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1 TEMPORAL VARIABILITY OF SUSPENDED SEDIMENT SOURCES IN AN ALPINE  
2 CATCHMENT COMBINING RIVER/RAINFALL MONITORING AND SEDIMENT  
3 FINGERPRINTING

4

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20

21 Keywords: river gauging, suspended sediment fingerprinting, radar imagery, geochemistry,  
22 radionuclide, wash load

23 **ABSTRACT**

24 Influence of the rainfall regime on erosion and transfer of suspended sediment in a 905-  
25 km<sup>2</sup> mountainous catchment of the southern French Alps was investigated by combining  
26 sediment monitoring, rainfall data, and sediment fingerprinting (sediment geochemistry and  
27 radionuclide concentrations). Suspended sediment yields were monitored between October  
28 2007 and December 2009 in four subcatchments (22–713 km<sup>2</sup>). Automatic sediment sampling  
29 was triggered during floods to trace the sediment origin in the catchment  
30 Sediment exports at the river catchment outlet ( $330\pm 100$  t km<sup>-2</sup> yr<sup>-1</sup>) were mainly driven  
31 (80%) by widespread rainfall events (long duration, low intensities). In contrast, heavy, local  
32 and short duration storms, generated high peak discharges and suspended sediment  
33 concentrations in small upstream torrents. However, these upstream floods had generally not  
34 the capacity to transfer the sediment down to the catchment outlet and the bulk of this fine  
35 sediment deposited along downstream sections of the river. This study also confirmed the  
36 important contribution of black marls (up to 70%) to sediment transported in rivers, although  
37 this substrate only occupies ca. 10% of the total catchment surface. Sediment exports  
38 generated by local convective storms varied significantly at both intra- and inter-flood scales,  
39 because of spatial heterogeneity of rainfall. However, black marls/marly limestones  
40 contribution remained systematically high. In contrast, widespread flood events that generate  
41 the bulk of annual sediment supply at the outlet were characterised by a more stable lithologic  
42 composition and by a larger contribution of limestones/marls, Quaternary deposits and  
43 conglomerates, which corroborates the results of a previous sediment fingerprinting study  
44 conducted on riverbed sediment.

## 45 1. INTRODUCTION

46

47       Suspended sediment transported by rivers has fundamental environmental and economical  
48 consequences. An excess of sediment leads for instance to an increase in water turbidity,  
49 eutrophication, alteration of river habitats and reservoir siltation (e.g. Carpenter et al., 1998;  
50 Packman and Mackey, 2003; Owens et al., 2005). The suspended load comprises all the  
51 particles with a diameter lower than 2 mm (i.e. sand-sized or less). The finer particle fraction  
52 (<63  $\mu\text{m}$ ; i.e. silt and clay-sized material) transports a significant part of biogeochemical  
53 fluxes conveyed by rivers and its transfer needs to be better understood. By transporting the  
54 nutrients required by all the living organisms, fine sediment plays an essential role in the  
55 productivity of riverine, estuarine and marine ecosystems (House and Warwick, 1999; Collins  
56 et al., 2005). This fraction is also one of the main vectors of contaminants in rivers, including  
57 polychlorinated biphenyls (PCBs), dioxins, radionuclides, heavy and trace metals (Salomons  
58 and Forstner, 1984; Droppo, 2001; Walling and Collins, 2008). Very expensive management  
59 operations are generally achieved to cope with the problems associated with fine particle  
60 sedimentation. River dredging is often conducted to prevent flooding, to maintain navigation  
61 or to restore wetlands. Furthermore, the production of energy by hydroelectric power plants  
62 requires reliable predictions of Suspended Sediment Concentrations (SCC) and Yields (SSY)  
63 at the flood scale in order to avoid the major disturbances that could be induced by the  
64 massive and sudden siltation of reservoirs.

65       There is hence a preliminary need to evaluate the dynamics of suspended sediment within  
66 rivers in mountainous catchments in order to implement appropriate and effective control  
67 measures along the downstream river network. Suspended sediment supply to lowland rivers  
68 is indeed mainly dominated by local erosion processes and by the transfer of fine sediment  
69 from highly erodible mountainous catchments (Gallart et al., 2002; Regües and Gallart, 2004;

70 Esteves et al., 2005; Mathys et al., 2005; Nadal-Romero et al., 2009; Wang et al., 2009;  
71 Skalak et al., 2010; Lopez-Tarazon et al., 2010). In those areas, erosion processes are mainly  
72 driven by the temporal and spatial patterns of precipitations, their nature (i.e., hail, rainfall,  
73 snow) and the antecedent soil moisture conditions (Regües and Gallart, 2004; Nadal-Romero  
74 et al., 2008). Furthermore, erosion is characterised by strong spatial variations within  
75 catchments, associated with the heterogeneity of sediment sources, the presence of a soil  
76 cover by vegetation or snow, and the connectivity of sediment sources up to the river network  
77 (e.g. Ollesch et al., 2006). Transfer of sediment within rivers is also affected by their specific  
78 flow regime (Dedkov and Moszherin, 1992). In mountainous environments, a significant  
79 proportion of the total annual discharge can be controlled by the snowmelt occurring in winter  
80 and spring (Gallart et al., 2002; Lenzi et al., 2003; Schmidt and Morche, 2006, Mano et al.,  
81 2009). An increase in discharge can also lead to an important resuspension of sediment  
82 accumulated on the river bed during storms in spring and summer (Navratil et al., 2010). Even  
83 though it is widely accepted that different rainfall regimes generate different sediment  
84 dynamics patterns and that they involve the contribution of different sediment sources, the  
85 relative contribution of those different rainfall regimes to the sediment export from  
86 mountainous catchments should be quantified.

87 This paper aims to analyse the influence of two contrasted rainfall regimes on the  
88 mobilisation of sediment sources and the transfer of fine sediment during floods within the  
89 905-km<sup>2</sup> Bléone catchment located in the Southern French Alps. Widespread rainfall events  
90 are characterized by long duration (about a day) but low-intensity rainfall (<20 mm h<sup>-1</sup>),  
91 whereas the heavy storm regime is defined by a short duration (several hours) but a high-  
92 intensity (>20 mm h<sup>-1</sup>). The study catchment is drained by steep-slope torrents and braided  
93 rivers (Navratil et al., 2010). This complex type of river is characterised by a wide active  
94 channel and the presence of vegetated bars, where the processes of fine sediment deposition,

95 release and resuspension from the riverbed may be exacerbated. The combination of  
96 traditional monitoring techniques (i.e., the installation of river gauges, turbidimeters and  
97 sediment samplers in several subcatchments of a larger mountain catchment), rainfall  
98 monitoring (i.e., rain gauges, rainfall radar imagery) and sediment tracing (i.e., using  
99 radionuclides and elemental geochemistry) could provide valuable information about the  
100 temporal variability of substrates supplying sediment and sediment fluxes within this complex  
101 mountainous catchment. A recent sediment fingerprinting study conducted in this Alpine  
102 catchment quantified the contribution of different sediment sources supplying fine material to  
103 the river (Evrard et al., 2011). This study analysed several dozens of composite riverbed  
104 sediment samples and showed the important contribution of local sources to sediment  
105 deposited on the riverbed. In this paper, we will apply a similar fingerprinting approach on  
106 suspended sediment collected during floods, rather than on sediment deposited on the  
107 riverbed, to consider intra- and inter-event variation in sediment sources. We will therefore be  
108 able to explore temporal variations in sediment source contributions, which was not possible  
109 in the previous study. Comparison and integration of results obtained by both studies will  
110 finally be discussed to characterise overall spatial and temporal variations of sediment sources  
111 in this highly erosive Alpine catchment.

112

113

## 114 2. STUDY AREA

115

116 The Bléone catchment (905 km<sup>2</sup>), with altitudes ranging between 405 and 2927 m A.S.L.  
117 (Above Sea Level), is a mountainous alpine catchment located in the Durance River district,  
118 in southeastern France (Figure 1). The catchment is characterised by a dendritic drainage  
119 network dominated by the Bléone River and several tributaries, among which the Bès (233

120 km<sup>2</sup>-subcatchment), the Arigéol (66 km<sup>2</sup>), the Duyes (125 km<sup>2</sup>), the Bouinenc (28 km<sup>2</sup>) and  
121 the Eaux Chaudes (61 km<sup>2</sup>) Rivers are the most important. A digitised 1:50,000 spatially-  
122 distributed geological map of the catchment provided by the French Geological Survey  
123 (BRGM) allowed defining the main geological units (Figure 2). The geological bedrock is  
124 calcareous (marls, molasses, limestones), with rather large areas of exposed Cretaceous and  
125 Jurassic black marls, as well as Lias marly limestones. Severely eroded areas (11% of the  
126 Bléone catchment, Figure 2) are defined as zones without vegetation and characterised by the  
127 presence of erosion features (e.g., rills, gullies, badland morphology). They were delineated in  
128 a GIS using aerial photographs taken during flight campaigns conducted in 2004 by the  
129 French National Geographic Institute (IGN). Eroded areas cover a mean surface of 0.45 km<sup>2</sup>  
130 (between 811 m<sup>2</sup> and 1.85 km<sup>2</sup>) and were classified into three groups: debris slope areas (22%  
131 of the total eroded area), sheet and rill erosion areas (48%) and gully erosion areas (30%). The  
132 areas covered by black marls are strongly affected by erosion and they are characterised by a  
133 badland morphology, which generally develops in semiarid areas (Mathys et al., 2005; Nadal-  
134 Romero et al., 2009). Forest is by far the main land use in the catchment (44% of the total  
135 catchment surface; Table 1). Siltation of Malijai reservoir located at the outlet of the Bléone  
136 catchment leads to operational problems for hydroelectric power plants located downstream  
137 along the Durance River and to an important siltation in the Berre lagoon (Accornero et al.,  
138 2008). To limit this problem, French authorities fixed a maximal SSY that can be delivered to  
139 the lagoon, which leads to extra management costs for the company exploiting the power  
140 plants.

141 The climate is transitional and undergoes continental and Mediterranean influences. Mean  
142 annual temperature ranges between 12–13°C at 400 m A.S.L., with a high temperature range  
143 between summer and winter (about 18°C). Mean annual rainfall in the catchment varies  
144 between 600–1200 mm at 400 m A.S.L. Rainfall is characterised by important seasonal

145 variations, with a maximum in spring and autumn (Mano et al., 2009). Two main contrasted  
146 rainfall regimes dominate the weather in the Southern French Alps. Widespread rainfall  
147 events affect by definition the entire Bléone catchment. They are mainly associated with  
148 widespread depressions centred on France, or with Mediterranean fluxes and Western weaker  
149 depressions (oceanic influence). Local convective storms and rainfall generated by storm-  
150 fronts are generally associated with Eastern fluxes and local air mass instability that affects  
151 briefly (i.e., during several hours) very local areas of the catchment (i.e., a few km<sup>2</sup>). These  
152 very short duration and intense events mostly occur between June and September.  
153 Peak flow observed in spring can be accentuated by the snowmelt. In contrast, severe low  
154 base flow periods are observed in summer and winter. In winter, the low water stage of the  
155 river is mostly explained by the predominance of snowfall (Mano et al., 2009).

156

157

### 158 3. MATERIALS AND METHODS

159

#### 160 3.1. Methodological framework

161 Rainfall volume (RV) and maximum intensity (RI), river discharges (Q) and  
162 Suspended Sediment Concentrations (SSC) were measured at several locations within the  
163 Bléone catchment (Figure 1). This monitoring network provided with a high temporal  
164 frequency estimations of Suspended Sediment Yields (SSY) and their dynamics during each  
165 flood. Suspended sediment samples collected manually or by automatic samplers were  
166 analysed by gamma spectrometry (i.e., radionuclides) and by Inductively Coupled Plasma –  
167 Mass Spectrometry (ICP-MS; i.e., elemental geochemistry) in order to trace suspended  
168 sediment sources during selected widespread rainfall events and local convective storms  
169 (Table 2).



170 Selection was guided by (1) significance and representativeness of the floods according to the  
171 hydro-sedimentary regime, and (2) data availability (e.g., suspended sediment sampling  
172 during floods without any monitoring problems).

173

### 174 **3.2. Rainfall monitoring**

175 Ten rain-gauges managed by the *Laboratoire d'étude des Transferts en Hydrologie et*  
176 *Environnement* (R1–R5) and the French *Cemagref* research agency (R6–R10) provided  
177 continuous precipitation records (resolution of ca. 0.2 mm; Figure 1). Five meteorological  
178 stations managed by the French meteorological office (i.e., *Météo France*) provided rainfall  
179 depths and durations, snow depth, temperature as well as information on the occurrence of  
180 storm or hail events (R11–R15). These last stations only provided daily records (with the  
181 exception of R12 that provided hourly records).

182 Rainfall radar images provided by *Météo France* were also available for this region. We used  
183 the rainfall estimation provided by the Bollène (lat.: 04°45'08''E, long.: 44°17'01''N),  
184 Nîmes (lat.: 04°21'28''E, long.: 43°50'21''N) and Collobrières (lat.: 06°18'25''E, long.:  
185 43°14'12''N) weather radars (bipolar, doppler, s-band; Figure 1). Low resolution images  
186 (with 1 km<sup>2</sup>-resolution at hourly time-step) were used in this study. These radars are located at  
187 more than 60 km from the Bléone catchment, which induced signal mitigation. Moreover,  
188 mountain belts probably attenuated the radar waves. Those images were therefore only used  
189 to derive qualitative information on the spatial and temporal variability of rainfall, to  
190 complement the information provided by the rain gauge network.

191

### 192 **3.3. Hydrological and sediment monitoring**

#### 193 **River monitoring**

194 Four river gauging stations were installed within the catchment (Table 1, Figure 1). At  
195 two stations (Bléone River at Le Chaffaut, i.e. STA1; Bès River at Pérouré, i.e. STA4), flow  
196 discharges were provided by the *Electricité de France* (EDF) company and the regional *Flood*  
197 *Forecasting Service* (SPC-Grand Delta; Poirel, 2004; Mano et al., 2009; Navratil et al., 2010).  
198 These records are available at a variable time-step, from 1963 at STA4 and from 2000 at  
199 STA1. The two other stations (Galabre River at La Robine, i.e. STA 2; Bléone River at Prads,  
200 i.e. STA5) were equipped with a 24-GHz radar (Paratronic Crusoe<sup>®</sup>) to measure the water  
201 level with a 10-minutes time-step. Flow discharges were regularly gauged and water level-  
202 discharge rating curves were built for each site. At all the four stations, a nephelometric  
203 turbidimeter (WTW Visolid<sup>®</sup> 700-IQ or Hach Lange<sup>®</sup> at STA1) measured the water turbidity  
204 using the backscattering of infrared light.

