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### Suspended sediment flux at the Rhone River mouth (France) based on ADCP measurements during flood events 2

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at the mouth of the Rhone River for two annual flood events. The estimates were based on 21 ADCP acoustic backscatter intensity and using calibration and post-processing methods to 22 account for the grain-size distribution (GSDs). The fluxes were very similar to those obtained 23 24 from suspended sediment measurements based on surface sampling at an automated station located 35 km upstream. Suspended Sediment Concentrations (SSC) and GSDs showed little 25 variation along the channel cross section, except for a graduate suspension that appeared at 26 the maximum of discharge, corresponding to velocities lower than 1 m.s<sup>-1</sup> near the bottom. 27 However, without post processing to account for the GSD, an under-estimation of 10% was 28 observed during the two floods periods. The two flood events, separated by only two weeks, 29 had clear differences in suspended fluxes and SSC, with twice more flux during the first 30 event. 31

Keywords: Suspended sediment flux, ADCP measurements, Backscatter calibration, Grain-32

33 size distribution, flood events, Rhone River, France

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### 1. Introduction

Determination of the quantity and quality (e.g., grain size, pollutants) of sediment 36 delivered by rivers to the ocean is critical for managing and preserving deltas, shorelines, and 37 marine ecosystems (Vörösmarty et al., 2003; Limber et al., 2008). Both the morphology of 38 these systems and the habitat they support depend directly on the sediment flux delivered by 39 40 the river, which itself depends on sediment production in the catchment (e.g. geology, precipitation, land use) and on the continuity of its transfer to the coast (e.g. retention dams, 41 42 dredging; Blum and Tornqvist, 2000; Syvitski & Saito, 2003; Antonelli et al., 2004; Provansal et al, 2014). 43

Suspended sediment fluxes (SSF) have been measured worldwide for a wide range of rivers 44 (e.g. Walling et al., 1992; Inman and Jenkins, 1999; Picouet et al., 2001; Meybeck et al., 45 2003; Rovira et al., 2005; Hu et al., 2011; Boateng et al., 2012; Unverricht et al., 2014), and 46 best practices for estimating these fluxes have been discussed by Moatar et al. (2006), 47 Horowitz (2008) and Horowitz et al. (2015). The vast majority of these sediment flux 48 estimates are based on suspended sediment concentrations (SSC) measured from a surface 49 sample of the flow, and do not take into account variations in grain-size distributions and/or 50 suspended sediment concentrations within the water column and the channel section. 51

Meybeck et al (2003) compiled a database of SSC and SSF measured in rivers worldwide and covering a range of flow regimes. According to their study, the difference in flux estimates from surface versus depth-integrated samples can induce one hundred percent variations in SSC, but they note that this range is negligible compared to the variation of up to six orders of magnitude due to temporal variation (e.g. discharge fluctuation). However, Horowitz (2008) demonstrated the marked spatial (vertical and lateral) and temporal variability in SSC in rivers for both constant and varying discharge and recommended that both depth and width-

integrated samples are needed to generate representative samples. Alternative methods that 59 have been proposed and explored in order to measure SSC within the water column include 60 measurements using an Optical Backscatter Sensor (Schoellhamer and Wright, 2013) and/or 61 an Acoustic Doppler Current Profiler (ADCP, e.g. Tessier et al., 2008; Defendi et al., 2010; 62 Duclos et al., 2013) – which was the focus of this study. However, as we will discuss in detail 63 later, accurate estimates based on these techniques require analysis of water samples collected 64 in real time in order to determine the grain size distribution (GSD) and calibrate its 65 relationship with SSC. 66

