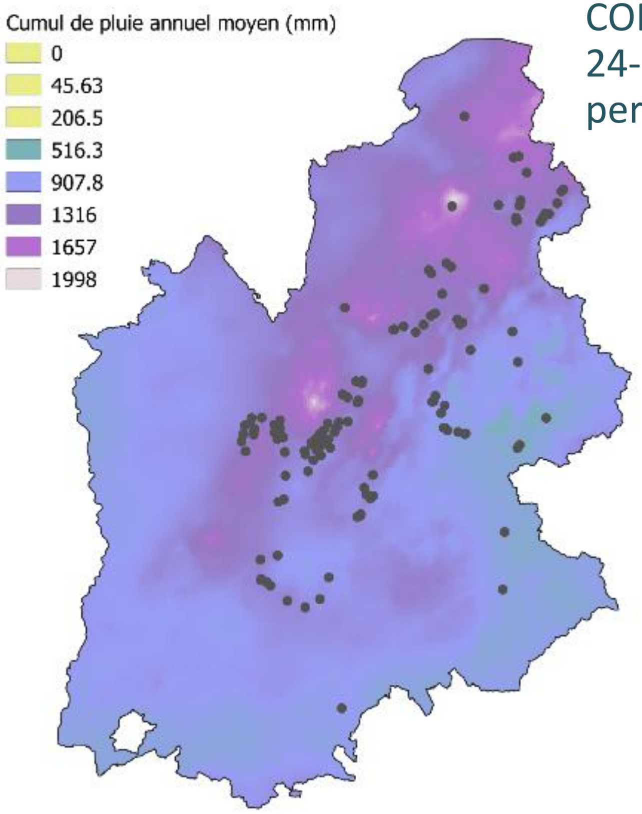


Sediment connectivity index (SedInConnect software, Cavalli et al. 2013, Geomorphology). The red points indicate the location of the sediment retention basins (outlet).

Descriptions of characteristics of catchments

We also calculated the meteorological characteristics for each catchment.

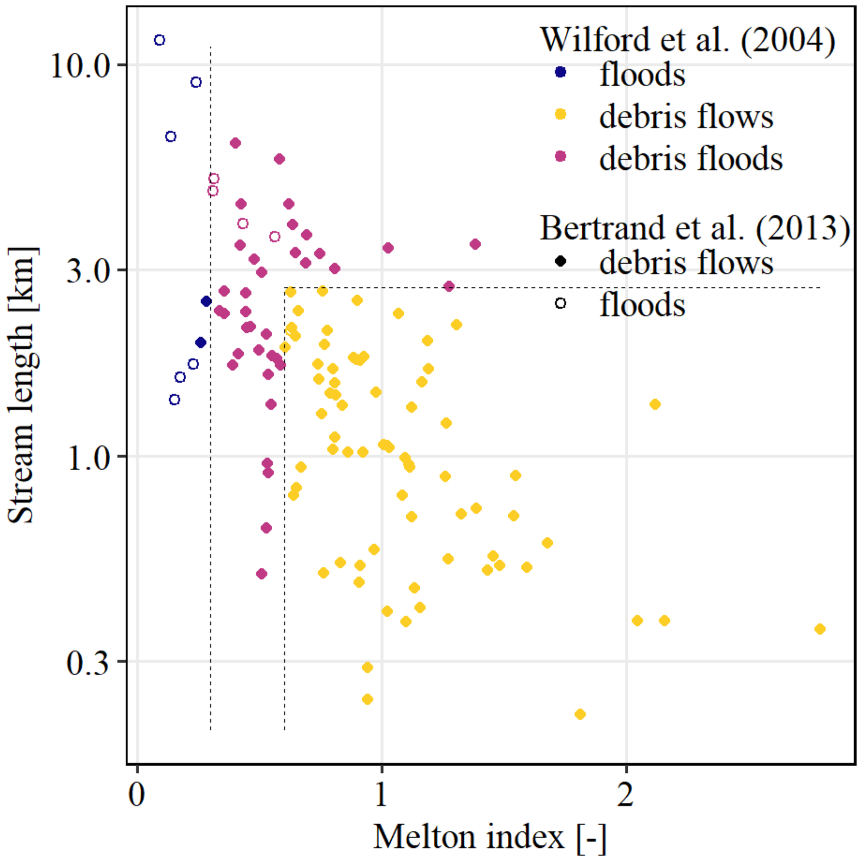
- Collection of rainfall data from COMEPHORE estimation of 1-, 6- and 24-hours events for 10 years return period



