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RESEARCH ARTICLE

**Core-derived historical records of suspended sediment origin in a mesoscale
mountainous catchment: the Bléone River, French Alps**

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Abstract

Purpose: Quantifying suspended sediment fluxes and dynamics across mountains and identifying the origin of sediment in severely eroded areas are of primary importance for an equilibrate management of water resources. This contribution aims at generalising previous results of suspended sediment fingerprinting obtained during the 2007-2009 period in a mesoscale Alpine catchment, the Bléone River (905 km²) and to possibly check their validity throughout the second half of the 20th century.

Materials and methods: Sediment fingerprinting based on elemental geochemistry and radionuclide measurements was conducted on a sediment core collected in an alluvial floodplain at the basin outlet. This technique was combined with long hydro-sedimentary time-series to reconstruct the origin of suspended sediment that deposited at this location throughout the last 50 years.

Results and discussion: Hydro-sedimentary interpretation of sedimentation based on historical hydrological databases corroborates core dating obtained with ¹³⁷Cs and ²¹⁰Pb_{xs} activity measurements. Black marls and (marly) limestones provided the bulk of sediment throughout the sequence (40% and 22%, respectively), while they only occupies 10% of the total catchment area. However, we also showed the occurrence of major floods carrying large quantities of sediment originating from Quaternary deposits and conglomerates (25% and 16%, respectively). The variability of sediment sources throughout the sequence may reflects the spatial variability of rainfall within the catchment, depending on air mass origin. However, the relatively homogeneous sediment composition throughout the sequence confirms that core-derived information is representative of large-scale flood events.

Conclusions: In conclusion, these results are consistent with the ones obtained in previous studies. They also outline the need to take account of the entire grain size range of fine sediment to provide an overall picture of sediment sources and transfers within highly erosive catchments. This study finally emphasize the relevance of using archive data to validate sediment fingerprinting generally conducted during short monitoring programs across larger time period and large widespread floods.

Keywords Braided river • Erosion • Geochemistry • Radionuclide • Sediment core • Sediment fingerprinting

1 Introduction

In mountainous regions, hillslope erosion and mass movements supply large quantities of fine-grained sediment ($< 63 \mu\text{m}$) to rivers where they generally cause numerous environmental and economical problems, such as reservoir siltation and operational problems for hydroelectric power plants (e.g., Valero-Garcés et al. 1999). An excess of sediment supply can also lead to an increase in water turbidity, eutrophication and degradation of riverine habitats in lowland areas (e.g. Owens et al. 2005). Furthermore, although suspended sediment conveys the biogenic elements required by all the living organisms, the finest fraction ($< 63 \mu\text{m}$) is also one of the main vectors of contaminant transfer (e.g., PCBs, heavy metals) within catchments (Owens and Walling 2003; Collins et al. 2005).

The Rhône River that flows across Switzerland and France has become the main sediment supplier to the Mediterranean Sea since damming of the Nile River (Sempéré et al. 2000). Downstream reaches of this river are confronted with particularly severe contamination and siltation problems (Antonelli et al. 2008; Sicre et al. 2008). Previous studies hypothesised that a significant part of sediment probably originated from the badland areas constituted of black marls and located in the Durance River catchment (e.g. Pont et al. 2002; Di Giovanni et al. 2002). During the 3-year STREAMS (Sediment TRansport and Erosion Across MountainS) research project funded by the French Research Agency, a large hydro-sedimentary database was compiled in the Bléone River catchment (905 km²) which is one of the main contributor of sediment to the Durance River (Mano et al. 2009). The catchment is equipped with 7 hydrometric stations at intermediary scales (i.e., 10–1000 km²). Each station is characterised with high frequency acquisition of discharge and turbidity, and suspended sediment sampling during floods. This network provided a useful complement to the existing installations of the Draix Observatory that have been used since 1985 to investigate sediment dynamics in small ($< 1 \text{ km}^2$) severely eroded headwater catchments (Mathys et al. 2003). Sediment fingerprinting studies were conducted in this catchment to better understand the dynamics and to define the origin of the suspended sediment in the catchment. Evrard et al. (2011) and Navratil et al. (2012) outlined the very large spatial and temporal variability of sediment sources and exports during this study period. The preliminary results showed that 80% of suspended sediment was produced by floods generated by widespread low-intensity rainfall across the catchment. Such result corroborates the conclusions of Duvert et al. (2010, 2011). Furthermore, the analyses of several 1-2 yrs return period floods and one major flood (10 yrs-return period flood) that occurred in a subcatchment confirmed the important contribution of black marls (up to 70%) to sediment transported in rivers, although this substrate only occupies ca. 10% of the total catchment surface. Sediment exports generated by local

convective storms varied significantly at both intra- and inter-flood scales, because of spatial heterogeneity of rainfall. However, black marls/marly limestones contribution remained systematically high. In contrast, widespread flood events that generate the bulk of annual sediment supply at the outlet were characterised by a more stable lithologic composition and by a larger contribution of limestones/marls, Quaternary deposits and conglomerates (Navratil et al. 2012).

In order to validate those findings over a longer time period and to enlarge the scope of our fingerprinting study to a larger set of weather and flood conditions, we investigated the evolution of suspended sediment origin and dynamics over a 50-year period from the severely eroded Bléone river catchment (905 km²). To this end, we collected a sediment core in the alluvial floodplain at the Bléone catchment outlet. Long-term meteorological and hydrological datasets were used to interpret the structure of this core and to associate the sediment deposits with different hydrological periods. Radionuclide and elemental geochemistry properties were then measured on the core sediment samples. A mixing model was finally used to trace the origin of suspended sediment transported during a selection of past large floods.