205 An additional monitoring station was installed on the Bès River at Esclangon (STA3; Figure  
206 1; Table 1) to monitor SSC only, in order to investigate the transfer of suspended sediment  
207 over a short river section located downstream of STA4 (i.e., ca. 5.3 km; Navratil et al., 2010).  
208 At each station, a sequential sampler (ISCO 3700<sup>®</sup>) containing 24 one-liter bottles was  
209 programmed to trigger sampling as soon as critical turbidity thresholds were reached. A data  
210 logger (Campbell CR800<sup>®</sup>) recorded the water level and the turbidity during one minute every  
211 10 minutes. Collected samples were filtered in laboratory using pre-weighed standard  
212 Durieux<sup>®</sup> 0.7- $\mu\text{m}$ -diameter glass microfiber filter paper. The filters were then dried for 2 h at  
213 105 °C and weighed with a high precision balance (uncertainty  $\pm 0.1$  mg). In case of high  
214 SSC ( $>2$  g l<sup>-1</sup>), the sample was dried for 24 h at 60 °C and the residue was weighed. A reliable  
215 turbidity-SSC calibration curve was built for each station using a polynomial function and it  
216 was subsequently used to calculate the SSC time series (e.g. Navratil et al., 2010, 2011;  
217 Duvert et al., 2011). Suspended sediment flux SSF [t s<sup>-1</sup>] was then calculated using Eq. (1).

218  ~~$SSF = \int_{t_0}^{t_1} SSC \cdot Q \cdot dt$~~  (1)

219 where  $Q$  is the discharge ( $\text{m}^3 \text{s}^{-1}$ ) and  $SSC$  is the suspended sediment concentration ( $\text{g L}^{-1}$ ).  
220 Then, suspended sediment yields ( $SSY$ ; in tons,  $t$ ) were calculated for each flood as follows  
221 (Eq. 2):

$$222 \quad SSY = \int_{t_0}^{t_f} SSC \cdot Q \cdot dt \quad (2)$$

223 with  $t_0$  and  $t_f$  corresponding to the beginning and the end of the period considered.  
224 Uncertainties on  $SSC$  monitoring with turbidimeters mainly depend on the turbidity  
225 calibration curve, the representativity of the automatic sediment collection by ISCO samplers  
226 – i.e., position of the intake in the water flow,  $SSC$  homogeneity in the channel cross-section  
227 – and the laboratory errors (Lewis and Eads, 2008; Némery et al. 2010).  $SSY$  thus cumulate  
228 uncertainties on both  $SSC$  and discharges. Navratil et al. (2011) showed that global  
229 uncertainties reached on average 20% for  $SSC$  (range, 1 – 30 %) and 30 % (range, 20 – 50 %)  
230 for  $SSY$  at STA2 when considering uncertainties of ca. 20% on discharges. In this study, all  
231 monitoring stations were installed using the same methodology and in the same physiographic  
232 context. We therefore consider that  $SSC$  and  $SSY$  uncertainties remained in the same order of  
233 magnitude at the other stations.

234

### 235 **Data analysis**

236 Rainfall events were first characterized by their total volume (mm) and intensity (10 minutes  
237 time-step;  $\text{mm h}^{-1}$ ). Rainfall spatial extent and propagation of the rainfall fronts were  
238 estimated with radar imagery and information delivered by the rain gauge network. Flood  
239 timing was defined by analysing flood hydrographs and sedigraphs. In this study, a flood was  
240 identified as soon as rainfall occurred in the catchment and triggered sediment transport in the  
241 river.

242 Several flood indicators were estimated: peak discharge (referred to as  $Q_{mx}$ ); mean annual  
243 runoff depth ( $Q_m$ ); baseflow discharge ( $Q_b$ ); mean and maximum suspended sediment  
244 concentrations (respectively  $SSC_m$  and  $SSC_{mx}$ ); suspended sediment yield ( $SSY$ );  
245 percentage of total mass of suspended solids and water volume transported during 2% of the  
246 monitoring period ( $M_{s2\%}$ ,  $V_{2\%}$  respectively; Meybeck et al., 2003); and the fraction of inter-  
247 annual sediment yield produced by widespread rainfall events ( $SSY_w$ ).

248 Floods were also classified according to their Q–SSC hysteretic pattern (i.e., clockwise,  
249 anticlockwise or concomitant hysteretic loops), using the categories initially defined by  
250 Williams (1989). These patterns provide indeed relevant information to outline the spatial  
251 location of sediment sources in the catchment (Williams, 1989; Lenzi and Marchi, 2000;  
252 Seeger et al., 2004; Smith and Dragocich, 2008; Duvert et al., 2010). Basically, Q–SSC  
253 clockwise patterns are generally attributed to close sediment sources or to the resuspension of  
254 fine sediment stored on the river bed or banks. In contrast, Q–SSC anticlockwise patterns  
255 would mainly reflect a contribution of sediment sources located at a substantial distance from  
256 the outlet. When Q–SSC curves for both hydrograph rising and falling limbs are symmetrical  
257 (i.e., concomitant peak), it would reflect that fine sediment availability is never exhausted  
258 during the flood; the suspended sediment flux would then only be constrained by the sediment  
259 transport capacity of the river. Even though hysteresis analyses provide valuable information  
260 to outline the sources of sediment and the timing of its transfer, it is not sufficient to conclude  
261 about the sediment origin. We therefore provided additional information derived from  
262 sediment fingerprinting, topographical surveys and river monitoring at intermediate stations  
263 of the river network to strengthen our findings regarding sediment sources and transfer.

264 When flood peak propagation could be clearly identified at two successive river monitoring  
265 stations, we also estimated the transfer time of SSC peak between both stations. The distance

266 between the stations was therefore measured using GIS functions to calculate the mean  
267 velocity of suspended sediment propagation between successive monitoring stations.

268

### 269 **3.4. Analysis of diachronic aerial pictures and topographic survey**

270 Aerial pictures taken at two different dates in 2004 and 2010 by the French National  
271 Geographical Institute (IGN) were used to analyse the variations of the lateral margins of the  
272 braided channels, and the changing width of the main braided channel. Topographical surveys  
273 were also conducted with a total station at three different dates and on three cross-sections  
274 (ca. 70 points for each cross-section, located at the main morphological changes). These  
275 cross-sections are located along the Bès River (lat.: 44° 11' 14.64"N, long.: 6° 16' 5.72"E)  
276 between the Pérouré (STA4) and Esclangon stations (STA3; Figure 1). These data allowed us  
277 determining whether significant bed load transport and fine sediment remobilisation occurred  
278 during the study period.

279

### 280 **3.5. Sediment fingerprinting**

#### 281 **Gamma spectrometry analysis**

282 For all the investigated floods, a selection of suspended sediment collected by ISCO samplers  
283 was dried and sieved (to 63 µm) before analysis. Selection was conducted in order to analyse  
284 sediment transported by floods generated by the representative rainfall regimes occurring in  
285 the catchment.

286 Radionuclides were measured in all the collected samples. Sediment was placed in a counting  
287 box containing sufficient material (i.e., 10 g). Radionuclide concentrations (Be-7, Cs-137,  
288 excess-Pb-210, K-40, Ra-226, Ra-228, Th-234, Th-228) were determined by gamma-  
289 spectrometry using the very low-background coaxial N- and P-types GeHP detectors  
290 (Canberra / Ortec / Eurisys) available at the *Laboratoire des Sciences du Climat et de*

291 *l'Environnement* (Gif-sur-Yvette, France). Efficiencies and background levels of the detectors  
292 were periodically controlled with internal and IAEA soil and sediment standards (Evrard et  
293 al., 2011). When there was a very low quantity of material available (i.e., < 10 g), filters were  
294 placed in tubes and counting was conducted at the *Laboratoire Souterrain de Modane* in the  
295 French Alps, using a very low background, high-efficiency well-type Ge detector (Reyss et  
296 al., 1995).

297

### 298 **Elemental geochemistry analysis**

299 For the measurement of elemental geochemistry, dried subsamples (ca. 80 mg) were analysed  
300 by Inductively Coupled Plasma – Mass Spectrometry (ICP-MS; XII CCT Series, Thermo  
301 Electron), in solutions containing 0.2 g of solid L<sup>-1</sup>. The sediment digestion procedure is  
302 described by Le Cloarec et al. (2010). Concentrations were determined for several major (Al,  
303 Ca, Mg, Ti) and trace (Ag, Ba, Cd, Cu, Mn, Ni, Pb, Se, Tl, V) elements. Analytical  
304 uncertainties associated with this method did not exceed 20% for major elements and 10% for  
305 trace elements.

306

### 307 **Selection of fingerprints and design of a mixing model**

308 Based on the geological map of the catchment, we grouped the geological classes  
309 corresponding to our sediment source samples into six main sediment source types: (1) marly  
310 limestones; (2) limy marls; (3) conglomerates and sandstones; (4) Quaternary deposits; (5)  
311 black marls and (6) gypsum (see Evrard et al., 2011, for more details on sediment source  
312 sampling). Given suspended sediment has a finer grain size than riverbed sediment, in this  
313 study we sieved the source material to < 63 µm before characterising their content in  
314 radionuclides and geochemical elements (Table 3). We first checked that the properties of the  
315 suspended sediment samples remained in the range of the source values. This condition was

316 not met for Al, Cd and Ti. They were therefore removed from further analysis. The ability of  
317 the 19 other potential fingerprinting properties to discriminate between the potential sediment  
318 sources was then investigated by conducting a Kruskal-Wallis *H*-test as initially proposed by  
319 Collins and Walling (2002). Results outlined 10 potential variables to discriminate the  
320 sediment sources (difference significant at  $p = 0.05$ ): Ra-226, Th-234, Ba, Cu, Mn, Ni, Pb, Sb,  
321 Tl, V. Based on this set of discriminating properties, an optimum ‘composite fingerprint’ was  
322 identified by performing a stepwise selection procedure. This procedure consisted in  
323 minimising Wilk’s lambda, as suggested by Collins and Walling (2002). Thus, among those  
324 10 potential variables, 6 properties were sufficient to design the optimum composite  
325 fingerprint. Only one geogenic radionuclide was pointed out (Ra-226). The other selected  
326 fingerprints were V, Ni, Mn, Sb and Cu. Then, we constructed a Monte Carlo mixing model  
327 as already detailed by Evrard et al. (2011) in order to quantify the range of contribution of  
328 each sediment source to the suspended sediment samples collected at the different river  
329 monitoring stations. The gypsum geological class was removed from the analysis because of  
330 its rapid dissolution in the river during floods.

331 In total, 10,000 random source concentrations were generated by the Monte Carlo mixing  
332 model for each suspended sediment sample. The outputs of the mixing model appeared to be  
333 very stable, all outputs being very close (and systematically within a range of  $\pm 3\%$ ) to their  
334 mean value. We therefore decided to only present the mean suspended sediment composition  
335 in black marls, limestone/marls, Quaternary deposits and conglomerates.

336

337

## 338 **4. RESULTS**

339

### 340 **4.1. Inter-annual rainfall, runoff and sediment analysis**

341           Among the 196 rainfall events that occurred in the Bléone catchment between October  
342 2007 and December 2009, about one-third of them generated suspended sediment that was  
343 recorded by our river monitoring stations. The monitored hydrological years Oct. 2007– Sept.  
344 2008 and Oct. 2008 – Sept. 2009 were rather wet (870 mm and 930 mm, respectively) when  
345 compared to the mean annual rainfall depth recorded from 1934 to 2009 (i.e., 820 mm yr<sup>-1</sup>;  
346 data from raingauge R15; Figure 1). Rainfall increased with altitude (i.e., orographic effect)  
347 and was strongly heterogeneous within the catchment, depending on the dominant weather  
348 regime. Mean annual runoff depth remained relatively constant during the two monitored  
349 years because of the relatively equivalent rainfall inputs.

350

351           On average, widespread rainfall events are longer (20 hours at R2) than storm events (6 hours  
352 at R2). Both rainfall regimes are rather well discriminated (Figure 4): storms are generally  
353 associated with higher intensities (>20 mm h<sup>-1</sup>). Widespread events are associated with a high  
354 rainfall volume (up to 120 mm), but with low-moderate intensities (<20 mm h<sup>-1</sup>). Storms can  
355 be particularly heavy and they can affect very local areas, with much higher rainfall  
356 intensities (maximum of 162 mm h<sup>-1</sup> with 10-minutes time-step rainfall data at R1). These  
357 events are sometimes accompanied with hail.

358

359           All the results outline a strong seasonality and inter-annual variability of SSY in the Bléone  
360 catchment (Figure 3a and 6). Our monitoring at the different stations showed that 75 – 99.9%  
361 of the total sediment yield were produced during ca. 2% of time and transported at each  
362 station by less than 18% of the total water volume (Ms2% and V2%; Table 4). Furthermore,  
363 30–70% of total SSY (respectively at STA2 and STA4) were transported during the last three  
364 months of the study (Oct. 2009 – Dec. 2009; Figure 3a). These results show the strongly  
365 episodic behaviour of suspended sediment transport in the Bléone catchment.



366 SSY measured on the Bléone River at STA1 (close to the catchment outlet) between Oct.  
367 2007 and Dec. 2009 reached  $641,900 \pm 192,600$  tons (Table 4). This value corresponds to an  
368 inter-annual specific sediment yield (SSY\*) of  $330 \pm 100 \text{ t km}^{-2} \text{ yr}^{-1}$ . However, SSY\* were  
369 found to fluctuate within the Bléone catchment; they varied indeed between  $452 \pm 136 \text{ t km}^{-2}$   
370  $\text{yr}^{-1}$  on the Bléone at Prads (STA5) and  $690 \pm 200 \text{ t km}^{-2} \text{ yr}^{-1}$  on the Bès River (STA4). Higher  
371 SSY\* (more than  $5,000 \text{ t km}^{-2} \text{ yr}^{-1}$ ) were observed at Draix in smaller subcatchments (Mathys  
372 et al., 2003). Those rates remained in the same order of magnitude as the ones observed in  
373 other similar mountainous catchments (e.g. López-Tarazón et al., 2009). The difference in  
374 sediment yields observed between Oct. 2007 – Sept. 2008 and Oct. 2008 – Sept. 2009 (100–  
375 700% variation; Figure 3a) can partly be explained by the presence of a deep and persistent  
376 snow cover during the 2009 winter and spring seasons, which probably protected the soil  
377 against erosion.

378

379 Sediment yields recorded in all the monitored subcatchments were mainly generated by  
380 widespread rainfall events (SSYw ranges, 72–89 %). The upper Bléone (STA5) subcatchment  
381 was more affected by storms than the other stations probably because of its higher altitude.

382

383 Interannual analysis masks strong annual variations: in Oct. 2007 – Sept. 2008, the bulk of the  
384 sediment yield was mainly attributed to S–W Mediterranean depressions that generated  
385 widespread rainfall, whereas between Oct. 2008 and Sept. 2009, convective storms (local  
386 storm or storm-front) dominated and produced 70% of sediment. For instance, between Oct.  
387 2007 and Sept. 2008, convective storms produced 70% of the annual SSY at STA4. In  
388 contrast, during the Oct. 2008 – Sept. 2009 period, widespread Mediterranean events  
389 produced 67% of the sediment transport recorded at the same station. The rest (i.e., 23%) was  
390 generated by storms that mainly occurred in the upstream parts of the catchment monitored at

391 Pérouré (STA4) and Prads stations (STA5). Seven hail storms were reported at the Seyne  
392 station (1300 m A.S.L.) between Oct. 2008 – Sept. 2009, but only four between Oct. 2007 –  
393 Sept. 2008, which indicates the more frequent occurrence of heavy storms in spring and  
394 summer 2009.