Average annual rainfall (mm)

We did a classification of torrential phenomena

- Based on existing methods in litterature (Wilford et al. 2004 *Landslides*; Bertrand et al. 2013, *Natural Hazards*)



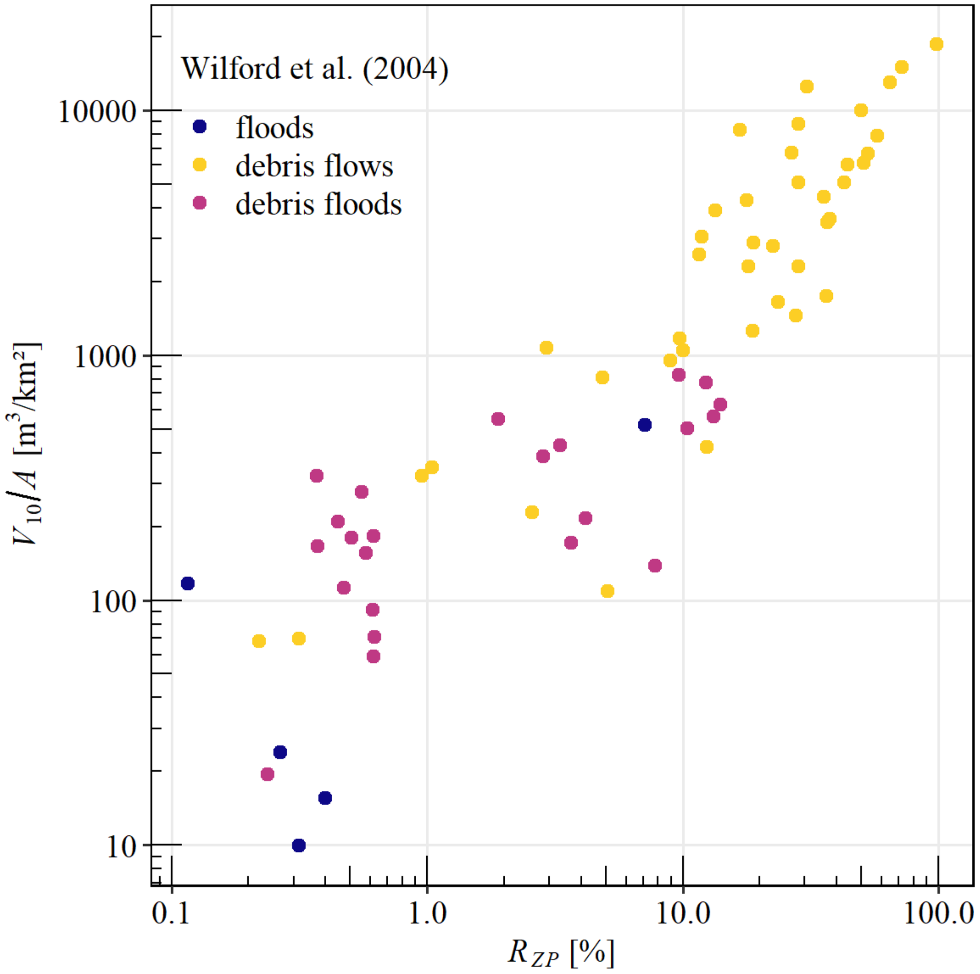
Classification of sediment transport processes for all catchments depending on existing methods

Multivariate statistical analysis

- We analyzed the relationships between sediment supply volumes and geomorphological and hydro-climatic characteristics