2 Study area

The Bléone catchment (905 km²; lat.: 44°05'34''N, long.: 06°13'53''E), with altitude ranging between 405 and 2961 m A.S.L. (Above Sea Level), is a mountainous Alpine catchment located in the Durance River district, in southeastern France (Fig. 1). The catchment is characterised by a dendritic drainage network dominated by the Bléone River and several tributaries, among which the Bès River (233 km²-subcatchment) is the most important. Forest is by far the main land use in the catchment (44% of the total catchment surface; Table 1). The lithology mainly consists of marls, molasses and limestones, with large areas of exposed Cretaceous and Jurassic black marls, as well as Lias marly limestones (Fig. 2). Geological information was derived from a digitised 1:50,000 spatially-distributed geological map of the catchment provided by the French Geological Survey (BRGM). Eroded surfaces (covering 11% of the total Bléone catchment area, see Fig. 2) were delineated in a GIS using aerial photographs taken during flight campaigns conducted in 2004 by the French National Geographic Institute (IGN). Eroded surfaces cover a mean surface of 0.45 km² (between 811 m² and 1.85 km²) and were classified into three groups: debris slope areas (22% of the eroded areas), sheet and rill erosion areas (48%), and gully erosion areas (30%). Areas

covered by black marls are strongly affected by erosion and are characterized by a badland morphology (Mathys et al. 2005).

The climate is transitional and undergoes mountainous and Mediterranean influences. Mean annual temperature ranges between 12–13°C at 400 m A.S.L., with high temperature variations between summer and winter (about 18°C). Mean annual rainfall in the catchment varies between 600–1200 mm at 400 m A.S.L. According to local archives (*Archives Départementales des Alpes de Haute Provence*), the largest historical flood at the basin outlet is reported to have occurred in July 1854, with a peak discharge estimated at $\sim 1,100 \text{ m}^3 \text{ s}^{-1}$ (Sogreah, 2005). Over the past decades, the maximum specific peak discharges were significantly higher in the Bès River subcatchment (165 km²) than in other similar catchments of the Southern French Alps (Fig. 3c): $3.6 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ for the Bès River, against less than $1.4 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ in other catchments. This subcatchment has therefore a very specific behaviour. Furthermore, floods that occurred in this area from 1960 to 2009 were characterised by a strong seasonality. Most of the floods occurred in autumn (see Fig. 3a). South or South-Western atmospheric fluxes originating from the Mediterranean Sea and characterised by humid and warm air flows provide the bulk of annual rainfall in this region. They triggered most of the largest floods observed since 1960 (see Fig. 3b). The presence of a widespread depression centered on France is also associated with heavy rainfall in the entire country and generates large and widespread floods at the basin scale. In contrast, Western weaker depressions coming from the Atlantic Ocean generally dry up over the first French mountain ranges (i.e., Massif Central and Pyrénées), so that they only provide low-intensity rainfall when they reach the Southern Alps. Northern and North-Western fluxes occur when the Azores High is located at high latitudes; midlatitude cyclones can then arrive from the Northern Alps and produce the bulk of the snow cover. Eastern fluxes are associated with a high pressure cell standing over central Europe. Contact between this cold and dry air mass with the Mediterranean air mass can trigger particularly heavy storms over the Southern Alps in spring and summer. Finally, when high pressure cells dominate in the region, local convective storms can also occur due to local air mass instability (Gottardi 2009). These storms mostly occur between June and September. They are associated with heavy downpours that may trigger flash floods and debris flows that are otherwise restricted to small headwater streams.

3 Materials and methods

3.1 Coring site

A 3-meter long sediment core (5-cm diameter) was collected on 26 November, 2009 with a Cobra corer in the Bléone River floodplain, upstream of the Malijai dam close to the outlet (see Fig. 1b; 905 km²). Coring was conducted in collaboration with the *Laboratoire de Géophysique Interne et Tectonophysique* (LGIT) and the *Laboratoire des Sciences de l'Environnement* (LSE). The sampling site was selected on a vegetated bar composed of very fine sediment, adjacent to the river channel, and located about 1 meter above the mean floodplain level. During floods, water level and flow velocity are controlled so as to ensure good operating conditions for the dam. In the recent period, we observed that the floodplain was systematically submerged during the largest floods. There was no evidence of bank erosion in the vicinity of the coring site. We therefore hypothesize that this site located within the dam reservoir has underwent a slow sedimentation since the dam building. Malijai dam was built by the French national electricity producer (EDF) in 1962. During base flow periods, the dam is closed to divert part of the clear water into a canal. To limit supply of sediment and associated substances to the downstream Berre lagoon (Accornero et al. 2008), French authorities fixed a maximal suspended sediment concentration that can be delivered to the canal, which leads to extra management costs for the company exploiting the power plants. Consequently, during floods, the dam is opened manually in order to divert water and sediment into the main channel. Sediment siltation mainly occurs during large floods (>1-2 yrs return period) in the reservoir area where we sampled the sediment core. From 1962 onwards, the dam has accumulated sediment, whereas resuspension of fine sediment and bedload only occurred in the middle part of the active river channel (see Fig. 1b).

3.2 Stratigraphic structure of the sediment core

In this study, we used X-ray measurements and visual observations to outline the stratigraphic structure of the core, i.e. the succession of flood deposits since the Malijai dam construction (1962).

The core was X-rayed at the *Eaux Claires* Hospital of Grenoble, with the aim to associate specific densities with grey level intensities (de Montety et al. 2003). Longitudinal image resolution was 2 mm; mean and standard deviation of grey level intensities were then measured in each section (i.e. horizon) within a 2 by 2 cm window centered on the core axis. Grey shades are considered to reflect the density of sediment as the grey-scale intensity of an X-ray image is proportional to beam attenuation of the incident X-ray (Lofi and Weber 1999).