395

396 Convective storms generate lower peak discharges ( $Q_{mx}$ ) than widespread events at STA1  
397 and STA4 (Wilcoxon rank sum test;  $p$ -value $<0.05$ ). At STA2 and STA5 stations (i.e.  
398 headwater catchment), mean  $Q_{mx}$  was higher during widespread events than during storms,  
399 even though this difference is not significant ( $p$ -value $>0.4$ ). This difference could be  
400 explained by the local pattern of rainstorms. Differences between distributions of maximum  
401 suspended sediment concentrations ( $SSC_{mx}$ ) during widespread events and local storms were  
402 not significant for all the monitoring stations (Wilcoxon rank sum test;  $p$ -value $>0.9$ ). The  
403 difference between both rainfall regimes was only significant for the flow discharge indicator  
404 at a larger catchment scale (713 km<sup>2</sup> at STA1 and 165 km<sup>2</sup> at STA4). We can hypothesize  
405 that, at larger spatial scales, important sedimentation can occur in braided rivers during  
406 storms, given that the flow is not able to transfer as much sediment as during widespread  
407 floods. Field observations showed that storms generate significant sedimentation along the  
408 river network, and particularly in braided channel reaches (Navratil et al., 2010). Those  
409 deposits probably provide the bulk of the total SSY during widespread rainfall events that  
410 generate higher flow discharges in the rivers.

411

412 Q–SSC hysteretic patterns tend to confirm the importance of those sedimentation/erosion  
413 processes along the river network (Figure 3b). On the Upper Bléone River at STA5 station,  
414 anticlockwise hysteretic loops were the main patterns controlling the sediment export. This  
415 would mean that the bulk of suspended sediment was rapidly transported from highly erodible

416 areas to the outlet (during a single flood), and that only limited sediment amounts were stored  
417 in the river channel. In contrast, at STA2 station, sediment storage on the riverbed and  
418 remobilisation would be more important, given that 40% of sediment was delivered by  
419 clockwise events at this location. However, this pattern could also be attributed to the delivery  
420 of sediment sources located in the vicinity of the gauging station. At STA1 and STA4  
421 stations, floods with clockwise hysteresis patterns were the most frequent (Figure 3c) and they  
422 transported the bulk of the annual sediment load (>80% of annual SSY). Sediment dynamics  
423 were then probably mainly controlled by the remobilisation of fine sediment from the large  
424 and well-developed braided river channels that can be observed in this river section.

425

426 Overall, the relative contribution of direct sediment supply to the river and sediment  
427 remobilisation from the channel to the total sediment exports from the catchment would  
428 mainly be explained by the type of rainfall regime that strongly influences the hydraulic  
429 conditions and thus the suspended sediment dynamics. The variability of erosion and  
430 sediment transfer processes probably explains part of the observed variability affecting the  
431 SSY–Q<sub>mx</sub> relationship at the different stations (Figure 5). In the next sections, we propose to  
432 focus our detailed analyses on a selection of widespread rainfall events recorded in the entire  
433 catchment (section 4.2) and on a selection of storms (section 4.3; Table 2; see the timing of  
434 the studied flood on Figure 6).

435

#### 436 **4.2. Detailed analysis of widespread rainfall events**

437 We chose two representative events (Figures 4, 7) to illustrate the variety of sediment  
438 erosion/transport processes observed in this mountainous catchment (Figures 6; Table 4): (1)  
439 a major flood that occurred on 22 December 2009 on the Bès River and monitored at STA4

440 (referred to as case W1); (2) a comparison of three floods that occurred between 31 October  
441 2008 and 12 November 2009 on the Galabre River and recorded at STA2 (case W2a/b/c).

442

#### 443 **Case W1: Analysis of the 22 December 2009 flood on the Bès River at Pérouré (STA4)**

444 This 10-yr return period flood was recorded at STA4 ( $Q_{mx} = 140 \text{ m}^3 \text{ s}^{-1}$ ; Table 4; Figure 7). It  
445 was the second largest flood observed in the Bléone catchment during the 27-months  
446 monitoring period (Figures 5, 6). The return period of this flood is probably lower  
447 downstream than in upstream subcatchments (i.e., Bès) because of a strongly heterogeneous  
448 rainfall pattern. The flood occurred after a succession of 6 low-intensity floods in autumn. It  
449 was followed two days later by a 15-yr return period flood ( $Q_{mx} = 180 \text{ m}^3 \text{ s}^{-1}$ ). These floods  
450 were generated by a rapid air temperature warming associated with a wet Mediterranean  
451 South-Western depression, when the catchment was covered by a substantial snow layer.  
452 Minimum daily temperature increased indeed from  $-12^\circ\text{C}$  to  $+5^\circ\text{C}$  within four days (data  
453 from the R15 station). Rainfall volume was very important (108 mm during one day; Figure  
454 7c), but rainfall intensity remained low ( $20 \text{ mm hr}^{-1}$ ). Rainfall was distributed homogeneously  
455 over the Bès subcatchment, upstream of STA4 (Figure 7a). Sediment export at the outlet  
456 reached  $57,500 \pm 17,500$  tons, i.e., 50% of the mean annual SSY. Its contribution to the total  
457 SSY produced during the 27-months monitoring period was significant at all the stations  
458 (Figure 6). Transfer time of the SSC peaks between the Bès River at Pérouré (STA4) and the  
459 Bléone River at Le Chaffaut (STA1) stations reached about 4 hours, with a mean flow  
460 velocity of about  $1.8 \text{ m s}^{-1}$ . Mean flow velocity estimated from STA4 to STA5 was higher ( $3$   
461  $\text{m s}^{-1}$ ), showing a significant slow-down of the sediment propagation that could be associated  
462 with the river bed slope decrease (from 1.4% at STA5 to 0.8% at STA1).

463 Q–SSC relationship during this flood is characterised by a well-marked clockwise hysteretic  
464 pattern (Figure 7e) that reflects a rapid contribution of sediment sources to the outlet. After

465 the flood rising phase, SSC remained stable (at ca.  $25 \text{ g l}^{-1}$ ) and did not vary with discharge  
466 anymore, which probably indicates a significant remobilisation of riverbed sediment.

467 Six suspended sediment samples were analysed to outline the potential variations of sediment  
468 origin during the flood (Table 5; Figure 7d). We observed a major contribution of black marls  
469 (45%) during the rising phase of the hydrograph that can be attributed to a contribution of  
470 black marl sources located close to the outlet and that were first eroded during the rainfall  
471 front propagation from the southwest to the northeast. During the flood peak that coincided  
472 with the maximum sediment transport, sediment was provided by the different lithological  
473 sources available along the river network, i.e. black marls (mean, 33%), limestones/marls  
474 (mean, 25%), Quaternary deposits (mean, 24%) and conglomerates (mean, 18%); Figure 7d).

475 Overall, contribution of the different sources corresponded to their occurrence in the draining  
476 catchment (Figure 2).

477 Sediment composition was stable during the flood (Figure 7d). When considering the  
478 contribution of those lithological variations to the sediment yield, we observe that the mean  
479 sediment composition at the flood scale is very similar to the sediment composition of the  
480 flood peak sample ( $< 4\%$  of difference). Sediment composition of the flood peak could  
481 therefore be usefully used as an indicator of sediment composition during widespread events.

482 Q–SSC clockwise hysteresis (Figure 7e) corroborates the results obtained from aerial picture  
483 analysis and topographical surveys conducted before and after this flood on the Bès River  
484 between STA4 and STA5 (Figure 8a) along three cross-sections (T1–T3). River bed erosion  
485 was found to reach a mean of 34 cm at T3 and 4 cm at T1 location, and erosion depth reached  
486 up to 1.5 m at other locations. Furthermore, a diachronic comparison of aerial pictures (Figure  
487 8c) shows that the main channel has significantly divagated within the entire braided channel,  
488 which completely modified all braided river morphological features (i.e., gravel bars, braided  
489 channels, vegetated bars and river banks; Figure 8a). Bank erosion was found to fluctuate

490 between about 5 m at T1 (Figure 8b) and up to 50 m at several locations in the reach (Figure  
491 8c). These values corroborate the ones obtained by previous topographical measurements and  
492 the outputs of a LiDAR analysis conducted on a 7-km long reach of the Bès River (Tacon et  
493 al., 2011). Navratil et al. (2010) estimated that fine sediment concentration deposited in a  
494 braided river reach (between STA4 and STA5) represented a mean of  $7 \text{ kg m}^{-2}$  per 10 cm  
495 depth. If we hypothesise that the braided channels located upstream of station SAT5 (about  
496  $730,000 \text{ m}^2$  on the Bès and its tributaries) was disturbed over a mean of ca. 0.6–1.5 m depth,  
497 we can estimate that 80–100% of SSY (i.e.  $57,500 \pm 17,500$  tons) were remobilised from the  
498 riverbed and the river banks.

499

500 **Case W2: Inter-flood analysis on the Galabre River at La Robine (STA2) between 31**  
501 **October 2008 and 12 November 2008**

502 Those three autumnal floods were generated by a central and southwestern depression that  
503 generated a moderate rainfall volume with a low intensity (about  $15 \text{ mm hr}^{-1}$ ; Table 4; Figure  
504 9). Snowfall occurred above 1500 m ASL (data from R15 meteorological station).  
505 Precipitation was distributed homogeneously across the Galabre subcatchment (Figure 9a, c).  
506 Those events occurred after a succession of storms in summer and early in autumn that  
507 generated very high SSC (up to  $130 \text{ g l}^{-1}$ ), but low-moderate peak discharges ( $<2.2 \text{ m}^3\text{s}^{-1}$ ).  
508 River capacity was then probably insufficient to transport all the suspended sediment down to  
509 the outlet. A significant proportion of this sediment probably deposited along the trunk river  
510 and the tributaries. Those deposits hence constituted an important source of fine sediment that  
511 was made easily available during the 2008 autumn floods. SSY exported by those 3 events  
512 correspond to ca. 6 % of the mean annual sediment yield in this subcatchment (Figure 9a).  
513 Sediment was mainly provided by limestones/marls (20-31%) and black marls (50-61%).  
514 Overall, those contributions remained stable throughout the period, even though the

515 dominance of black marls was particularly observed during the 12 November flood which  
516 was characterised by a sharp rising limb (Figure 9). As shown in case study W1, we  
517 hypothesise that the composition of those flood peaks is representative of the mean sediment  
518 composition during the flood in terms of SSY.

519 We observed a concomitant Q–SSC pattern during the first flood, a clockwise pattern during  
520 the second flood and two concomitant patterns during the third flood (Figure 9d). It probably  
521 reflects a significant remobilisation of fine sediment stored on the riverbed during summer.  
522 During the second flood, we observed a stabilisation of SSC at ca. 30 g L<sup>-1</sup> during the flood  
523 rising limb. As for case W1, this phenomenon can be attributed to a high and rapid  
524 remobilisation of fine sediment from the riverbed. Sediment availability was probably never  
525 exhausted during these periods. Each of these three floods was characterised by several (2–4)  
526 SSC peaks (Figure 9a). Magnitude of these intra-event peaks systematically decreased,  
527 whereas peak discharges remained stable or even increased. These observations outline a  
528 rapid supply or “first-flush” of fine sediment that was probably stored in the river network  
529 and easily available (Lawler et al., 2006), followed by the sediment supply by remote sources,  
530 and finally by the occurrence of sedimentation in the main channel during the falling limb of  
531 the flood.

532

#### 533 **4.4 Analysis of local storms**

534 Storms generally affected local areas and mainly occurred in upstream parts of this  
535 mountainous catchment. For instance, 28 local convective storms were recorded in 2009 by  
536 the Seyne rain gauge (R15; 1550 m ASL) vs. only 3 events by the Digne rain gauge (R12; 550  
537 m ASL). These events mainly affected small but highly erodible upstream areas. They even  
538 generated debris flows in some torrents.

539 We analysed three floods characterised by different spatial patterns (Table 2; Figure 6): (1) a  
540 storm that occurred in the Galabre subcatchment (case S1); (2) the propagation of a flood  
541 wave from the summits of the Upper Bléone subcatchment at STA5 down to the Bléone  
542 catchment outlet (case S2); (3) and the contribution of a small tributary, the Aigue-Belle  
543 torrent (draining about 4 km<sup>2</sup>) to the total sediment yield generated by a storm on the Bès  
544 River between 2 successive monitoring stations (i.e., STA3 and STA4) separated by ca. 5 km  
545 (case S3).

546

#### 547 **Case S1: 12 August 2008 storm on the Galabre River at La Robine (STA2)**

548 A convective summer storm occurred in the Galabre subcatchment on 12 August 2008  
549 (Figure 10a; Table 4). It corresponds to the most important storm recorded during the 27-  
550 months monitoring period at this station, with a total rainfall depth of 24 mm and an intensity  
551 of 90 mm hr<sup>-1</sup> (partly accompanied with hail). Significant sediment loads were recorded (638  
552 ± 190 tons) at STA2, representing ca. 4% of the mean annual SSY at this location. Similar  
553 storms occurred at many other locations of the Bléone catchment and generated significant  
554 but variable SSY characterised by different temporal patterns. Total SSY recorded in the  
555 Bléone upstream subcatchments reached 3,200 ± 1000 tons whereas the total export at STA1,  
556 close to the outlet, was estimated at 1,300 ± 400 tons (Figure 6). This difference outlines a  
557 significant storage of fine sediment within the braided river network (i.e., at least 1,900 ± 600  
558 tons during this storm).

559 Black marls supplied a large but progressively decreasing part of sediment during the flood  
560 rising stage (from 48% to 34%; Figure 10d). Then, sediment contribution from Quaternary  
561 deposits clearly dominated (52% to 78%; Figure 10d). Q–SSC relationships were  
562 characterised by the succession of a clear anti-clockwise pattern (Figure 10c; A2–A5). The  
563 first SSC peak can mainly be attributed to the direct supply of sediment generated by close



564 black marl sources (Figure 2). In contrast, the second peak was supplied by remote  
565 Quaternary deposit sources in the catchment.

566

567 **Case S2: The 30 June 2009 flood that propagated along the entire Bléone catchment**

568 The 30 June 2009 storm corresponds to a heavy eastern storm-front associated with hail falls  
569 (Figure 11a). It was mainly observed at STA5 (Figure 11a, b, c), but it also affected the Bès  
570 and Galabre River subcatchments even though it was less important in those latter areas. This  
571 storm produced  $1,000 \pm 300$  tons of sediment recorded at STA5 (i.e. more than 3% of the  
572 mean annual SSY);  $1,500 \pm 450$  tons at Pérouré (i.e., 1%); 44 tons at La Robine (i.e., 0.5%)  
573 and  $600 \pm 180$  tons at STA1. At least  $1,900 \pm 600$  tons of sediment were therefore stored in  
574 the river channel during this flood. SSC peak propagated from STA5 to STA1 (Figure 1) in  
575 about 6.5 hours with a mean velocity of about  $1.7 \text{ m s}^{-1}$ .

576 This flood mainly mobilized the upstream sediment from Prads down to the outlet (see for  
577 instance the source contribution similarity of C3 sample – collected at upstream Prads station  
578 – and C5 sample – collected at the catchment outlet; Figure 11d) during the flood peak.  
579 Sediment composition (i.e., dominance of black marls and marly limestones) determined at  
580 Robine (STA2) and Pérouré (STA4) stations was different, but their contribution to the total  
581 sediment export was minor (Figure 11d). The source contribution at the outlet (STA1; C6)  
582 during flood recession is found to be very consistent with these subcatchment contributions  
583 (C2, C4) and confirms their late contribution to the suspended sediment yield. Anticlockwise  
584 or concomitant patterns at each station confirm that the bulk of sediment was provided by  
585 hillslope erosion and by a direct propagation of sediment down to the catchment outlet.