  $$For\ example : V_{10} = f(Melton, channel\ slope, etc\ldots)$$

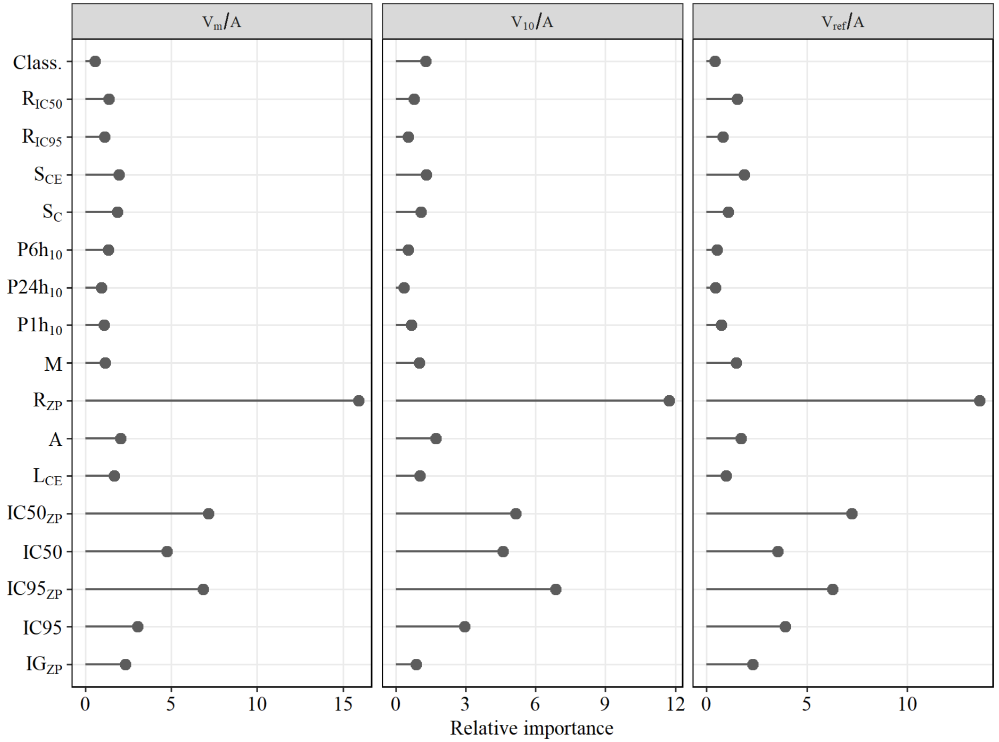
- We used random forests and multiple linear regressions techniques
- We selected of the most relevant variables
- Predictive models were developped
- We assessed models performance



Relationship between specific sediment supply volume for return period of 10 yrs (V_{10}/A) and proportion of sediment production areas in catchment (R_{ZP}). Colors indicate the classification of the catchment by the dominant transport processes. (n = 68 catchments)

Results

- The proportion of sediment production areas in the catchment area is the most significant variable for predicting sediment supply volumes.
- To a lesser extent, variables such as the 95th quantile value of the connectivity index or the mean channel slope index are significant variables too.
- Based on the significance of the variables, several formulations of simple models (monovariate, bivariate or three-parameter) are proposed.



Relative importance of the explanatory variables for the specific mean annual sediment supply volume (V_m/A), the 10 year return period volume (V_{10}/A) and the reference volume (V_{ref}).

Modèle	V_m/A	V_{10}/A	V_{ref}/A
#1	$f(R_{ZP})$	$f(R_{ZP})$	$f(R_{ZP})$
#2	$f(R_{ZP}, A)$	$f(R_{ZP}, A)$	$f(R_{ZP}, A)$
#3	$f(R_{ZP}, M)$	$f(R_{ZP}, M)$	$f(R_{ZP}, M)$
#4	$f(R_{ZP}, IC95_{ZP})$	$f(R_{ZP}, IC95_{ZP})$	$f(R_{ZP}, IC95_{ZP})$
#5	$f(R_{ZP}, S_{CE})$	$f(R_{ZP}, S_{CE})$	$f(R_{ZP}, S_{CE})$
#6	$f(R_{ZP}, S_{CE}, A)$	$f(R_{ZP}, S_{CE}, A)$	$f(R_{ZP}, S_{CE}, A)$
#7	$f(R_{ZP}, IC95_{ZP}, A)$	$f(R_{ZP}, IC95_{ZP}, A)$	$f(R_{ZP}, IC95_{ZP}, A)$

Parameters used in the different random forest and regression models.