The grey intensity variations in that core would therefore undoubtedly reflect the succession of flood deposits (i.e., varves).

Then, the sediment core was cut into two longitudinal parts, photographed, and subsampled based on two strategies: (1) sections were made following the stratigraphic structures of varves detected by X-ray analysis and visual observation, on the first half of the core; (2) 2-cm wide sections were cut on the second half of the core. Sediment samples were ground to a fine powder and dried at 105°C for 2 hours.

Then, we measured the grain-size of a selection of core samples to analyse the inter- and intra- varve variations of grain-size fraction. Subsamples were analysed with a Malvern® particle laser sizer after 7-min of stirring and sonication. Grain size distributions and statistics were computed with Gradistat software (Blott and Pie 2001).

3.3 Origin of fine sediment

3.3.1 Soil and core sediment sampling

Representative soil samples were collected in the Bléone basin to characterize potential source materials (see Evrard et al. 2011 for details). They were taken mostly on colluvial toeslopes adjacent to the drainage network to be representative of material eroded from adjacent hillslopes. Soil samples were dried at 105°C and disaggregated prior to analysis. As the core sediment samples have a finer grain size than the soil samples (i.e., potential sediment sources), we sieved this source material to <63 µm before conducting radionuclide and geochemical analyses (Navratil et al. 2012).

We used the 2-cm core section samples (n = 92 for the core dating and n = 34 for the sediment fingerprinting) to cover the entire sequence of sediment deposit. The sediment samples were dried at 40°C, disaggregated and sieved to 63µm.

3.3.2 Measurement of radionuclide and elemental geochemistry

In total, we measured gamma-emitting radionuclide activity in 92 core samples and the 150 source samples. Sediment was placed in a counting box when there was sufficient material (≥10 g). Radionuclide activities (²⁴¹Am, ¹³⁷Cs, ⁴⁰K, ²¹⁰Pb, ²²⁶Ra, ²²⁸Ra, ²³⁴Th, ²²⁸Th) were determined by gamma-spectrometry using the very low-background coaxial N- and P-types GeHP detectors (Canberra / Ortec / Eurisy) available at the *Laboratoire des Sciences du Climat et de l'Environnement* (Gif-sur-Yvette, France). Efficiencies and background levels of the detectors were periodically controlled with internal and IAEA (International Atomic Energy Agency) soil and sediment standards (Evrard et al. 2010; Evrard et al. in press). When

there was < 10 g sediment available, filters were placed in tubes and counting was conducted at the *Laboratoire Souterrain de Modane* (LSM; CNRS-CEA) under the French Alps, using a very low background, high-efficiency well-type Ge detector (Reyss et al. 1995).

For the measurement of elemental geochemistry, dried subsamples (c. 80 mg) of selected 2-cm core sections (n = 34) were analysed by inductively coupled plasma – mass spectrometry (ICP-MS; XII CCT Series, Thermo Electron), in solutions containing 0.2 g of solid L⁻¹. The sediment total digestion procedure is described by Le Cloarec et al. (2011). Concentrations were determined for five major (Al, K, Fe, Mg, Ti) and thirteen trace (Ag, Ba, Cd, Co, Cr, Cu, Mn, Ni, Pb, Sb, Tl, V, Zn) elements. The accuracy of the elemental concentration determination was evaluated through the repetitive analysis of the certified reference material SL-1 (lake sediment, AIEA, Vienna, Austria). The obtained values (n=4), agreed with the certified concentrations, when available. Certified values are not available for Ag, Al, Ca, Mg and Tl. The accuracy of the determination of these four elements in SL-1 was cross-checked with values determined by neutron activation analysis (Ayrault et al. 2010; Evrard et al. 2011). Analytical uncertainties associated with this method did not exceed 20 and 10% for major and trace element determination, respectively. Analysis of source material is described in detail in Navratil et al. (2012).

3.3.3 Selection of fingerprints and design of a mixing model

Based on the French Geological Survey (BRGM) map of the catchment (see Fig. 2), we grouped the geological classes represented on the map and corresponding to our sediment source samples types into 5 classes: (1) marly limestones; (2) limy marls; (3) conglomerates; (4) Quaternary deposits; (5) black marls (see Evrard et al. 2011). As described by Navratil et al. (2012), we selected 10 fingerprinting properties that can discriminate between these five different sediment sources. Among them, 6 properties were sufficient to design the optimum composite fingerprint. Only one geogenic radionuclide was pointed out (²²⁶Ra). The other selected fingerprints were V, Ni, Mn, Sb and Cu. Then, we constructed a Monte Carlo mixing model as detailed by Navratil et al. (2012) in order to quantify the contribution of each sediment source to the core sediment samples.

3.4 Core dating

Dating of the sediment cores relied on the measurement of two radionuclides (i.e., ¹³⁷Cs and ²¹⁰Pb_{xs}) that strongly sorb onto fine sediment (Owens et al. 1999). ¹³⁷Cs was used as an event-tracer, whereas ²¹⁰Pb_{xs} provided the sediment age (Appleby 2000). Both

radionuclides are gamma emitters and they can be detected without any previous chemical treatment of sediment.

^{137}Cs is an artificial radionuclide ($t_{1/2} = 30$ years) produced by the thermonuclear bomb testing conducted between the 1950s and the 1980s (with a maximum input in 1963) and, depending on local weather conditions, after the Chernobyl accident in 1986. ^{137}Cs is now stored in soils, and this ^{137}Cs stock decreases by radioactive decay and by fine sediment transfer to the rivers. Uncertainty on measurements was ca. 0.5%, and the detection limits reached 0.3 Bq kg^{-1} .