586

587 **Case S3: The 7 August 2009 flood on the Bès River at Pérouré (STA4) and Esclançon**  
588 **stations (STA3)**

589 A convective summer storm occurred in the Bès and Upper Bléone subcatchments on 7  
590 August 2009 (Figure 12a). It generated a total rainfall depth of 55 mm with an intensity of 57  
591 mm hr<sup>-1</sup> (without hail). This event was even more local than the two events detailed  
592 previously, and it did not affect the other subcatchments (Figure 5). About 3,900 ± 1,200 tons  
593 were exported by the Bès River at STA4 (ca. 3.5% of mean annual SSY) and 170 ± 50 tons  
594 (i.e., 0.5%) were exported by the Bléone River at STA5. 1,700 ± 500 tons of sediment  
595 reached the outlet at SAT1 (i.e. less than 1% of annual SSY). We can therefore estimate that  
596 at least 2,400 ± 700 tons of sediment deposited on the riverbed. Suspended sediment  
597 propagated from Pérouré (STA4) to Esclangon (STA3) with a mean velocity of about 0.7 m s<sup>-1</sup>  
598<sup>1</sup>; which is very low compared to the mean propagation of 3 m s<sup>-1</sup> observed during the 22  
599 December 2009 flood (case W1).

600 We also analysed suspended sediment collected during this event at two stations (STA4 and  
601 STA3). Three samples corresponding to different positions in the hydrograph (i.e. rising limb,  
602 peak, falling limb) were analysed at each station. It is generally assumed that the bulk of  
603 sediment transported during an anticlockwise flood originates from distant sources. This is  
604 confirmed by the results obtained for the anticlockwise flood sampled at both STA3 and  
605 STA4 (Figure 12). Black marls provided indeed 60–70% of sediment during peak flow.  
606 According to the geological map of the Bléone catchment (D2 and 3 samples; Figure 2), there  
607 is an important presence of black marls in the upstream part of the Bès subcatchment. The  
608 composition of the sediment at the downstream station is very similar (D5, D6), indicating the  
609 transfer of this sediment and the conservation of the sediment composition. In contrast, at the  
610 beginning of the flood, the important contribution of conglomerates and Quaternary deposits  
611 supplied by a small but very active torrent significantly modified sediment composition  
612 between STA4 and STA3 (i.e., Aigue-Belle torrent; Figure 12d).

613

614

## 615 **5. GENERAL DISCUSSION**

616

### 617 **5.1. Influence of rainfall regime on temporal variability of sediment origin**

618 Overall, widespread flood events transported the bulk of SSY (72–89%) in the Bléone  
619 catchment during the 2007-2009 period. Convective storms generated lower discharges than  
620 widespread events in the downstream monitored rivers. They were generally associated with  
621 high suspended sediment concentrations and were associated with a high sedimentation in the  
622 river channel. At the downstream stations, floods with clockwise Q–SSC hysteresis  
623 transported the bulk of sediment, indicating an efficient re-suspension of the fine sediment  
624 stored on the riverbed.

625 Black marl/limestone contribution was found to be very large during both storms and  
626 widespread rainfall events. Given that those later events produce a much higher proportion of  
627 the total sediment fluxes exported from the entire catchment, black marls contribute to  
628 30–61% of the global sediment export. Quaternary deposits (molasses) and limestone/marl  
629 contributions were also significant. These sources covered the bulk of the catchment surface  
630 (89%) and supplied also a significant fraction of sediment.

631

### 632 **5.2. Relative contribution of channel sediment and wash load**

633 Wash load is generally defined as the fraction of sediment transported in suspension  
634 from sources up to the outlet having no or little interaction with the river bed or banks. Our  
635 results put into question the relevance of this concept in mountain catchments. Topographic  
636 surveys and Q-SSC hysteresis analysis provided consistent results and showed that there was  
637 a significant contribution of fine sediment remobilised from the river channel to the global  
638 sediment export during widespread events. Fine sediment recharge in the river network would

639 mainly occurs (1) during storms characterised by low discharges but very high SSC or (2)  
640 during the falling limb of the flood hydrograph, with sand-sized particle sedimentation in  
641 braided channels and silt/clay-sized infiltration in the gravel bed layer. Further studies should  
642 focus on inter-flood weather patterns – freezing–heating cycles, hail occurrence, soil moisture  
643 – and their effect on sediment erosion (e.g. Yamakoshi et al., 2009), as well as on the  
644 sediment size and on sediment degradation processes that occur during sediment transfer  
645 between hillslopes and the catchment outlet.

646

### 647 **5.3. Composition of suspended sediment vs. riverbed sediment (as determined by Evrard** 648 **et al., 2011)**

649

650 Figure 13 provides a general comparison of substrate composition in the area draining to  
651 each river monitoring station of the Bléone catchment, and to the corresponding composition  
652 derived from sediment fingerprinting conducted on both riverbed material (Evrard et al.,  
653 2011) and suspended material (this study) collected at each station. Overall, our results  
654 showed a systematic over-representation of black marls (i.e., more erodible sources) and an  
655 under-representation of limestones (i.e., less erodible material) in sediment. An over/under-  
656 representation refers here to the contribution that might be expected based on the relative  
657 proportion of the catchment occupied by a particular rock type. In contrast, sediment supply  
658 by Quaternary deposits and conglomerates better corresponds to the surface that they occupy  
659 in the different draining catchments. At Pérouré station on the Bès River (STA 4; Figure 13a),  
660 the bulk of riverbed sediment is supplied by conglomerates and Quaternary deposits (Evrard  
661 et al, 2011). This result is logical in the sense that limestones are less erodible. In suspended  
662 sediment, we observed in contrast a mix of the different sources, with an over-representation  
663 of limestones and black marls. Those source materials are probably exported by the finest

664 sediment fraction. In the Galabre subcatchment (at Robine station; STA2; Figure 13b), the  
665 bulk of riverbed sediment is supplied by black marls (77%; Evrard et al, 2011), the remaining  
666 part being supplied by limestones. In suspended sediment, this trend is confirmed, with an  
667 important additional contribution of Quaternary deposits. These results are consistent with a  
668 recent study conducted on the same flood with the DRIFTS approach (Poulenard et al., in  
669 review). Both methods show a large contribution of black marls during the first rising limb  
670 (providing 47% of sediment according to this study vs. 67% after Poulenard et al., in review)  
671 and an important contribution of limestones (30% vs. 18%) and Quaternary deposits (15% vs.  
672 15%). During the second part of the flood characterised by a sediment supply by remote  
673 sources, the contribution of black marls (24% vs. 59%) and limestones (12% vs. 5%)  
674 decreased, whereas the contribution of Quaternary deposits increased (60% vs 35%). We need  
675 to outline that we have considered the same flood, but not the same sediment samples (event  
676 S1; 12/08/2009), which can partly explain the contribution differences existing between both  
677 approaches.

678 At Prads, in the Upper Bléone River (Figure 13c), we outlined the dominant contribution of  
679 Quaternary deposits and conglomerates in riverbed sediment (Evrard et al., 2011) vs. the  
680 dominance of limestones and Quaternary deposits in suspended sediment. This contribution  
681 difference would reflect the fact that riverbed sediment is composed of coarser material (with  
682 a larger proportion of sand-sized material derived from conglomerates and sandstones) than  
683 suspended sediment (with a larger proportion of finer material derived from marls).

684 At the Bléone outlet (Malijai station; Figure 13d) the contribution of the four lithologies  
685 observed in the entire catchment to riverbed sediment and to suspended sediment is much  
686 more comparable to the surface of the different lithologies observed in the catchment than at  
687 the upstream stations. Those results show the particularly large sediment supply by black  
688 marls. They also confirm that conglomerates are mostly exported in the form of riverbed

689 sediment, whereas the bulk of black marls/marly limestones are exported in the form of  
690 suspended sediment.

691

### 692 **5.3. Implications for river management**

693         Suspended sediment fingerprinting outlined the very important contribution of black  
694 marls during both widespread and storm events, although they only cover ca. 10% of the total  
695 catchment surface. Contribution of limestones/marls to the catchment sediment export during  
696 widespread events is also important (case W1, W2).

697 This finding corroborates the results obtained by the spatial analysis conducted by Evrard et  
698 al. (2011) and has important management implications. Because of locally very high erosion  
699 rates in terrains covered by black marls, erosion mitigation was concentrated in those areas  
700 (e.g., Rey, 2009). Our results confirm that these restoration works are crucial to control  
701 erosion in this catchment where black marls dominate. However, at the entire catchment  
702 scale, this study also outlined the significant supply of sediment by limestone/marly terrains  
703 to the river as well as the significant contribution of Quaternary deposits and conglomerates  
704 (21-79% for the investigated widespread floods).

705

706

## 707 **6. CONCLUSION**

708

709         This study, conducted in a 905-km<sup>2</sup> mountainous catchment of the southern French Alps,  
710 combined the use of a river monitoring network – gauging stations, raingauges, radar imagery  
711 – and sediment fingerprinting using radionuclide and elemental geochemistry concentrations  
712 as input properties to a Monte Carlo mixing model. Our results showed the strong diversity of  
713 the erosion processes involved in the catchment at the different spatial scales considered (22 –

714 713 km<sup>2</sup>). It also outlined the dominant control of the rainfall regimes on the erosion and  
715 sediment transfer processes. During the study period (Oct. 2007 – Dec. 2009), erosion rates  
716 reached a mean of  $330 \pm 100 \text{ t km}^{-2} \text{ yr}^{-1}$  in the Bléone catchment, but they strongly fluctuated  
717 between the different subcatchments ( $85 - 5000 \text{ t yr}^{-1} \text{ km}^{-2}$ ). Sediment exports generated by  
718 local convective storms varied significantly at both intra- and inter-flood scales because of  
719 spatial heterogeneity of rainfall. However, black marl/marly limestone contribution remained  
720 systematically high. In contrast, widespread lower intensity rainfall events that generate the  
721 bulk of annual sediment supply at the outlet were characterised by a much stable lithologic  
722 composition and by a larger contribution of limestones/marls, Quaternary deposits and  
723 conglomerates, which corroborates the results of a previous sediment fingerprinting study  
724 conducted on riverbed sediment collected in this catchment. This study also outlined the  
725 importance of fine sediment storage in the river network and the major contribution of the re-  
726 suspension of those deposits and/or the supply of channel bank material to the bulk of  
727 sediment exported during widespread events. This finding raises questions about the  
728 relevance of the washload concept in mountain rivers. Further research should focus on the  
729 use of fallout radionuclides (e.g., Be-7, excess-Pb-210; Evrard et al., 2010) with a higher  
730 spatial and temporal frequency to better understand sediment dynamics within the river  
731 network. *In situ* suspended sediment-size monitoring could also be performed to further  
732 investigate the mechanisms of sedimentation and degradation of the different sediment types  
733 within the catchment. Our results strongly defend the use of a combination of different  
734 techniques to get more insight on the origin and the dynamics of sediment in highly erosive  
735 mountainous catchments.

736

737

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746

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894

895 **Table and Figure captions**

896 Table 1: River monitoring stations and characteristics of their draining areas

897

898 Table 2: Floods investigated in this study (W: widespread; S: storm) and analyses conducted  
899 (X: available; n/a: not available).

900

901 Table 3: Concentrations in geochemical elements ( $\text{mg kg}^{-1}$ ) and mean radionuclide activities  
902 (in  $\text{Bq kg}^{-1}$ , except for K – in %) analysed in the representative source material samples  
903 sieved to  $< 63 \mu\text{m}$ .

904

905 Table 4: Discharge and sediment indicators derived from the river station monitoring between  
906 October 2007 and December 2009.

907

908 Table 5: Concentrations in geochemical elements ( $\text{mg kg}^{-1}$ ) and mean radionuclide activities  
909 (in  $\text{Bq kg}^{-1}$ , except for K – in %) analysed in the samples of suspended sediment.

910

911 Figure 1: Location of the study area, rainfall radars, river monitoring stations (STA1–STA5)  
912 and raingauges (R1–R15) within the Bléone catchment.

913

914 Figure 2: Geology of the Bléone catchment and location of the river monitoring stations.

915

916 Figure 3: Suspended Sediment Yield (SSY) within the Bléone catchment between 2007 –  
917 2009. (a) Inter-annual variability (in % in Figure 3a and in  $\text{t km}^{-2}$  in associated Table). (b)  
918 Fraction of the total SSY attributed to Q–SSC clockwise, anticlockwise and concomitant

919 floods. (c) Occurrence of Q–SSC clockwise, anticlockwise and concomitant floods at each  
920 station and for each rainfall regime (widespread and storm).

921

922 Figure 4: Rainfall intensity ( $\text{mm h}^{-1}$ ) vs. rainfall total amount (mm) measured at the  
923 raingauges of the Bléone catchment with a 10-minutes time-step (R1 – R10).

924

925 Figure 5: Relationship between suspended sediment yield (SSY; t) and peak discharge ( $Q_{\text{mx}}$ ;  
926  $\text{m}^3 \text{s}^{-1}$ ) for the floods that occurred in the Bléone catchment between October 2007 and  
927 December 2009. Several events were selected for further analysis (see Table 2 for details).

928

929 Figure 6: Hydrological regime close to the catchment outlet (STA1) between 2007 and 2009,  
930 and timing of the floods selected for further investigation (W1, W2; S1 – S3).

931

932 Figure 7: Case study W1: temporal dynamics of the December 22, 2009 flood that occurred  
933 on the Bès River at Pérouré (STA4) station (a) Radar rainfall image showing the maximum  
934 hourly rainfall depths during the event; (b) Picture of the Bès river reaching a  $30 \text{ m}^3 \text{ s}^{-1}$   
935 discharge and taken from the monitoring station, (c) evolution of rainfall (data available from  
936 R1 – R2 and R15 gauges; Fig. 1), discharge (Q; red curve) and SSC (black curve) during the  
937 flood and timing of sediment sampling (F1–F6); (d) evolution of sediment source contribution  
938 (in t per 10 min) in suspended sediment; (e) Q–SSC clockwise hysteretic relationship (and  
939 timing of sediment sampling) observed on the Bès River at Pérouré.

940

941 Figure 8: Topographical survey of a selected braided reach of the Bès River. (a) Picture of the  
942 reach located between Pérouré and Esclangon and taken on 3 March 2009. (b) Topographical  
943 survey of cross-section T1 before (18 April 2009) and after (3 March 2010) the 22 December



944 2009 flood. (c) Aerial pictures of the reach taken in 2004 and 2010 with the delineation of the  
945 alluvial margins (dashed lines) and the main channel (plain line) before the 22 December  
946 2009 flood.

947

948 Figure 9: Case study W2: temporal dynamics of the succession of floods that occurred  
949 between 31 October 2008 and 12 November 2008 on the Galabre River at Robine (STA2). (a)  
950 Evolution of rainfall (P; R3 raingauge), discharge (Q; red curve) and SSC (black curve)  
951 during the flood and timing of sediment sampling (B1– B3); (b) Evolution of sediment source  
952 contributions to suspended sediment (pie-charts); (c) radar images showing the maximum  
953 hourly rainfall depths during the events; (d) Q–SSC hysteretic relationship (and timing of  
954 sediment sampling).