Parameters :

A	Catchment area
$IC50$	Median value of the connectivity index
$IC95$	Quantile 95 of the connectivity index
ICm	Mean value of the connectivity index
$IC50_{ZP}$	Median value of the connectivity index in sediment production areas
$IC95_{ZP}$	Quantile 95 of the connectivity index in sediment production areas
ICm_{ZP}	Mean value of the connectivity index in sediment production areas
R_{ICm}	Ratio of ICm_{ZP} on ICm
R_{IC95}	Ratio of $IC95_{ZP}$ on $IC95$
M	Melton index
L_{CE}	Stream length
R_{ZP}	Proportion of sediment production areas in the catchment
IG_{ZP}	Geological index of the sediment production areas
S_{CE}	Mean channel slope
S_C	Fan slope
$P1h_{10}$	1 hour rainfall for a 10 years return period
$P6h_{10}$	6 hour rainfall for a 10 years return period
$P24h_{10}$	24 hour rainfall for a 10 years return period

Results

Here, we present, for example, the different equations for predicting the 10-year return period volume and reference volume depending on the parameters used. These equations predict specific volumes (m³/km²) :

10-years return period volumes

$$V_{10}/A = 168 \cdot R_{ZP}^{0.88}$$

$$V_{10}/A = 274 \cdot R_{ZP}^{0.75} \cdot A^{-0.28}$$

$$V_{10}/A = 125 \cdot R_{ZP}^{0.81} \cdot 10^{0.2 \cdot M}$$

$$V_{10}/A = 830 \cdot R_{ZP}^{0.70} \cdot 10^{0.18 \cdot IC95_{ZP}}$$

$$V_{10}/A = 110 \cdot R_{ZP}^{0.81} \cdot 10^{0.6\sqrt{S_{CE}}}$$

$$V_{10}/A = 309 \cdot R_{ZP}^{0.75} \cdot A^{-0.29} \cdot 10^{-0.13\sqrt{S_{CE}}}$$

$$V_{10}/A = 592 \cdot R_{ZP}^{68} \cdot 10^{0.1 \cdot IC95_{ZP}} \cdot A^{-0.23}$$

Reference volumes

$$V_{ref}/A = 475 \cdot R_{ZP}^{0.94}$$

$$V_{ref}/A = 661 \cdot R_{ZP}^{0.85} \cdot A^{-0.18}$$

$$V_{ref}/A = 363 \cdot R_{ZP}^{0.87} \cdot 10^{0.19 \cdot M}$$

$$V_{ref}/A = 1982 \cdot R_{ZP}^{0.77} \cdot 10^{0.16 IC95_{ZP}}$$

$$V_{ref}/A = 373 \cdot R_{ZP}^{0.90} \cdot 10^{0.35\sqrt{S_{CE}}}$$

$$V_{ref}/A = 779 \cdot R_{ZP}^{0.85} \cdot 10^{-0.17\sqrt{S_{CE}}} \cdot A^{-0.21}$$

$$V_{ref}/A = 1630 \cdot R_{ZP}^{0.76} \cdot 10^{0.1 \cdot IC95_{ZP}} \cdot A^{-0.13}$$

Parameters :

R_{ZP}	Proportion of sediment production areas in the catchment
M	Melton index
A	Catchment area
S_{CE}	Mean channel slope
$IC95_{ZP}$	Quantile 95 of the connectivity index in sediment production areas