^{210}Pb is a natural radionuclide ($t_{1/2} = 22.3$ years) which is a decay product of ^{238}U ($t_{1/2} = 4.5 \times 10^9$ years). ^{238}U decays through a series of short-lived nuclides (e.g., ^{226}Ra and ^{222}Rn). ^{222}Rn is a gas that partly remains *in situ*, forming “supported” ^{210}Pb , and that partly escapes to the atmosphere, forming “excess” ^{210}Pb , which reaches the soil surface by wet and dry fallout. It then strongly sorbs to soil particles. The activity in “excess” ^{210}Pb was calculated by subtracting the supported activity (determined using a ^{238}U daughter, i.e. ^{214}Bi) from the total activity of ^{210}Pb . Uncertainty on measurements was thus higher than for ^{137}Cs (ca. 10%).

Sedimentation rates were then calculated based on the Constant Rate Supply (CRS) model (Appleby and Oldfield 1983).

3.5 Climatological and hydro-sedimentary databases

Classically, core interpretation involves a count-from-the-top correlation of the individual flood deposits with flood events that resulted in overbank deposition (e.g. Hobo et al. 2010). However, evident difficulties prevented to associate each individual varve with individual flood events: (1) the context of this study (mountainous river with flash floods, complex sedimentation due to dam functioning) and (2) the lack of long-term water-level/discharge time-series available at the coring location. We therefore analysed the correlation between the stratigraphic structure of the core (succession of varve thickness) and the inter-annual hydro-meteorological variations. Given the lack of discharge data available at the Bléone River outlet, we compiled data from various sources available at different spatial scales and temporal resolutions to interpret the flood deposits at the Bléone River outlet: databases of rainfall time-series, discharge and suspended sediment concentration time-series and historical floods and mass movements.

Ten rain-gauges managed by the *Laboratoire d'étude des Transferts en Hydrologie et Environnement* (R1–R5) and the French *Cemagref* research agency (R6–R10) provided continuous precipitation records (see Fig. 1; Table 1). Five meteorological stations managed by the French meteorological office (i.e., *Météo France*) provided rainfall depths and

306 durations, snow depth, temperature as well as information on the occurrence of storm or hail
307 events (R11–R15). Four of them provided daily rainfall for the 1960–2009 period (R11, R12,
308 R14, R15; Table 1). These last stations only provided daily records (with the exception of one
309 station, i.e., R12, providing hourly records). Altogether, these data provided good information
310 about spatial and temporal variability of rainfall at the Bléone River basin scale.

311 Discharge, suspended sediment concentration (SSC) and yields (SSY) were measured at 1-h
312 time steps by *EDF* at the Malijai station during the 2001–2003 and 2007–2009 periods (Table
313 1). Discharges were measured on the Bès River at Pérouré station (165 km²; see Fig. 1) during
314 the 1963–2009 period. SSC have been measured with turbidimeters since October 2007 – see
315 Navratil et al. (2010) and Navratil et al. (2011) for more information about SSC and SSY
316 equipments and methods. Discharge, SSC and SSY have also been measured at three other
317 stations within the catchment (i.e., Duyes River at Mallemoisson, Galabre River at Robine,
318 Bléone River at Prads) since October 2007 (see Fig. 1; Table 1). Discharge and sediment have
319 also been monitored since 1985 in the Draix Observatory managed by Irstea in Grenoble. We
320 took into consideration the data from the monitoring station of the Laval torrent (0.86 km²)
321 available since 1985 and still ongoing (Mathys et al. 2003; see Fig. 1; Table 1).

322 We also used a database of field observations made available by the office in charge of
323 mountain area restoration in France (i.e., *Restauration des Terrains en Montagne* service
324 (RTM) of the French National Forest Office; RTM, 2010). Important historical information
325 has been compiled since 1351 in the Bléone River basin (i.e., the oldest information of
326 torrential flood available): the occurrence of avalanches, rock falls, debris flows, torrential
327 floods and landslides. In this study, we extracted from this database the annual frequency of
328 debris flows/flash floods and landslides observed in the Bléone catchment since 1960 to
329 document erosion intensity within the Bléone catchment throughout time.

331 4 Results and discussion

332 4.1 ²¹⁰Pb_{xs} and ¹³⁷Cs dating

333 Gamma spectrometry countings conducted at Gif-sur-Yvette and Modane laboratories
334 provided very complementary results. We observed a decay of ²¹⁰Pb_{xs} with depth in the
335 sediment core when taking all 92 analysed samples into account (Fig. 4) even though
336 precision obtained on activities was larger on the 45 samples analysed in Modane, because of
337 the very low level of background at this underground laboratory (see Fig. 4). Sedimentation
338 rate could be calculated based on ²¹⁰Pb_{xs} decay of activities and was estimated at 5.4 cm yr⁻¹
339 along the first 150 cm, and at 4 cm yr⁻¹ if we take the entire depth of the core into account.

Activities in ^{137}Cs provided additional information to date the core. Peak activities were measured between 278 and 288 cm depths (32–44 Bq kg⁻¹). Peak associated with the bomb fallout (maximum activity in 1963) usually reaches values $\geq 30\text{--}35$ Bq kg⁻¹ (e.g., Le Cloarec et al., 2011; Perga et al., 2010), which remains consistent with our findings. Furthermore, presence of ^{241}Am (ca. 1 – 1.5 Bq kg⁻¹) could be detected at this depth (265–290 cm), confirming the bomb origin of ^{137}Cs fallout. In contrast, ^{137}Cs activity peak associated with Chernobyl fallout in 1986 could not be detected. This peak absence can be justified by the very low cumulative rainfall amount (i.e., 9 mm) observed in the Bléone catchment when the radioactive cloud flew over the area (i.e., between 30 April – 4 May according to the cloud dispersion model developed by French Radioprotection and Nuclear Safety Institute (IRSN 2011)).