955

956 Figure 10: Case study S1: temporal dynamics of the flood that occurred on 12 August 2008 on  
957 the Galabre River at Robine (STA2). (a) Radar images showing the maximum hourly rainfall  
958 depths during the event; (b) Evolution of rainfall (P; R3 raingauge), discharge (Q; red curve)  
959 and SSC (black curve) during the flood and timing of sediment sampling (A1–A5); (c) Q–  
960 SSC hysteresis relationship (and timing of sediment sampling); (d) evolution of sediment  
961 source contributions to suspended sediment.

962

963 Figure 11: Case study S2: temporal dynamics of the 30 June 2009 flood that propagated  
964 across the entire Bléone catchment (STA1, 2, 4 and 5). (a) Spatial distribution of maximum  
965 hourly rainfall; (b) comparison of rainfall data provided by 4 different rain gauges; (c) This  
966 picture of the Bléone River at the Prads station was taken at 14:38 GMT. (d) Discharge and  
967 SSC measured at the different stations (corresponding to red and black curves, respectively);  
968 pie-charts indicate the sources of suspended sediment.

969

970 Figure 12: Case study S3: temporal dynamics of the 7 August 2009 flood that occurred on the  
971 Bès River at Pérouré (STA4) and Esclangon (STA3) stations. (a) Radar rainfall image  
972 showing the maximum hourly rainfall depths during the event; (b) evolution of rainfall during  
973 the event (as recorded by R1-R2-R3-R14 rain gauges), (c) evolution of discharge (Q; red  
974 curve) and SSC (Pérouré: black curve; Esclangon: grey curve) during the flood and timing of  
975 sediment sampling (D1–D6); (d) evolution of sediment source contributions to suspended  
976 sediment (pie-charts); (e) Q–SSC anti-clockwise hysteresis relationship (and timing of  
977 sediment sampling) observed on the Bès river at Pérouré.

978

979 Figure 13: Proportion of draining catchment surface occupied by the different lithologic  
980 sources (%; black bars), riverbed sediment composition (%; white bars; Evrard et al., 2011)  
981 and suspended sediment composition (grey bars; mean  $\pm$  min./max. range of values obtained  
982 for the entire series of samples collected; this study) at the different river monitoring stations  
983 in the Bléone catchment.

Table 1: River monitoring stations and characteristics of their draining areas

Station Number	River	Location	Drainage Area (km <sup>2</sup> )	Highly Eroded Area (%)	Geology (% area) <sup>(1)</sup>				Land use (% area) <sup>(2)</sup>					Sampling frequency	
					Quaternary deposits	Conglomerate	Limestones / marls	Black marls	Forest	Cropland	Bare rocks	Sparse vegetation	Grassland	Water Level	Turbidity
STA1	Bléone	Le Chaffaut	713	11	27	25	37	10	43.6	5.0	6.9	30.7	13.1	Variable time-step	60 min.
STA2	Galabre	La Robine	22	8	31	2	54	9	11.0	2.6	0.0	19.3	67.0	10 min.	10 min.
SAT3	Bès	Esclangon	181	17	20	15	51	12	42.6	1.9	15.7	18.2	21.4	n/a <sup>(3)</sup>	10 min.
STA4	Bès	Pérouré	165	17	20	15	51	12	42.6	1.9	15.7	18.2	21.4	Variable	10 min.
STA5	Bléone	Prads	65	7	37	15	46	2	24.2	0.0	33.9	33.9	6.3	10 min.	10 min.

<sup>(1)</sup> The remaining % correspond to gypsum

<sup>(2)</sup> The remaining % correspond to urban areas

<sup>(3)</sup> n/a: no data available

Table 2: Floods investigated in this study (W: widespread; S: storm) and analyses conducted (X: available; n/a: not available).

Event Date	Case study code	Samples	Hail	Snow Cover	Rainfall			Analysis			
					Duration (hr)	Volume (mm)	Intensity <sup>(1)</sup> (mm h <sup>-1</sup> )	River monitoring	Rainfall	Sediment fingerprinting	Topography and imagery
22/12/2009	W1	F1 – F6	no	yes	21	108 <sup>(4)</sup>	20	X	X	X	X
31/10/2008	W2a	B1	no	no	16	67 <sup>(3)</sup>	9	X	X	X	n/a
02/11/2008	W2b	B2	no	no	49	33 <sup>(3)</sup>	15	X	X	X	n/a
12/11/2008	W2c	B3	no	no	16	77 <sup>(3)</sup>	19	X	X	X	n/a
12/08/2008	S1	A1 – A5	no	no	4	24 <sup>(3)</sup>	90	X	X	X	n/a
29/06/2009	S2	C1 – C6	yes	no	5	6 <sup>(2)</sup>	30	X	X	X	n/a
07/08/2009	S3	D1 – D6	no	no	5	61 <sup>(2)</sup>	63	X	X	X	n/a

<sup>(1)</sup> Maximum intensity derived from 10-minutes time-step rainfall data, except for W3 and W4 case studies

<sup>(2)</sup> Estimated based on data from the Haut-Vernet raingauge

<sup>(3)</sup> Estimated based on data from the Ainac raingauge

<sup>(4)</sup> Estimated based on data from the Barles raingauge

<sup>(5)</sup> Estimated based on data from the Laval raingauge (Draix Observatory)

Table 3: Concentrations in geochemical elements (mg kg<sup>-1</sup>) and mean radionuclide activities (in Bq kg<sup>-1</sup>, except for K – in %) analysed in the representative source material samples sieved to < 63 µm.

Source type		Mg	Al	Ca	Ti	V	Mn	Ni	Cu	Ag	Cd	Sb	Ba	Tl	Pb	Pb-210	K (%)	Cs-137	Th-234	Ra-226	Ra-228	Th-228
Black marl (Bathonian) -	mean	9276	77328	148962	464	125	844	48	21	0.20	0.17	0.39	216	0.55	14	32	1.7	12	26	21	32	33
	SD	2816	10535	74803	810	28	132	9	9	0.04	0.04	0.10	24	0.10	5	19	0.4	26	6	3	7	7
Other black marls -	mean	8661	61733	127430	4272	90	549	41	20	0.17	0.18	0.41	248	0.47	16	39	1.6	26	26	22	33	32
	SD	3231	20399	57737	1118	26	121	8	6	0.03	0.05	0.07	87	0.12	5	14	0.5	24	7	5	11	11
Grey marls-	mean	41086	55698	134353	3565	88	634	43	18	0.18	0.20	0.77	192	0.35	12	62	1.5	71	28	25	28	28
	SD	64278	6261	104767	1084	12	404	4	3	0.06	0.09	0.54	49	0.05	3	43	0.5	121	11	8	8	8
Marly limestones-	mean	24744	49422	97944	3197	78	444	47	19	0.18	0.25	0.76	216	0.49	12	52	1.8	23	40	42	24	25
	SD	27485	1583	82709	207	17	38	21	11	0.08	0.14	0.35	78	0.22	5	1	0.9	4	4	2	2	1
Quarternary deposits-	mean	11355	41394	205027	3398	50	198	24	10	0.14	0.16	0.68	171	0.37	11	42	1.0	44	33	32	41	40
	SD	1307	355	11074	138	1	20	1	1	0.00	0.01	0.09	2	0.00	1	2	0.1	57	0	1	1	0
Conglomerates-	SD	10340	87905	162631	3480	86	658	60	32	0.29	0.38	0.74	397	0.49	24	51	1.4	40	24	20	33	33
	SD	2438	7914	22337	146	16	105	17	1	0.08	0.03	0.03	43	0.09	6	19	0.2	22	2	1	2	5

n/a: not available

To facilitate their analysis and interpretation, the six rock types were regrouped into five classes (black marls of Bathonian age and other black marls were regrouped in one class; grey marls and marly limestones were regrouped in one class entitled “limestones”).

Table 4: Discharge and sediment indicators derived from the river station monitoring between October 2007 and December 2009.

Station Number	Station Name	Number of events	$Q_m$ (mm)	$Q_{mx}$ ( $m^3s^{-1}$ )	$SSC_m$ ( $g\ l^{-1}$ )	$SSC_{mx}$ ( $g\ l^{-1}$ )	SSY (t)	SSY* ( $t\ km^{-2}\ yr^{-1}$ )	Ms2 (%)	V2 (%)	SSYw (%)
STA1	Bléone at Chaffaut	83	410	500	0.28	46	641,900 ± 192,600	330 ± 100	75	18	82
STA4	Bes at Pérouré	89	437	170	0.30	135	256,300 ± 76,900	690 ± 207	96	16	89
STA5	Bléone at Prads	55	572	18	0.12	360	66,200 ± 19,900	452 ± 136	99.9	12	72
STA2	Galabre at Robine	75	400	34	0.42	130	33,500 ± 10,000	680 ± 200	96	20	80

Discharge parameters:  $Q_m$  (mean annual runoff depth);  $Q_{mx}$  (instantaneous peak flow discharge); sediment concentration parameters:  $SSC_m$  (mean sediment concentration);  $SSC_{mx}$  (peak sediment concentration); sediment yield parameters:  $SSY$  (total sediment yield);  $SSY^*$  (specific sediment yield); Ms2% and V2%, respectively the percentage of total mass of suspended solid and water volume transported during 2% of the observational period;  $SSY_w$ , the fraction of inter-annual sediment yields transported during widespread rainfall events;  $(1-SSY_w)$  is the  $SSY$  transported during storms.

Table 5: Concentrations in geochemical elements (mg kg<sup>-1</sup>) and mean radionuclide activities (in Bq kg<sup>-1</sup>, except for K – in %) analysed in the samples of suspended sediment.

Sample	Date	Time	Site	SSC (g l <sup>-1</sup> )	Mg	Al	Ca	Ti	V	Mn	Ni	Cu	Ag	Cd	Sb	Ba	Tl	Pb	excess- Pb-210	K (%)	Cs- 137	Th- 234	Ra- 226	Ra- 228	Th- 228	Be- 7	
<i>Case S1: Summer storm on the Galabre river at Robine (STA2)</i>																											
A1	12/08/2008	20:00	Robine	69	9260	60567	152613	5074	122	495	48	19	0.13	0.10	0.54	303	0.56	16.0	31.8	2.0	11.1	0.0	33.0	27.1	3.3	n/a	
A2	12/08/2008	21:00	Robine	5	93184	643623	960926	1986	90	369	19	15	0.05	0.10	0.13	124	0.26	6.0	59.2	2.1	17.5	19.5	4.5	22.0	0.9	n/a	
A3	12/08/2008	23:20	Robine	60	14075	65480	164390	3367	83	406	37	12	0.11	1.23	0.35	172	0.49	23.9	15.3	1.8	3.6	23.9	3.8	21.5	0.7	n/a	
A4	13/08/2008	00:20	Robine	133	12593	70991	213958	2763	69	279	29	9	0.09	0.56	0.27	145	0.41	13.8	14.1	1.5	4.2	27.5	3.7	22.5	0.7	n/a	
A5	13/08/2008	07:20	Robine	38	8881	61401	157484	3134	87	229	29	9	0.12	0.24	0.36	182	0.55	11.9	17.9	1.7	4.7	0.0	33.0	27.1	3.3	n/a	
<i>Case W2: Widespread flood on the Galabre river at Robine (STA2)</i>																											
B1	31/10/2008	12:30	Robine	8	10894	47052	204417	3663	103	526	42	18	0.13	0.11	0.66	198	0.45	13.5	14.9	1.7	3.6	21.2	3.5	22.6	0.7	n/a	
B2	02/11/2008	21:30	Robine	26	12841	44731	203326	3525	101	575	42	19	0.12	0.14	0.63	198	0.45	15.3	0.0	1.8	3.0	27.8	3.7	23.2	0.7	n/a	
B3	12/11/2008	02:20	Robine	25	16681	48372	176958	3804	111	675	39	23	0.14	0.12	0.70	212	0.54	19.5	10.4	2.0	4.4	29.9	2.5	25.2	0.5	n/a	
<i>Case S2: Storm propagation from Prads (STA5) to Chaffaut (STA1)</i>																											
C1	29/06/2009	16:40	Robine	21	10297	79426	99000	4725	97	349	42	15	0.14	0.19	0.37	289	0.62	11.8	12.4	2.1	5.8	36.4	3.8	26.6	0.7	n/a	
C2	29/06/2009	23:40	Robine	27	18741	107071	105745	4238	118	617	50	16	0.14	0.29	0.43	218	0.69	14.9	15.6	2.5	4.6	29.9	4.1	22.8	0.7	n/a	
C3	29/06/2009	14:30	Prads	61	9431	80880	191885	3313	96	294	50	39	0.29	0.48	0.46	598	0.64	16.4	36.3	1.8	17.8	31.4	3.3	27.0	0.6	n/a	
C4	30/06/2009	01:10	Pérouré	7	12484	104465	106063	5798	128	870	46	20	0.17	0.41	0.79	227	0.81	15.2	38.7	2.6	5.8	33.0	2.3	27.8	0.4	n/a	
C5	29/06/2009	23:00	Le Chaffaut	10	7475	68408	143835	3296	100	327	49	37	0.24	1.28	0.52	615	0.70	28.4	75.7	1.8	22.2	37.0	5.4	35.0	1.1	n/a	
C6	30/06/2009	05:30	Le Chaffaut	1	10361	88608	160721	4664	160	558	73	58	0.38	0.69	2.43	973	1.08	22.8	58.0	2.0	20.5	0.0	54.8	28.2	5.6	n/a	
<i>Case S3: Summer storm on the Bès river between Pérouré(STA4) and Esclangon (STA3)</i>																											
D1	07/08/2009	17:50	Pérouré	11	11103	60185	227286	3488	84	642	45	22	0.15	0.28	0.35	220	0.45	12.5	14.2	1.3	2.3	13.2	19.2	25.9	28.3	n/a	
D2	07/08/2009	19:50	Pérouré	157	8783	78061	129692	4204	118	1128	51	22	0.18	0.23	0.55	265	0.65	13.3	21.8	1.8	2.0	30.3	24.8	40.7	37.0	n/a	
D3	07/08/2009	22:50	Pérouré	46	7868	72041	127575	3552	103	796	44	21	0.16	0.14	0.29	278	0.58	10.4	14.9	1.9	4.5	22.6	23.5	39.0	36.6	n/a	
D4	07/08/2009	18:50	Esclangon	10	8567	44512	208399	2693	62	468	35	15	0.10	0.15	0.28	150	0.34	8.7	0.0	1.3	4.0	13.8	18.4	21.9	25.9	n/a	
D5	07/08/2009	21:50	Esclangon	128	8904	81752	132215	4463	130	1186	58	23	0.24	0.16	0.65	311	0.76	13.9	0.0	2.0	2.6	26.1	23.5	34.6	39.5	n/a	
D6	08/08/2009	01:50	Esclangon	33	8585	85098	135913	4190	126	869	51	24	0.23	0.28	0.59	263	0.71	13.2	31.2	2.0	5.5	30.1	22.2	38.8	38.8	n/a	
<i>Case W1: Widespread flood on the Bès river at Pérouré (STA4)</i>																											
F1	22/12/2009	16:00 - 18:00	Pérouré	1 - 4	12136	73591	157582	3667	96	546	47	19	0.15	0.17	0.63	178	0.53	11.6	0.0	1.8	2.9	24.3	6.6	21.8	1.2	33	
F2	22/12/2009	20:00	Pérouré	21	12052	63125	183479	2999	78	514	42	18	0.15	0.15	0.35	152	0.42	11.2	11.3	1.4	3.4	29.5	3.7	20.3	0.7	41	
F3	22/12/2009	22:00	Pérouré	28	12309	50620	202141	2645	69	580	39	18	0.11	0.24	0.45	164	0.45	14.6	11.0	1.4	5.2	21.3	4.5	25.9	0.9	<1	
F4	23/12/2009	00:00	Pérouré	28	13428	54016	194205	2783	72	641	40	16	0.12	0.21	0.46	178	0.48	11.2	9.3	1.6	6.9	20.2	4.3	25.4	0.9	<1	
F5	23/12/2009	03:00	Pérouré	14	10943	45461	173693	2860	74	720	42	19	0.13	0.19	0.52	210	0.47	12.2	14.8	1.4	5.1	25.9	4.2	22.8	0.8	18	
F6	23/12/2009	10:00 - 13:00	Pérouré	1 - 3	13533	58182	230516	2782	78	671	42	20	0.13	0.24	0.65	206	0.49	12.1	0.0	1.6	2.9	20.1	5.7	27.0	1.2	<1	

n/a: not available

Figure 1: Location of the study area and rainfall radars (Fig. a), river monitoring stations (STA1–STA5) and raingauges (R1–R15) within the Bléone catchment (Fig. b).