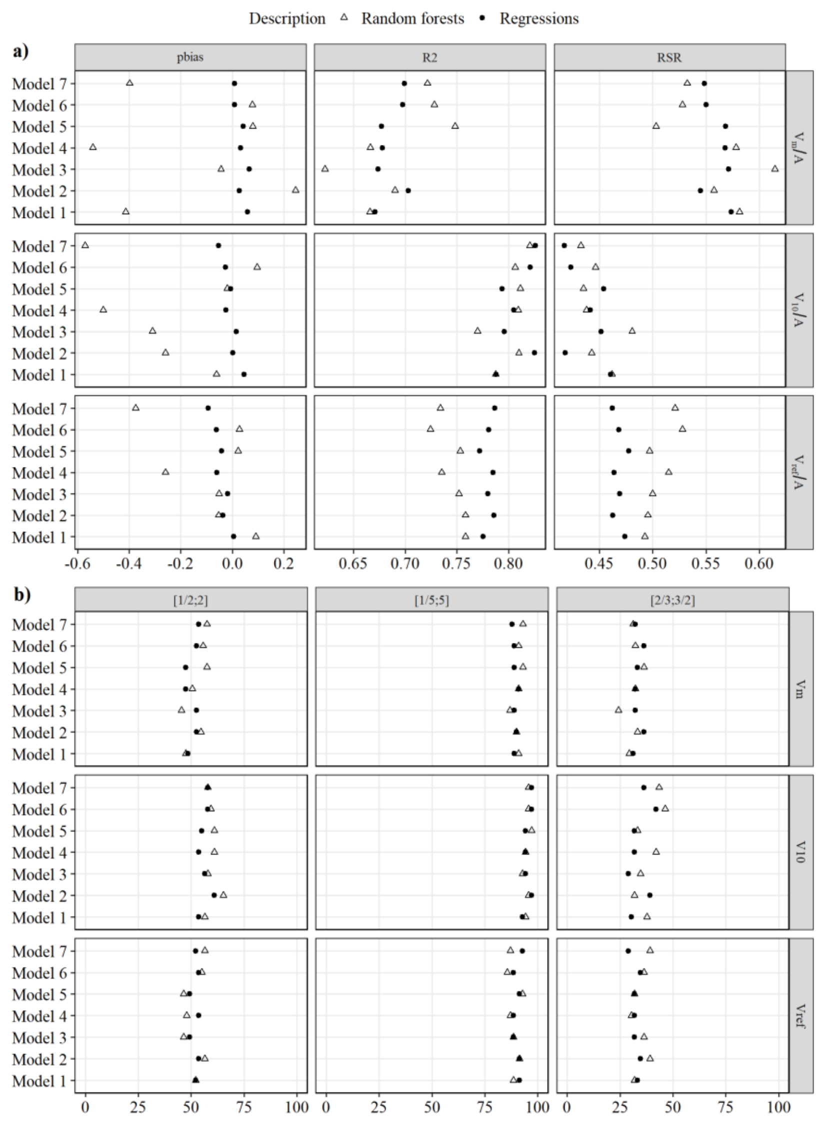
Results

Model performance assessment :

Modèle	V_m/A	V_{10}/A	V_{ref}/A
#1	$f(R_{ZP})$	$f(R_{ZP})$	$f(R_{ZP})$
#2	$f(R_{ZP}, A)$	$f(R_{ZP}, A)$	$f(R_{ZP}, A)$
#3	$f(R_{ZP}, M)$	$f(R_{ZP}, M)$	$f(R_{ZP}, M)$
#4	$f(R_{ZP}, IC95_{ZP})$	$f(R_{ZP}, IC95_{ZP})$	$f(R_{ZP}, IC95_{ZP})$
#5	$f(R_{ZP}, S_{CE})$	$f(R_{ZP}, S_{CE})$	$f(R_{ZP}, S_{CE})$
#6	$f(R_{ZP}, S_{CE}, A)$	$f(R_{ZP}, S_{CE}, A)$	$f(R_{ZP}, S_{CE}, A)$
#7	$f(R_{ZP}, IC95_{ZP}, A)$	$f(R_{ZP}, IC95_{ZP}, A)$	$f(R_{ZP}, IC95_{ZP}, A)$

Parameters used in the different random forest and regression models.

- We quantified the predictive performance of our models using three performance measures (R^2, pbias, RSR).
- The accuracy of the models was also assessed from the ratios of the predicted absolute value (i.e. expressed in m^3 and not in specific volume expressed in m^3/km^2) divided by the observed absolute value. The proportion of these ratios that fall within the ranges [2/3; 3/2]; [1/2; 2] and [1/5; 5] was measured.



Performance of models according to formulations and methods. pbias = percent bias of the models; R2 = coefficient of determination; RSR = RMSE-observations standard deviation ratio.