Overall datation of the core was therefore obtained by combining the sedimentation rate derived from $^{210}\text{Pb}_{\text{xs}}$ decay and the location of the bomb ^{137}Cs activity peak in depth (see Fig. 4c). We can note that the date of the bottom of the core corresponds to the Malijai dam building (i.e., 1962). These results only provide an indicative dating of the core, as we hypothesised a constant rate of sedimentation since 1962. Erosion rate varies between seasons and years depending on flood magnitude. This point will be explored in detail with the hydro-sedimentary interpretations.

4.2 Stratigraphic structure of the sediment core

In total, 114 varves corresponding to variations of grey shades on the X-ray images were detected (Fig. 5a, b). These layers were confirmed by visual description of the core after opening. Mean varve thickness reaches 2 cm, but it fluctuates between 0.2 and 13 cm. The sediment core is characterised by about 7 cycles having similar stratigraphic structures, i.e. a succession of several small varves (< 2 cm) followed by one to three larger varves (ranging from 2–13 cm). The layer located between 91–102 cm could not be analysed because of technical problems during field sampling. Oblique varves observed between 162–198 cm depth cannot be attributed to a disturbance of the core during sampling or transport. We will discuss its possible origin in section 5.

4.3 Hydro-sedimentary interpretations

The 1962-2009 discharge time-series available for the Bès River at Pérouré station (165 km²; Fig. 6c) provide information on flood occurrence within the catchment. However, because of the spatial heterogeneity of rainfall across the catchment, these data do not

systematically reflect the flood magnitude at the Bléone River outlet (905 km²). At the scale of the entire catchment, only qualitative information about flood occurrence is available (Sogreah 2005; RTM 2010; Fig. 7a). Nine major floods that led to infrastructure damages have been reported by mountainous area restoration office (RTM) at the outlet of the Bléone River catchment since 1970s (i.e., in July 1973, March 1974, January 1978, October 1979, 1992, 1993, January, September and November 1994). In January 1994, a 10-years return period flood was observed (Sogreah 2004; $\sim 400 \text{ m}^3 \text{ s}^{-1}$). The peak discharge observed on the Bès River at Pérouré was about $41 \text{ m}^3 \text{ s}^{-1}$ (i.e., a two-year return period flood) but the Bès River subcatchment was not included in the area of maximum rainfall intensity. Two additional 10-years return period floods were observed in November 1994 and 2000 at the Bléone River outlet. The corresponding peak discharges observed on the Bès River at Pérouré indicate that they were associated with a two-year return period at this station.

Furthermore, to obtain additional data at the river basin scale, we analysed the inter-annual variation of rainfall based on information provided by the different rain-gauges available within the catchment (see Table 1). A moving average (window size of one year; lag time of 6 months) was applied to monthly rainfall data (see Fig. 6a) and to the maximum daily intensity of each month (see Fig. 6b). No significant pluri-annual trend could be retrieved for the 1960-2009 period. We therefore defined “wet” years (i.e., with mean rainfall $> 900 \text{ mm yr}^{-1}$ and mean interannual rainfall intensity $> 25 \text{ mm day}^{-1}$; see Fig. 7b) and “dry” years (i.e., with mean rainfall $< 900 \text{ mm yr}^{-1}$ and mean interannual rainfall intensity $< 25 \text{ mm day}^{-1}$; see Fig. 7c). A pluri-annual cycle (mean period of ca. 3-5 years) with alternance/succession of “wet” and “dry” years can thereby be outlined (see Fig. 7 b, c). These periods were found consistent with the occurrence of large floods (Sogreah 2005; RTM 2010; see Fig. 7a), the hydrometric stations records (see Table 1) and the database of the hydro-sedimentary activity (RTM 2010; see Fig. 7a).

We can now attempt to correlate the flood deposits with inter-annual hydro-meteorological patterns by a two-step count-from-the-top method (Hobo et al. 2010). In the first step, the largest flood deposits were correlated with the occurrence of “wet” years and the largest floods. In the second step, the smallest intermediate varves were correlated with the “wet” and “dry” years that occurred between the major events. This correlation method is based on several assumptions: (1) the largest floods would be responsible for the deposition of the thickest varves (Hobo et al. 2010); (2) the “wet” years are the most likely periods for the occurrence of large floods at the Bléone River basin scale (905 km²); (3) other small and large-scale floods can also occur during the same period, but deposits from two or more

floods in the same hydrological season may sometimes not be identified separately. Sediment deposits are indeed likely to be remobilised during the next flood, unless they are fixed by vegetation during the growing season (Hobo et al. 2010); (4) ‘dry’ years can be associated with small/moderate overbank floods at the core location and may result in thinner varves.

Varve thickness distribution matches well with the variability of the hydro-sedimentary time-series (see Fig. 7d). The largest varves, i.e., between the horizons 230-260 cm, 150-220 cm, 80-110 cm and 30-50 cm, clearly correspond to the largest floods that occurred during the “wet” periods, respectively during the periods 1968-1973, 1977-1981, 1992-1994, 1999-2002. In contrast, the thinnest varves correspond to low magnitude floods that occurred during “wet” and “dry” periods: 1960-1967, 1974-1976, 1982-1991, 1995-1998, 2003-2009. The oblique varves observed between 160-200 cm are likely to correspond to the collapse of the river bank at that location and can be associated with the widespread flood that occurred in 1979 (RTM 2010).