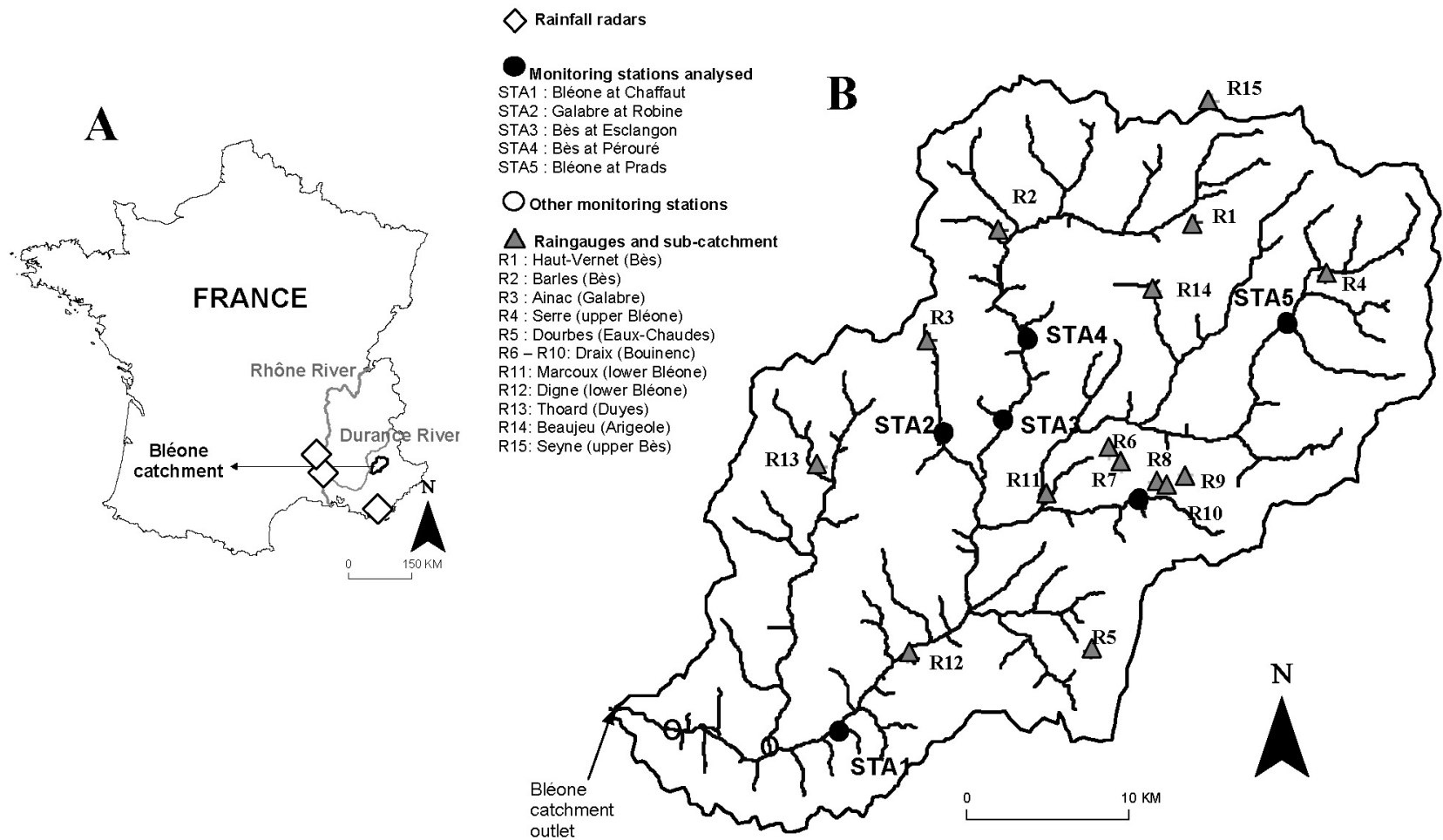




Figure 2: Geology of the Bléone catchment and location of the river monitoring stations

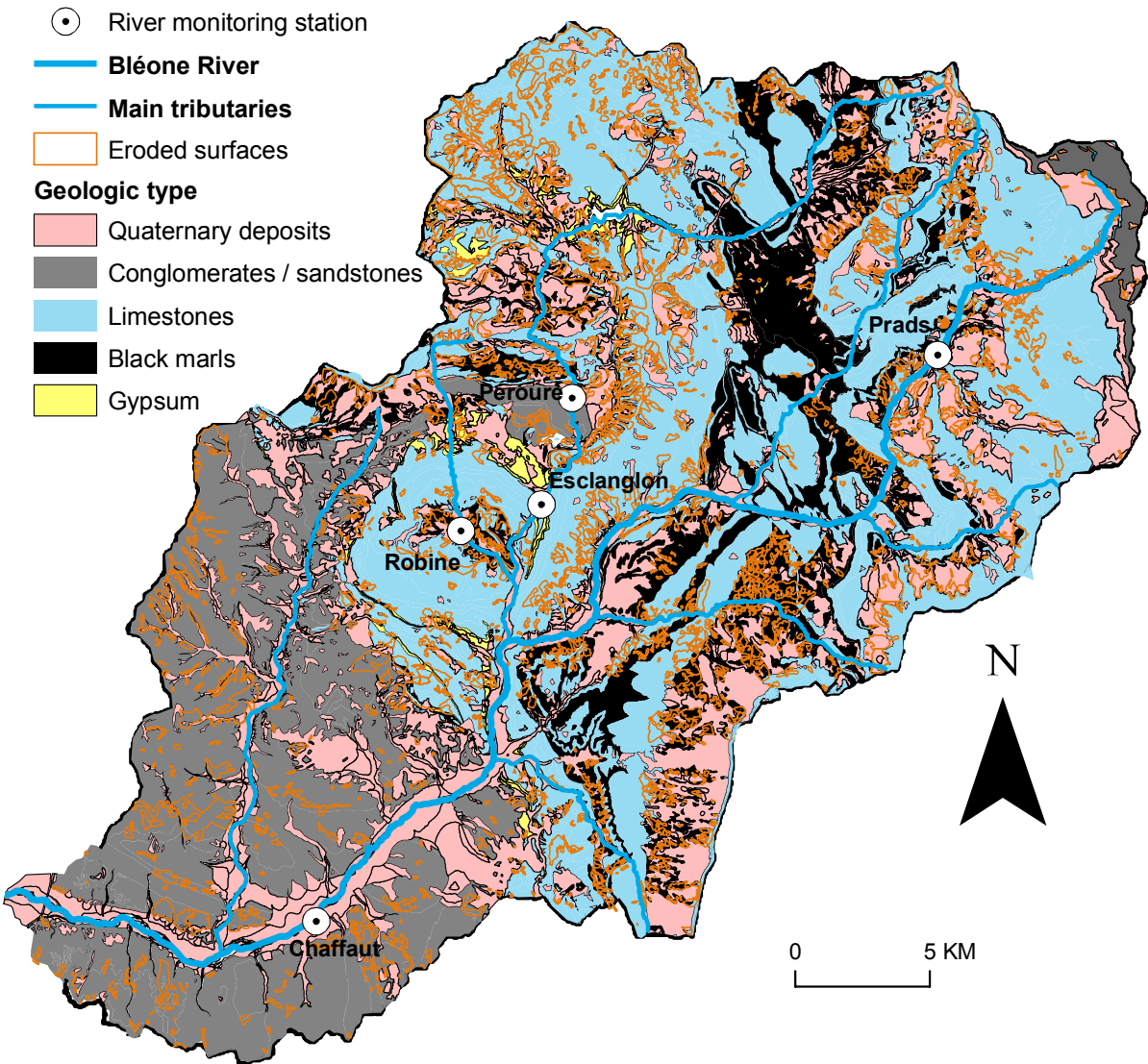


Figure 3: Suspended Sediment Yield (SSY) within the Bléone catchment between 2007 – 2009. (a) Inter-annual variability (in % in Figure 3a and in  $t\ km^{-2}$  in associated Table). (b) Fraction of the total SSY attributed to Q–SSC clockwise, anticlockwise and concomitant floods. (c) Occurrence of Q–SSC clockwise, anticlockwise and concomitant floods at each station and for each rainfall regime (widespread and storm).

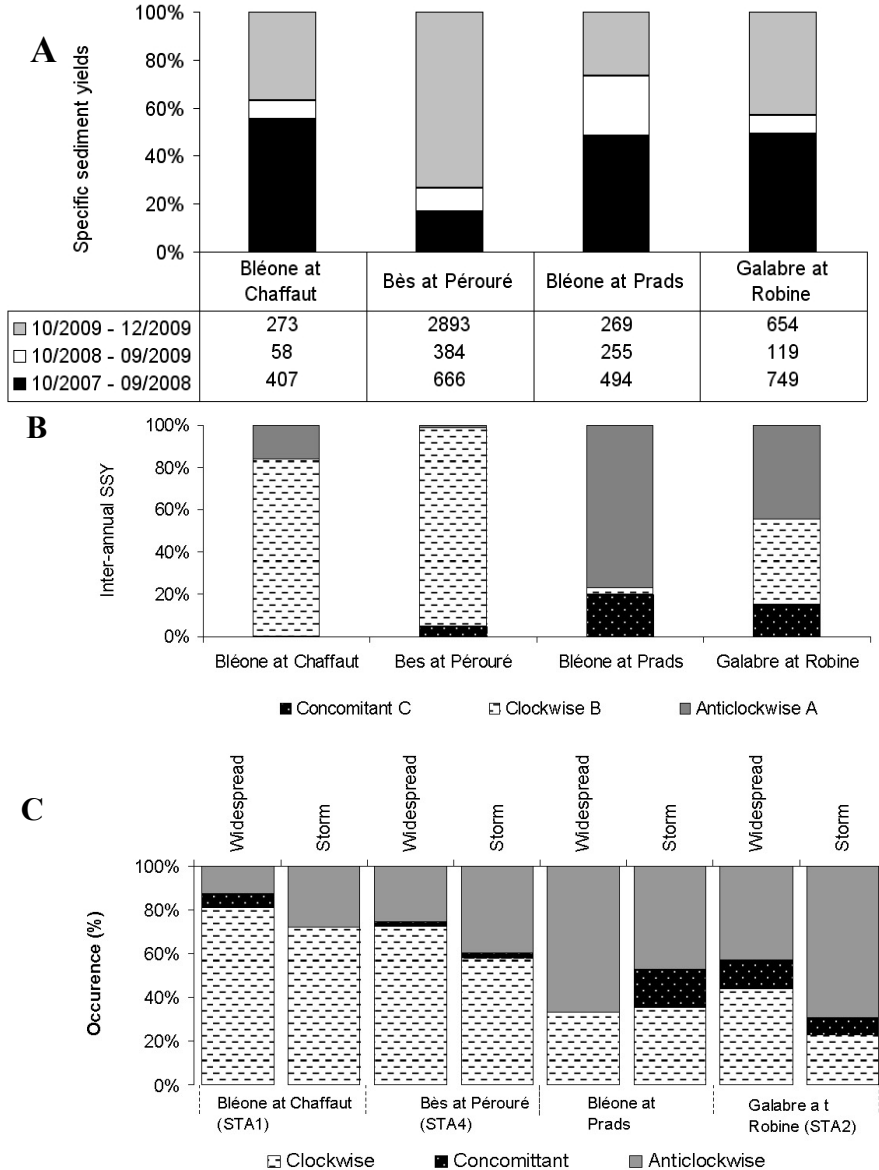


Figure 4: Rainfall intensity ( $\text{mm h}^{-1}$ ) vs. rainfall total amount (mm) measured at the raingauges of the Bléone catchment with a 10-minutes time-step (R1 – R10).

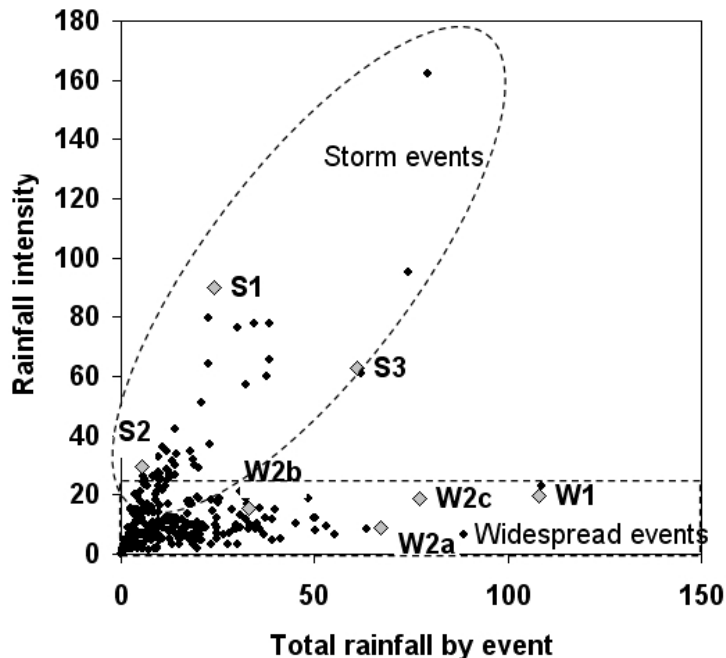


Figure 5: Relationship between suspended sediment yield (SSY; t) and peak discharge ( $Q_{mx}$ ;  $m^3 s^{-1}$ ) for the floods that occurred in the Bléone catchment between October 2007 and December 2009. Several events were selected for further analysis (see Table 2 for details).