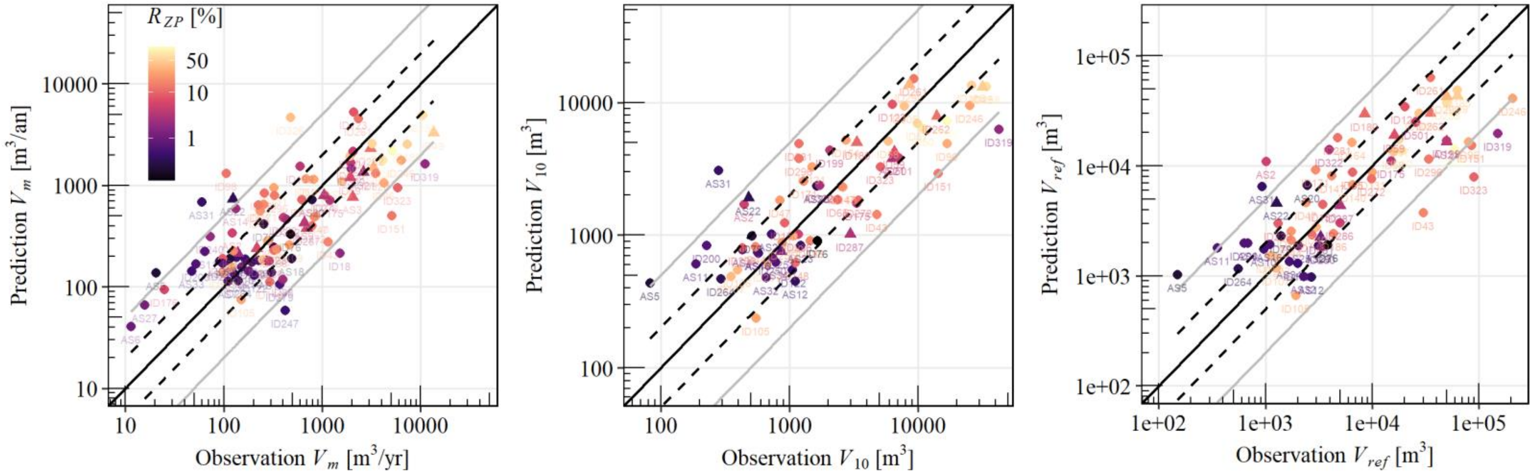
Results

Model performance assessment :
Examples for equations below :