The grain-size fraction (<2 mm) is variable (Fig. 8a), with a dominance of silt-clay sized fraction throughout the core (ca. 80%). The mean D50 is $18.5\ \mu\text{m}$ (range from $0.7 - 84\ \mu\text{m}$); the mean D10 is $2.3\ \mu\text{m}$ (range from $0.16-22.7\ \mu\text{m}$) and the mean D90 is $160\ \mu\text{m}$ ($<1000\ \mu\text{m}$). Sand fraction is higher between 120-250 cm (ca. 30%). This core section could correspond to the large floods documented during the 1970s (1973, 1978, 1979 floods; see Fig. 3c) thereby confirming our previous interpretation.

4.4 Sediment core fingerprinting

Results of the mixing model showed that sediment sources varied during the last 50 years for the selected core sections (see Fig. 8b). Globally, black marls and (marly) limestones provided the bulk of sediment throughout the sequence: on mean 40% for black marls (min. = 19% and max = 71%) and on mean 22% for limestones (min = 14%; max = 34%). Major floods can also generate huge quantities of sediment originating from Quaternary deposits and conglomerates (respectively, 25% (min = 3%, max = 54%) and 16% (min = 6%, max = 28%)).

According to this model, black marls and limestones provided the bulk of sediment during the 1960s (51–88%). Then, during the 1970s, sediment origin was much more equilibrated between material supplied by a mix of black marls, limestones, Quaternary deposits and conglomerates. In 1972–1973, a flood was characterized by sediment originating mainly from Quaternary deposits (84% of sediment), indicating the likely occurrence of mass movements in the catchment. After this event (between 1974–1978), we calculated again a mixed

contribution of four substrate types to the Bléone River sediment with a clear dominance of Quaternary deposit contribution in 1974. In 1979, a major flood occurred. At this horizon, we observed a series of vertical varves, indicating the collapse of the river bank at that location. Major mass movements are likely to have occurred during this period, as indicated by the dominant contribution of Quaternary deposits and conglomerates to sediment deposited in between 1970-1981. As reported from the hydrological time-series, rainfall data and past observations (RTM 2010), this period was very active in terms of sediment transport. Several other subsequent floods supplied sediment originating from Quaternary deposits and conglomerates up to 1985. During the other floods that were analysed in detail, black marls and (marly) limestones provided the bulk of sediment (36–85%), together with a mix of conglomerates and Quaternary deposits. Deposits corresponding to 1991, 1993 and 2006 were almost exclusively provided by black marls and marly limestones (74–89%). These variations of sediment origin can be mainly attributed to the spatial variability of rainfall in the catchment that triggered torrential floods, but also to the magnitude of the flood and its capacity to remobilise the fine sediment temporarily stored in the river channel and floodplain. Furthermore, the relative homogeneity of sediment composition within the core (coefficient of variation of 31, 22, 61, 30% respectively for black marls, limestones, Quaternary deposits, conglomerates) confirm that the core-derived information rather reflect the occurrence of widespread and large-scale floods, with a contribution of all sediment sources available in the catchment rather than the sediment export triggered by local storm events.

These results are in agreement with the sediment flux time-series recorded at the Laval Torrent at Draix (drainage area of 0.86 km²; Fig. 9). This site was indeed characterised by massive exports of black marl material (Mathys et al. 2003) in 1992, 1994, 1996 and 2004 and 2006. These floods probably provided the flood deposits observed between 85-105 cm depth and 28-35 cm depth in the core. For the other sites, only very limited data were available and they only covered the end of the study period (i.e., 2007-2009) characterised globally by a low sediment export at the Bléone outlet.

4.5 Comparison with flood scale analyses conducted during the 2007-2009 period

These results can be compared to previous findings obtained by sediment fingerprinting on both riverbed and suspended material collected in the Bléone River catchment during a more recent period (2007-2009; Fig. 10; Evrard et al. 2011; Navratil et al. 2012).

Analysis of the core deposits and the suspended sediment outlined very similar trends at the catchment outlet (see Fig. 10). Black marl contribution clearly dominates, providing a mean of 40% for the core deposits and 34% for the suspended sediment. Given this substrate only occupies 10% of the total catchment area, it underlines the high erodibility of black marls (e.g., Mathys et al. 2005; Poulenard et al. 2012). Limestones/marly limestones contributions are also significant (mean of 22% for core deposits and 30% for suspended sediment), but they remain in the same order of magnitude as the % of catchment surface that they occupy (ca. 37 %). It confirms the lower erodibility of those substrates compared to black marls. Analysis of core deposits and suspended sediment also remain consistent regarding Quaternary deposits (21 % vs. 23%, respectively). This contribution corresponds once again to the % of occurrence of those substrates within the catchment (ca. 27%). The lowest contribution corresponds to conglomerate sources (mean of 13% vs. 16%), whereas it occupies about 25% of the catchment. In contrast, black marls and limestones are under-represented in riverbed sediment compared to their occurrence within the catchment, whereas Conglomerates and Quaternary deposits are over-represented in this material. The grain size of these different sources may explain this variability, even though we could take those differences into account in our fingerprinting study by conducting appropriate sieving. Further studies should focus on the variation of grain size of sediments during their transfer across catchments in order to outline the different erosion/transfer processes that are involved at different spatial and temporal scales.

5 Conclusions

We can demonstrate from our core dating study that we could reconstruct the history of sedimentation since Malijai dam building by analyzing and dating a sediment core collected at this location, draining a 905-km² highly erosive Alpine catchment. Determination of 1963 bomb fallout peak is confirmed by the detection of ²⁴¹Am (emitted by the bombs but not by Chernobyl accident). We could not detect any peak corresponding to Chernobyl fallout in 1986 (which is confirmed by the very low rainfall amount observed in this catchment in April – May 1986), but we could derive a mean sedimentation rate during this period, providing a way to date the entire sediment core. The hydro-sedimentary interpretation corroborates this analysis, and we could associate each major varve with very active erosive periods that produced significant sediment exports since 1962 until 2009 at the Bléone River outlet.