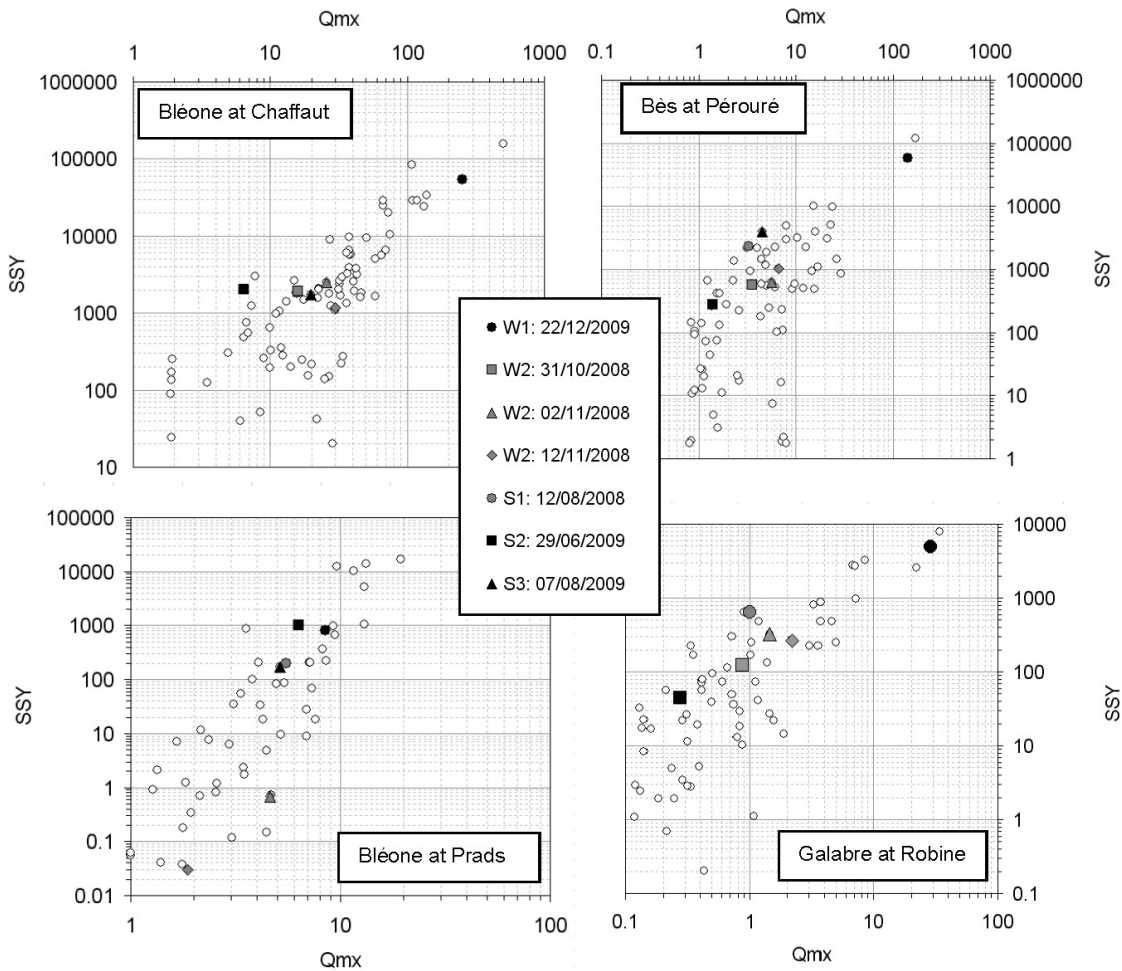


Figure 6: Hydrological regime close to the catchment outlet (STA1) between 2007 and 2009, and timing of the floods selected for further investigation (W1, W2; S1 – S3).

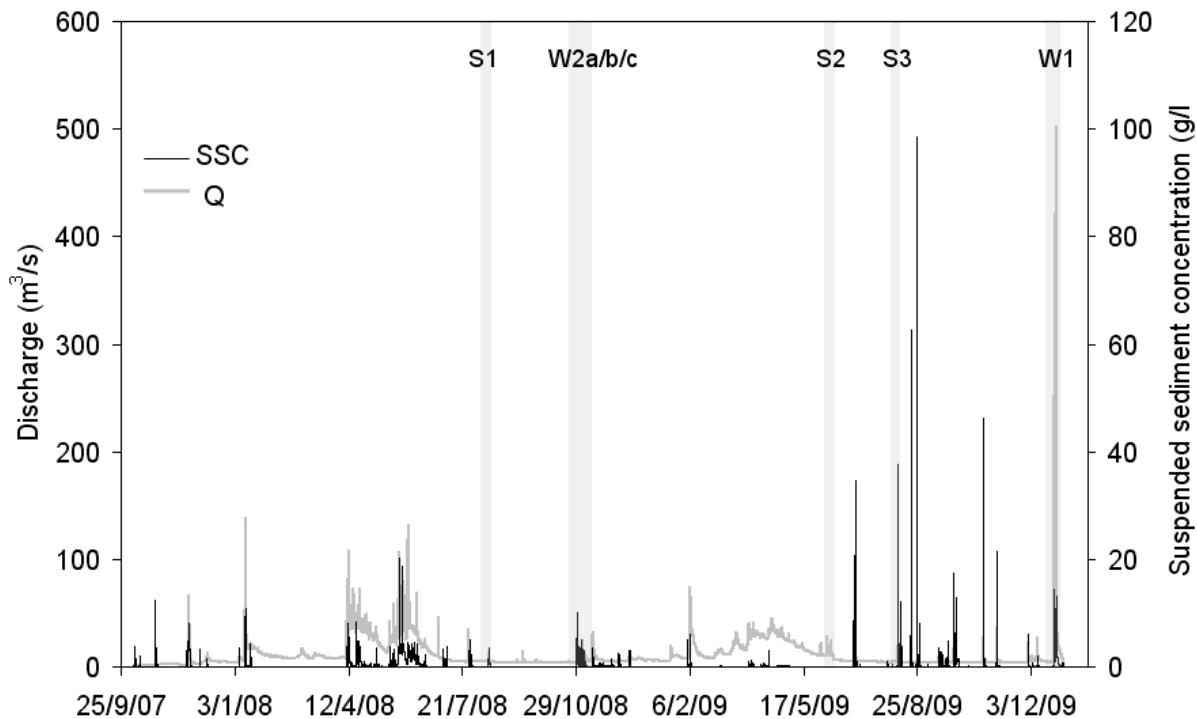


Figure 7: Case study W1: temporal dynamics of the December 22, 2009 flood that occurred on the Bès River at Pérouré (STA4) station (a) Radar rainfall image showing the maximum hourly rainfall depths during the event; (b) Picture of the Bès river reaching a  $30 \text{ m}^3 \text{ s}^{-1}$  discharge and taken from the monitoring station, (c) evolution of rainfall (data available from R1 – R2 and R15 gauges; Fig. 1), discharge (Q; red curve) and SSC (black curve) during the flood and timing of sediment sampling (F1–F6); (d) evolution of sediment source contribution (in t per 10 min) in suspended sediment; (e) Q–SSC clockwise hysteretic relationship (and timing of sediment sampling) observed on the Bès River at Pérouré.

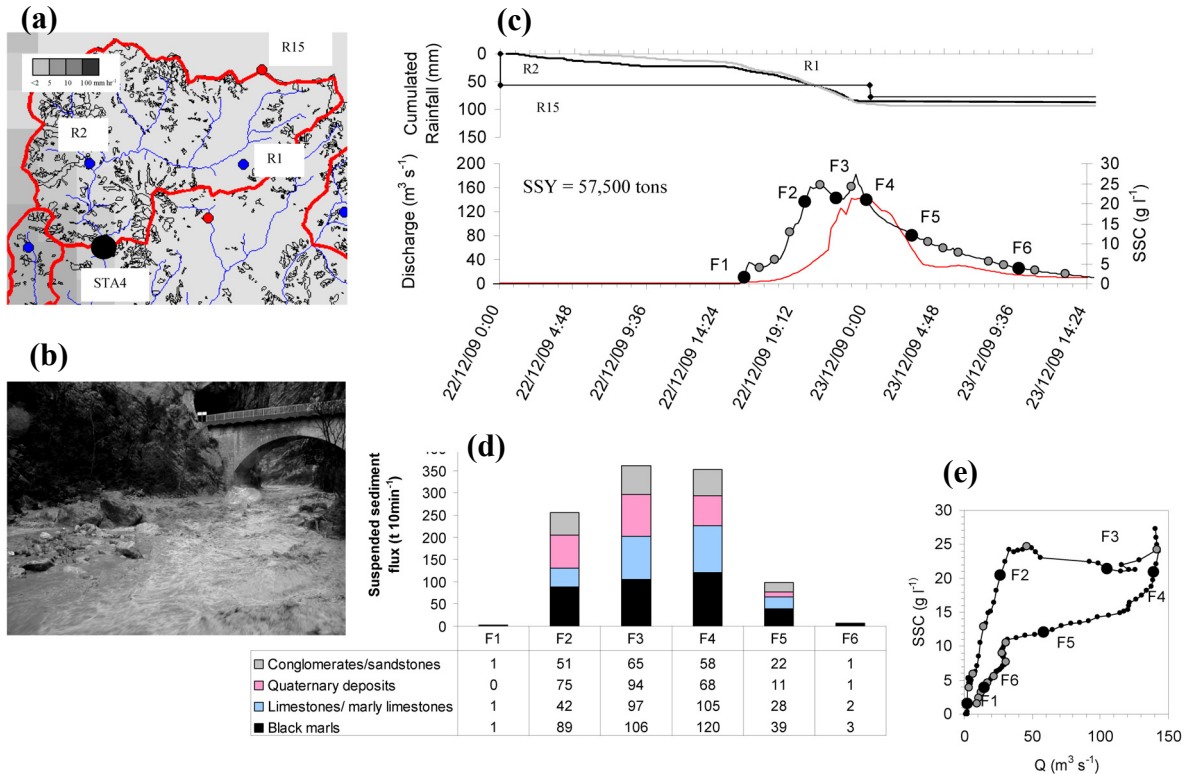


Figure 8: Topographical survey of a selected braided reach of the Bès River. (a) Picture of the reach located between Pérouré and Esclangon and taken on 3 March 2009. (b) Topographical survey of cross-section T1 before (18 April 2009) and after (3 March 2010) the 22 December 2009 flood. (c) Aerial pictures of the reach taken in 2004 and 2010 with the delineation of the alluvial margins (dashed lines) and the main channel (plain line) before the 22 December 2009 flood.

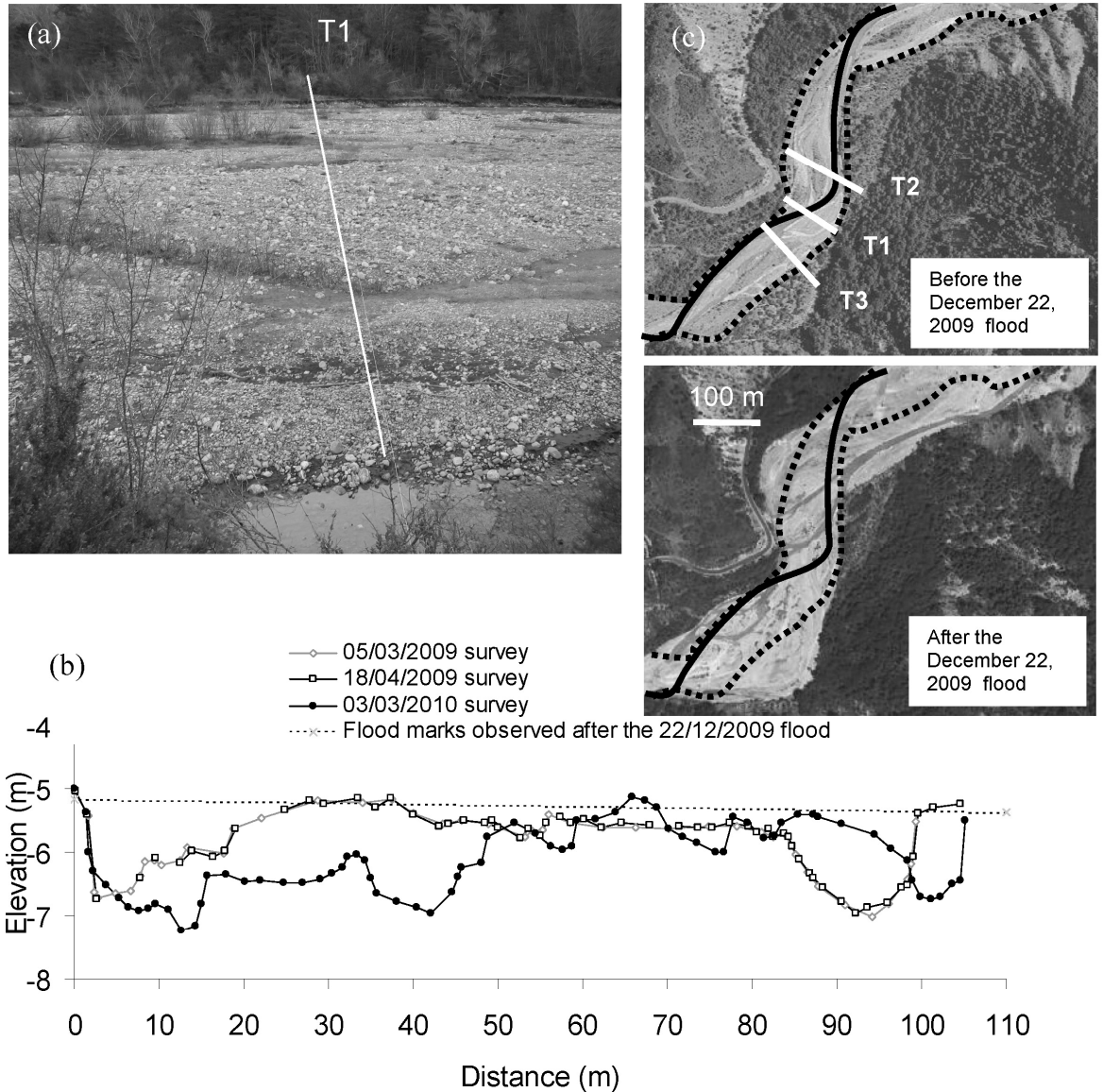


Figure 9: Case study W2: temporal dynamics of the succession of floods that occurred between 31 October 2008 and 12 November 2008 on the Galabre River at Robine (STA2). (a) Evolution of rainfall (P; R3 raingauge), discharge (Q; red curve) and SSC (black curve) during the flood and timing of sediment sampling (B1– B3); (b) Evolution of sediment source contributions to suspended sediment (pie-charts); (c) radar images showing the maximum hourly rainfall depths during the events; (d) Q–SSC hysteretic relationship (and timing of sediment sampling).