$$V_m / A = 77 \cdot R_{ZP}^{0.70} \cdot A^{-0.26}$$

$$V_{10} / A = 274 \cdot R_{ZP}^{0.75} \cdot A^{-0.28}$$

$$V_{ref} / A = 661 \cdot R_{ZP}^{0.85} \cdot A^{-0.18}$$

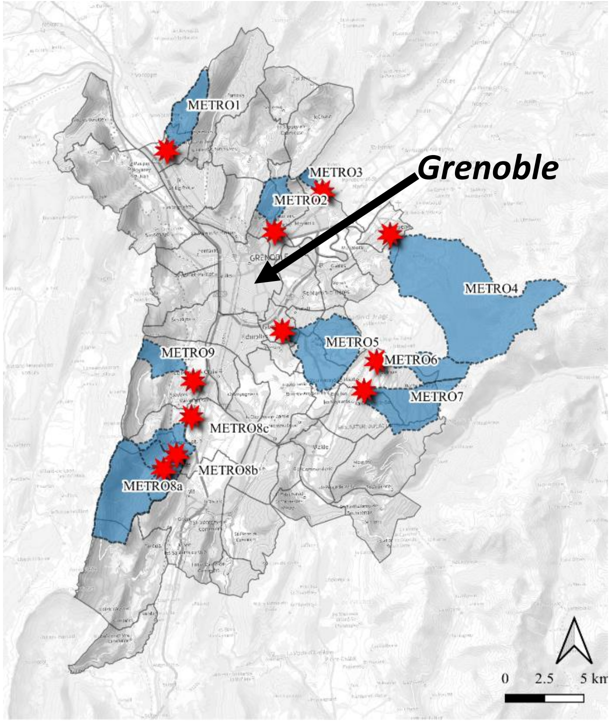


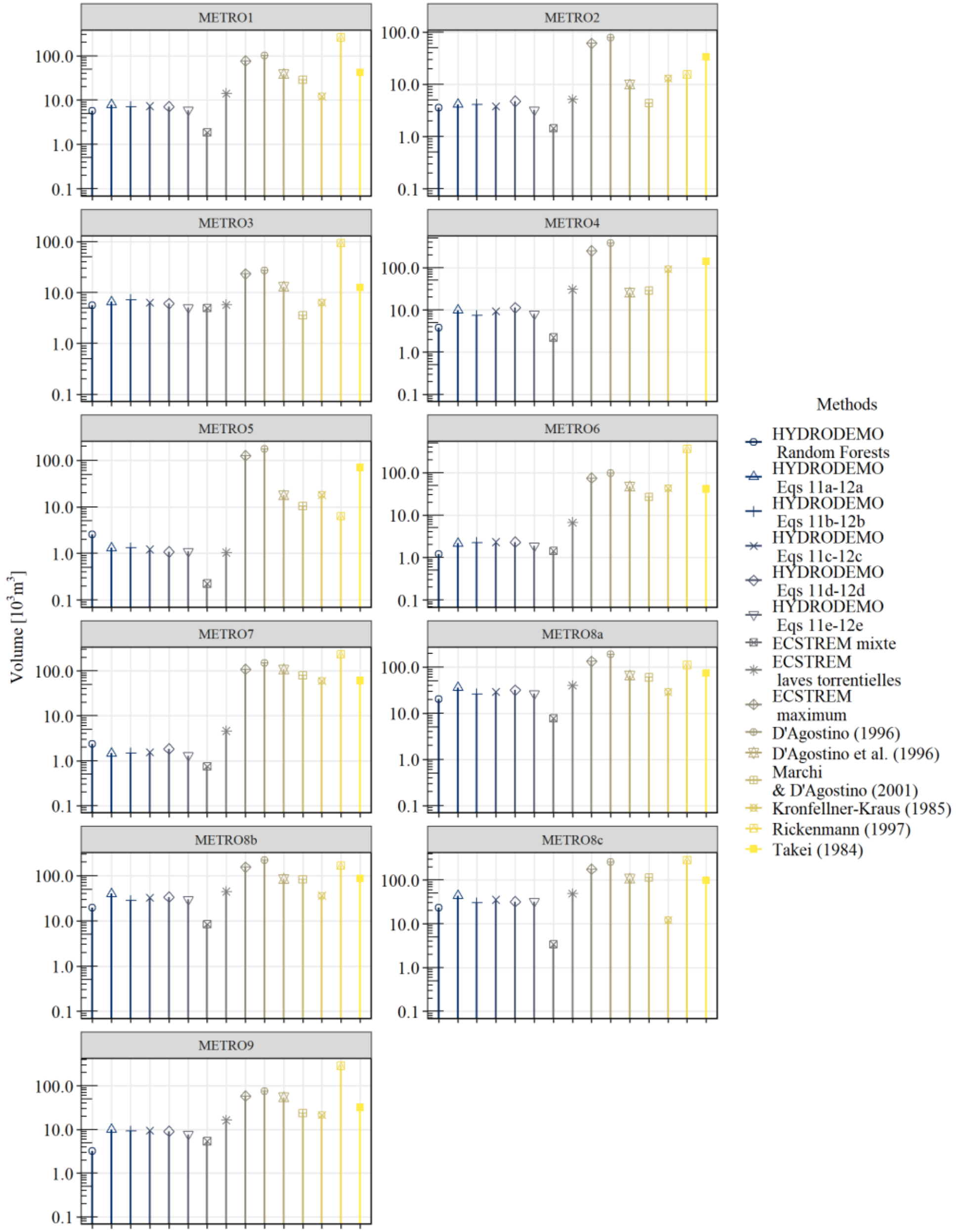
Comparison of observed and predicted volumes, for mean annual volume (V_m), the 10 year return period volume (V_{10}) and the reference volume (V_{ref}). The dashed line indicates the interval [1/2; 2] , the grey line indicates [1/5; 5] .

Analysis of the performance of the models showed that about 50% of the predictions are in the range [1/2; 2]. This shows that these models provide an order of magnitude and not a precise value of the sediment volume.

Application of the models

Location of the catchments where the formula were independantly tested.





Comparison of reference volume predictions using different existing methods.

- We made an application of the developed models on a selection of independent torrents located in the Grenoble region.
- We compared the results obtained with those of other methods generally used for the estimation of sediment production volumes in mountains area (e.g. D'Agostino, 1996).
- The detailed analysis of the historical events of these torrents shows that the predictions of our models are quite consistent.
- Some existing methods in the literature greatly overestimate the sediment production capacity of torrents. We suspect that this is mainly due to the absence of a parameter describing the sediment availability in their formulas.

Conclusion

- This study presents a new prediction approach based on multivariate statistical models calibrated from an original dataset covering 120 torrential watersheds in the Northern French Alps.
- These models are used to estimate mean annual production volumes, 10-year return period volumes and reference volumes.
- Statistical analyses show that the proportion of sediment production area in the catchment areas is the main parameter for predicting production volumes. This highlights the importance of considering sediment availability in the catchments.
- To a lesser extent, other indicators such as sediment connectivity index, stream slope, Melton index or catchment area are correlated with sediment production volumes.
- Variables describing geology or climate were not significant in our study.
- These models are based on geomorphic indicators that are relatively simple to characterize. They are therefore quick and easy to use.
- Despite the uncertainties associated with the limited duration of the observations and the parsimony of the approaches used, the sediment volume prediction models tested on a selection of torrents located around the Grenoble region provide results whose orders of magnitude seem satisfactory.
- These models complement existing approaches and can be useful for assessing sediment in catchments not equipped with sediment retention basins.