Black marls and (marly) limestones provided the bulk of sediment throughout the sequence (on mean 40% and 22%, respectively) but we could outline the occurrence of major floods generating huge quantities of sediment originating from Quaternary deposits and conglomerates (on mean 25% and 16%, respectively). These results are consistent with the ones obtained in previous studies where a similar sediment composition was found in suspended sediment collected during (or after) large and widespread floods that occurred between 2007 – 2009 in the Bléone River catchment. In contrast, those results slightly differed with the ones derived from riverbed sediment analysis, outlining the need to take account of the entire grain size range of sediment material within catchments to provide an overall picture of sediment sources and transfers within highly erosive catchments. Overall, this study also underlines the relevance of using archive data – i.e., hydrological time-series and sediment core – to validate sediment fingerprinting analyses conducted generally during short monitoring time-period (i.e., several years).

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Table and figure captions

Table 1 Summary of the meteorological and hydro-sedimentary data used in this study (SSC: suspended sediment concentration; Q: discharge; R: rainfall). “R” and “STA” referred to as the raingauges and hydrometric stations (Fig. 1)

Fig. 1 Location of the study area in France, and location of the river monitoring stations (STA1–STA7) and the raingauges (R1–R15) within the Bléone River catchment (Fig. A). Location of the sediment coring site at the catchment outlet (Fig. B)

Fig. 2 Geology of the Bléone River catchment and location of the river monitoring stations (from Evrard et al. 2011)

Fig. 3 Distribution of major floods (return period > 1 yr) recorded on the Bès River at Pérouré station during the 1962-2009 period. Relation with the main hydro-meteorological events (Fig. A). Seasonality of the major floods since 1962 (Fig. B). Regional variability of the maximum annual specific discharge in the South-Eastern French Alps (Fig. C)

Fig. 4 Sediment core dating derived from the distribution of ^{137}Cs (Fig. A) and $^{210}\text{Pb}_{\text{ex}}$ (Bq kg^{-1} , Fig. B) activities with depth. Time-scale based on radionuclide dating (Fig. C)

Fig. 5 Sediment core analysis and varve identification with X-ray intensity level (Fig. A, B). Time-scale based on radionuclide dating (Fig. C)

Fig. 6 Hydrometeorological data. Fig. A: monthly rainfall (in grey, the monthly data at the different raingauges). Fig. B: maximum daily rainfall. Fig. C: discharge data of the Bès River at Pérouré (daily and instantaneous discharge)

Fig. 7 Core interpretation. Flash floods/debris flows and landslides frequency (RTM source; Fig. A). Mean annual rainfall (moving average; Fig. B) and daily intensity rainfalls (moving average; Fig. C). The “wet” years (black) and “dry” years (grey) are defined for each variable. Varves’ thickness (Fig. D). Time-scale based on radionuclide dating (Fig. E)

Fig. 8 Sediment size composition (Fig. A) and sediment composition with geochemistry (Fig. B). Time-scale based on radionuclide dating (Fig. C)

686

687 **Fig. 9** Total sediment yield (suspended sediment and bedload) at the Laval catchment

688

689 **Fig. 10** Fine sediment origins at the Bléone River outlet. Proportion of draining catchment
690 surface occupied by the different lithologic sources (%; black bars), riverbed sediment
691 composition (%; white bars; Evrard et al. 2011), suspended sediment composition (grey bars;
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Basin name	Station location	Drainage area (km²)	Data type	Observation period	Station manager
Laval	Draix	0.86	Q, SSC (variable time step) STA8, R6 to R10 (5. min.)	1984-2010	Cemagref Grenoble/ETNA
Bès	Pérouré	165	Q, SSC (10. min.) ; STA3; STA4	1962- 2010 for Q 2007- 2010 for SSC	SPC Grand Delta, DIREN, EDF-DTG, LTHE
Duyes	Mallemoisson	120	Q, SSC (10. min.) STA 6	2007-2010	LTHE
Galabre	Roubine	22	Q, SSC (10. min.) STA2	2007-2010	LTHE
Bléone	Prads	65	Q, SSC (10. min.) STA5	2007-2010	LTHE
Bléone	Chaffaut	705	SSC (hourly) STA1	2001-2003 ; 2007-2010	EDF-DTG
Bléone	Malijai	870	Q (hourly) ; STA7	2007-2010	EDF-DTG
Arigéole	Beaujeu	---	R (daily); R14	1926-2010	Météo France
Bléone	Digne	---	R (daily); R12	1945-2010	Météo France
Bès	Seyne	---	R(daily); R15	1928-2010	Météo France
Duyes	Thoard	---	R(daily); R13	1999-2010	Météo France
Bléone	Marcoux	---	R(hourly); R11	1938-2010	Météo France
Bès	Haut-Vernet	---	R (5 min.) ; R1	2008-2010	LTHE
Bès	Barles	---	R (5 min.) ; R2	2008-2010	LTHE
Galabre	Ainac	---	R (5 min.) ; R3	2008-2010	LTHE
Bléone	Serre	---	R (5 min.) ; R4	2008-2010	LTHE
Bléone	Les Dourbes	---	R (5 min.); R5	2008-2010	LTHE
Bès	Barles	---	R (5 min.) ; R2	2008-2010	LTHE

Tab. 2 Concentrations in geochemical elements (mg kg⁻¹) and mean radionuclide activities (in Bq kg⁻¹, except for K – in %) analysed in the sediment core sections (n=34)