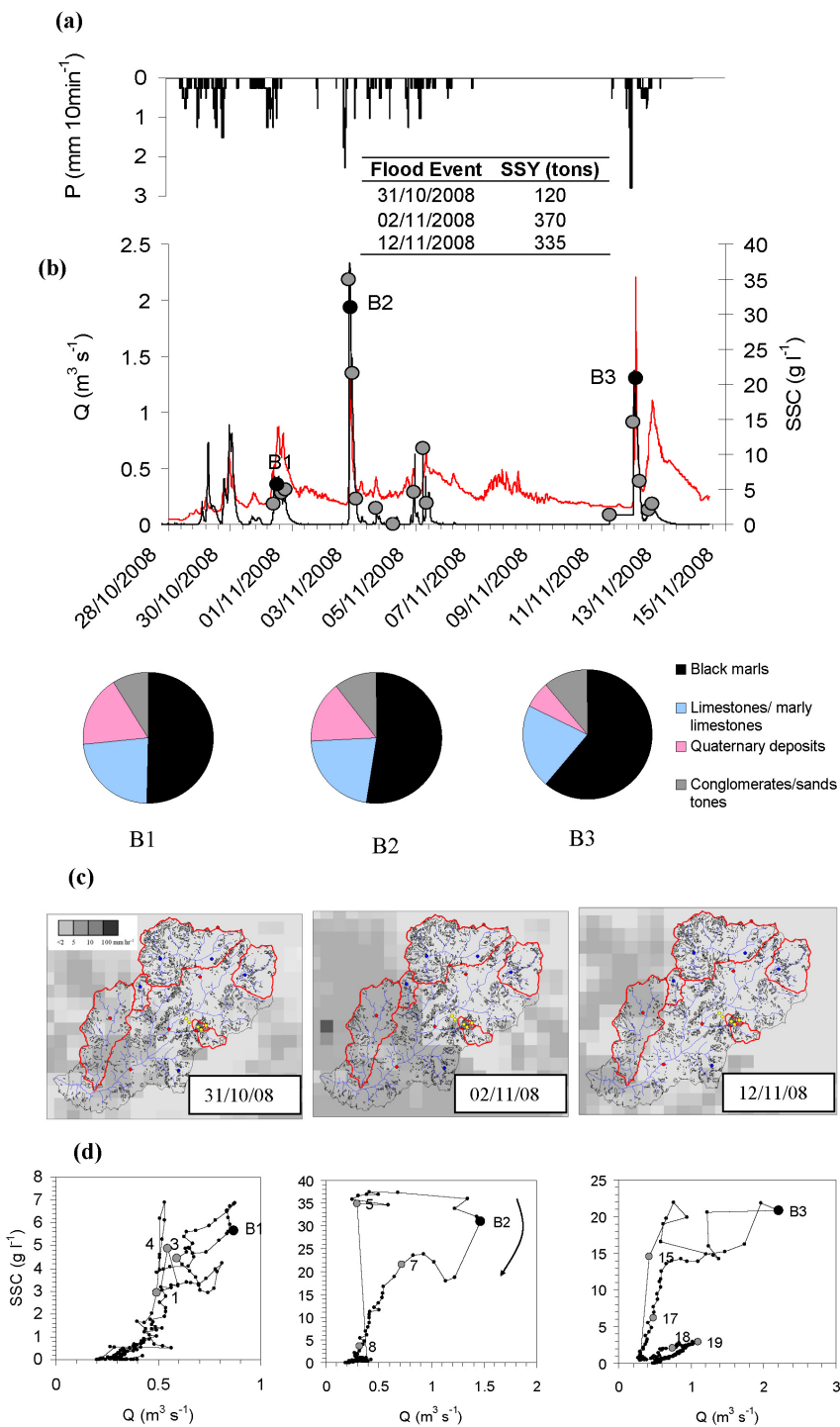
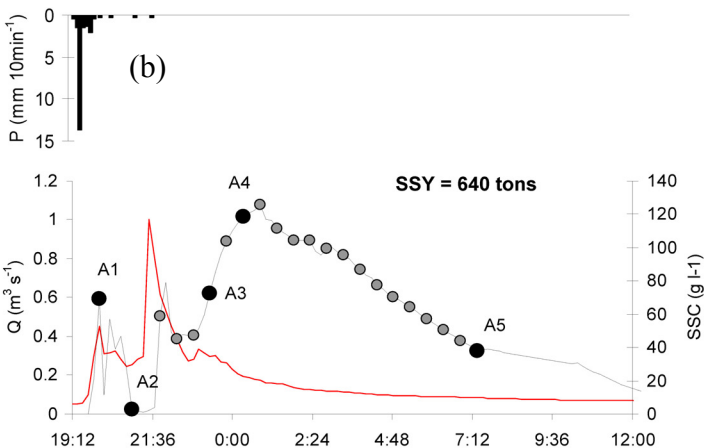
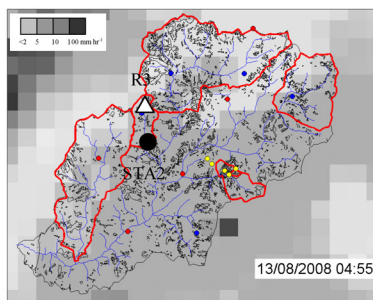


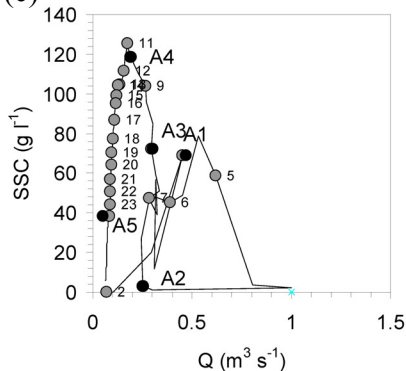


Figure 10: Case study S1: temporal dynamics of the flood that occurred on 12 August 2008 on the Galabre River at Robine (STA2). (a) Radar images showing the maximum hourly rainfall depths during the event; (b) Evolution of rainfall (P; R3 raingauge), discharge (Q; red curve) and SSC (black curve) during the flood and timing of sediment sampling (A1–A5); (c) Q–SSC hysteresis relationship (and timing of sediment sampling); (d) evolution of sediment source contributions to suspended sediment.

(a)



(c)



(d)

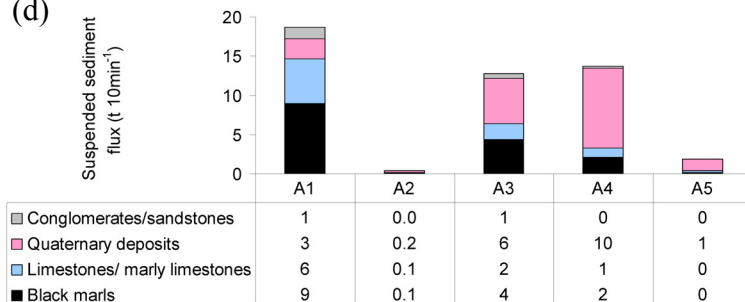


Figure 11: Case study S2: temporal dynamics of the 30 June 2009 flood that propagated across the entire Bléone catchment (STA1, 2, 4 and 5). (a) Spatial distribution of maximum hourly rainfall; (b) comparison of rainfall data provided by 4 different rain gauges; (c) This picture of the Bléone River at the Prads station was taken at 14:38 GMT. (d) Discharge and SSC measured at the different stations (corresponding to red and black curves, respectively); pie-charts indicate the sources of suspended sediment.

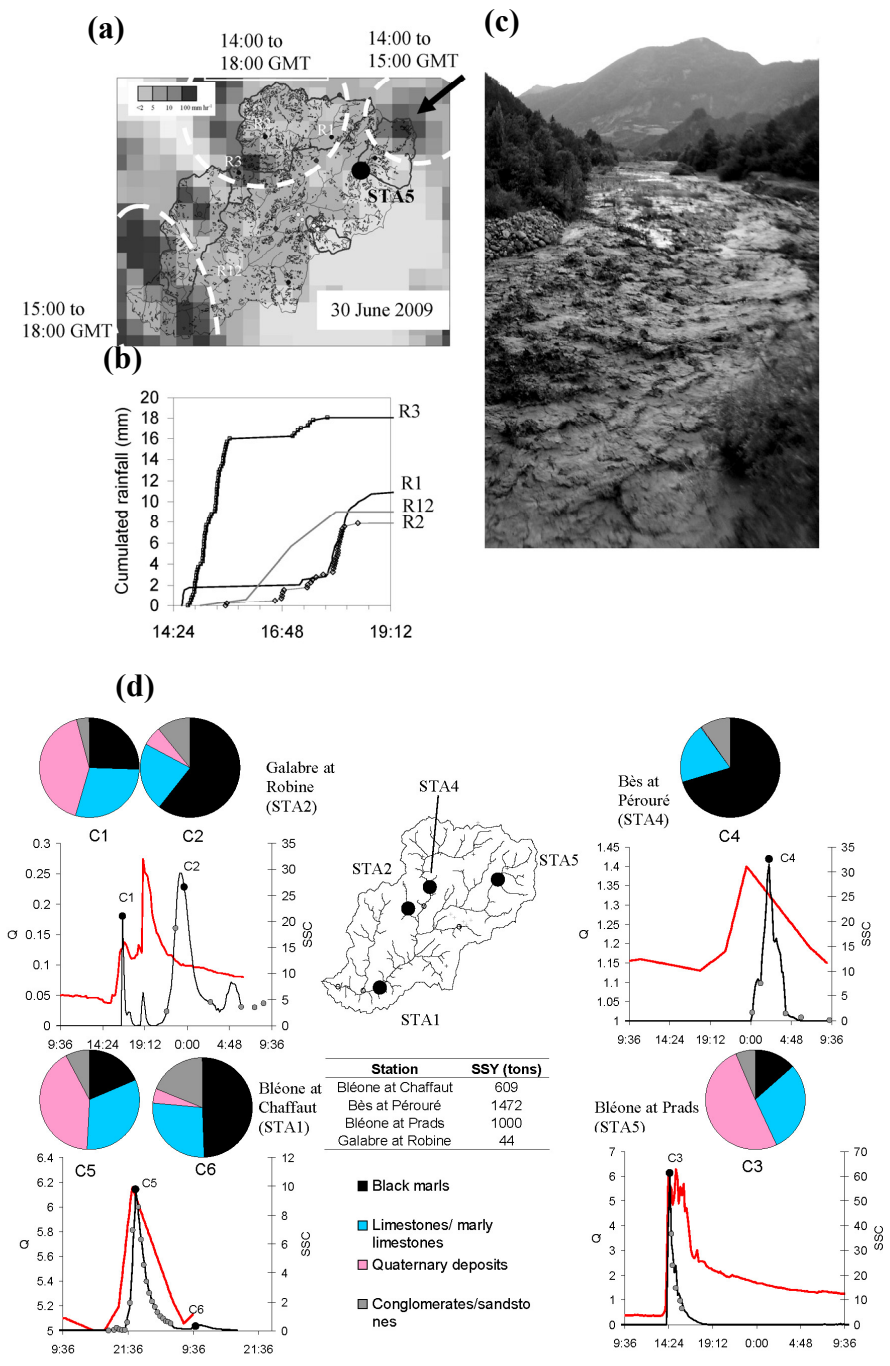


Figure 12: Case study S3: temporal dynamics of the 7 August 2009 flood that occurred on the Bès River at Pérouré (STA4) and Esclangon (STA3) stations. (a) Radar rainfall image showing the maximum hourly rainfall depths during the event; (b) evolution of rainfall during the event (as recorded by R1-R2-R3-R14 rain gauges), (c) evolution of discharge ( $Q$ ; red curve) and SSC (Pérouré: black curve; Esclangon: grey curve) during the flood and timing of sediment sampling (D1–D6); (d) evolution of sediment source contributions to suspended sediment (pie-charts); (e)  $Q$ –SSC anti-clockwise hysteresis relationship (and timing of sediment sampling) observed on the Bès river at Pérouré.

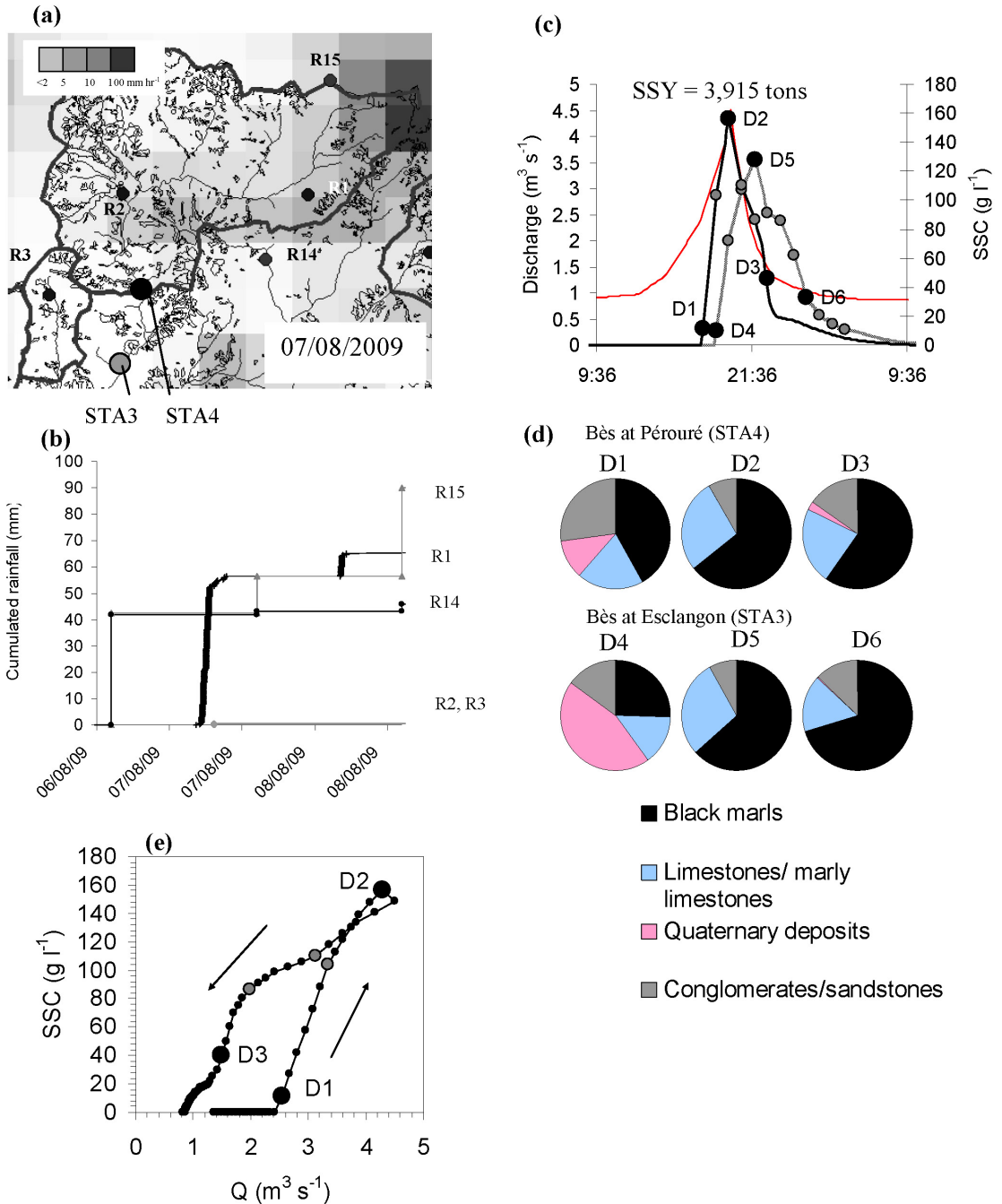


Figure 13: Proportion of draining catchment surface occupied by the different lithologic sources (%; black bars), riverbed sediment composition (%; white bars; Evrard et al., 2011) and suspended sediment composition (grey bars; mean  $\pm$  min./max. range of values obtained for the entire series of samples collected; this study) at the different river monitoring stations in the Bléone catchment.