Sediment core sections (n° 1-34)																			
Section n°	Core depth	Mg	Al	Ti	Mn	V	Ni	Cu	Ag	Cd	Sb	Ba	TI	Pb	K (%)	Th-234	Ra-226	Ra-228	Th-228
	(cm)																		
1	5.4	9055	6.6	3647	463	103	50	24	0.16	0.16	0.39	376	0.54	13	1.70	31.1	22.0	32.8	35.0
2	13.4	8463	4.8	3550	582	88	38	20	0.21	0.18	0.36	349	0.38	12	1.59	28.8	22.5	30.6	30.9
3	18.7	10005	6.5	3422	458	102	45	19	0.15	0.14	0.29	273	0.47	13	1.79	26.4	23.0	34.3	32.2
4	27	9348	5.8	4230	680	104	44	20	0.17	0.13	0.34	305	0.43	13	1.55	30.0	23.0	31.6	32.0
5	33.2	6168	5.2	2688	393	81	40	23	0.21	0.14	0.32	446	0.38	12	1.29	24.3	22.0	29.0	27.1
6	45.7	8535	4.0	2917	705	70	39	21	0.19	0.14	0.36	266	0.29	14	1.28	23.9	20.0	28.1	25.9
7	49.7	10306	5.5	3192	568	83	45	20	0.20	3.25	0.42	244	0.37	53	1.27	23.0	20.0	28.4	26.3
8	56.9	8315	4.9	3473	689	88	42	23	0.22	0.14	0.61	359	0.38	13	1.44	30.0	24.0	28.0	30.0
9	65.5	10735	5.1	2929	455	86	43	18	0.15	0.14	0.39	232	0.38	13	1.40	23.9	22.5	28.7	28.6
10	70.8	8211	6.3	4221	580	114	46	26	0.24	0.19	0.54	446	0.53	13	1.63	25.2	26.0	32.4	31.0
11	74.5	8598	4.7	3173	739	82	41	19	0.25	0.14	0.42	259	0.36	13	1.49	19.4	22.5	29.0	28.9
12	84.0	9768	5.8	3210	579	92	44	20	0.27	0.13	0.40	267	0.40	14	1.37	21.0	20.0	28.9	27.8
13	100	9021	5.0	3925	815	94	43	19	0.23	0.14	0.37	292	0.36	13	1.37	21.9	20.0	28.2	28.3
14	109.1	10028	7.8	4842	681	135	44	18	0.45	0.14	0.79	323	0.58	13	1.62	28.5	23.0	35.0	31.1
15	116.4	7221	3.6	1868	489	59	37	18	0.16	0.13	0.39	262	0.26	14	0.88	13.1	19.0	18.6	16.9
16	117.6	7740	3.1	2553	677	59	34	19	0.22	0.15	0.44	254	0.25	12	0.88	13.1	16.0	18.6	16.9
17	123.6	8312	5.1	3795	610	98	41	19	0.29	0.17	0.41	332	0.39	12	2.02	26.3	24.0	33.0	35.7
18	133.0	9406	6.5	3366	433	101	44	19	0.26	0.13	0.36	342	0.47	13	1.63	27.3	21.0	32.4	30.4
19	139.5	8063	4.3	3183	623	80	35	19	0.16	0.17	0.35	315	0.36	12	1.14	22.3	20.0	25.7	22.6
20	142	7579	3.3	2707	628	65	31	17	0.14	0.16	0.29	301	0.28	10	1.13	18.5	18.5	21.1	21.5
21	150.0	7270	3.1	1654	457	48	32	16	0.12	0.11	0.41	256	0.23	12	0.84	16.2	17.0	17.2	17.1
22	157.5	7889	2.8	2349	666	53	34	19	0.17	0.14	0.38	268	0.23	12	0.97	16.7	17.0	21.1	19.5
23	169.5	6995	3.0	1642	471	43	34	17	0.15	0.12	0.44	258	0.22	12	0.87	11.9	17.0	18.7	18.5
24	198.0	9490	4.3	2384	509	78	40	24	0.15	0.13	0.40	268	0.31	15	1.20	21.9	21.0	25.0	24.1
25	207.5	8381	4.2	2676	615	70	33	18	0.23	0.13	0.33	289	0.33	12	1.10	18.4	17.0	18.0	19.2
26	223.0	5620	2.0	914	430	27	26	10	0.04	0.10	0.25	170	0.16	9	0.67	10.4	13.0	11.9	10.8
27	231	7831	3.1	2843	711	66	36	20	0.16	0.17	0.54	246	0.28	15	0.92	13.1	15.0	17.5	16.0
28	241.0	8335	4.1	2282	483	72	39	19	0.15	0.13	0.36	261	0.30	14	1.11	23.8	20.0	24.4	23.9
29	247	9186	4.5	2988	610	72	33	17	0.19	0.14	0.37	286	0.31	11	1.23	23.4	20.5	24.0	24.4
30	255.5	8797	6.1	4093	670	114	47	21	0.21	0.17	0.38	366	0.50	13	1.47	24.5	21.0	27.9	27.3
31	260.0	9712	5.4	2918	523	93	43	19	0.14	0.18	0.36	290	0.39	14	1.59	23.9	23.0	30.6	29.9
32	275.3	10269	6.2	3292	524	98	48	23	0.12	0.18	0.38	382	0.49	15	1.72	27.2	29.0	30.2	31.0
33	280.8	9916	6.2	3818	620	110	42	18	0.21	0.14	0.47	366	0.59	12	1.81	20.1	23.0	31.8	30.5
34	286	12017	6.1	3743	500	105	40	15	0.22	0.13	0.50	307	0.57	12	2.07	30.4	23.0	36.1	36.7