The Rhone River, in the south of France, is the main source of freshwater and continentally 67 derived sediments to the Mediterranean Sea. The downstream-most SSF has been monitored 68 continuously since 2005 at the SORA monitoring station located in Arles (Figure 1a). These 69 flux estimates are based on SSC measured from an automated surface flow sample collected 70 once a day. While, this system provides an efficient and reliable method for obtaining a long 71 and continuous record (Eyrolle et al 2012), it is not well suited for accurately estimating 72 fluxes during floods, which can typically have strong vertical gradients in GSD and rapid 73 changes in SSC. Furthermore, the system is susceptible to technical malfunctions when SSC 74 is high, resulting in unreliable data. Annual SSF measured at Arles ranges between 1 and 11 75 Mt.yr<sup>-1</sup> (Pont et al., 2002; Antonelli et al., 2008; Ollivier et al 2011; Eyrolle et al., 2012). The 76 representativity of these SSC has been tested for discharges up to 3000 m<sup>3</sup>.s<sup>-1</sup>, but higher 77 discharges could well induce more pronounced vertical stratification in SSCs and therefore 78 larger errors in the estimation of SSF. Studies by Pont et al. (2002), Antonelli et al. (2008), 79 Ollivier et al (2011), and Eyrolle et al., (2012) estimate that between 80 - 90% of the Rhone 80 annual suspended sediment flux is associated with floods. As such, there is a clear need for a 81 more robust method to quantify SSF associated with these events. This study is part of an 82 ongoing effort to develop a continuous monitoring system using an ADCP to estimate SSFs 83

during floods at the mouth of the Rhone delta. The study, spanning two flood events, 84 highlights the potential of this technique for characterizing spatial and temporal variability in 85 SSF and its relationship to flow hydrodynamics. The insights from this study provide an 86 important first step towards putting in place a fully autonomous system for continuous 87 monitoring of SSF on a large river. Our objective is to get a more precise estimate of sediment 88 delivery to the Rhone delta in order to better inform coastal management strategies. On the 89 long-term, we seek to relate SSF to discharge patterns and meteorological conditions in order 90 to identify the main sources of variability in flux delivered to the delta. 91

In this paper we present an analysis of ADCP measurements conducted during two annual floods in 2012. XXXXX During both floods, we collected suspended sediment samples at different locations and depths that provided precise information about SSC and GSD. We used this data to calibrate the ADCP backscatter signal and compare flux estimates with and without taking into account GSD. In addition, the samples provide a first glimpse at how GSD distribution varies with depth over the course of annual floods on the Rhone River.

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### 2. Suspended Sediment Flux (SSF) estimates based on acoustic monitoring

Efforts to quantify SSF from the SSC distributions measured over the entire vertical 99 flow column and across an entire cross-section of channel have focused on the use of acoustic 100 Doppler Current Profilers (ADCPs; Alvarez and Jones, 2002; Gartner, 2004; Kostaschuk et 101 al., 2005; Tessier et al., 2008; Ghaffari et al., 2011; Duclos et al., 2013). ADCPs use the 102 Doppler effect of sound scattered back from particles transported in suspension to measure 103 flow velocity. Holdaway et al. (1999) were amongst the first to demonstrate that this 104 backscatter signal could be also analyzed to extract information on SSC. Such acoustic 105 measurements have been used for example to study sedimentary processes in sandy systems 106 over short spatial and temporal scales such as tidal periods (Tessier et al., 2008). Acoustic 107 Suspended Sediment Monitor is another system adapted for fine-grained cohesive sediment 108

and concentration ranging between 0.5 and 8 g.l<sup>-1</sup> (Shi, 2010).

Estimating solid flux from acoustic measurements requires calibrating the sound 110 intensity scattered by particles in the flow with SSC. This is typically done by comparing the 111 backscatter signal to measured SSC from samples collected at various depths in the water 112 column and along a cross-section. Software for using this data to performing the calibration 113 (e.g., Sediview, Plum Detection Toolbox) provide good results as long as data from direct 114 measurements are available (Defendi et al., 2010). However, a limitation of this technique is 115 that the acoustic signal is grain-size dependent. In other words, for a given sediment 116 concentration, the relative backscatter sensitivity can be different whether the GSD is coarser 117 or finer, expressed in terms of relative percentages of clay, silt and sand (Guerrero et al., 118 2011). The implication of this, is that flux estimates based on these calibrations are only 119 accurate if the GSD remains constant over the range of flows that are monitored acoustically. 120

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### 3. Description of the study site and ADCP monitoring

The Rhone River basin has an area of approximately 97,800 km<sup>2</sup> and drains several 122 different mountain ranges including the Alps, the Jura, and the Cevennes. The mean annual 123 flow discharge at the downstream is approximately 1700 m<sup>3</sup>.s<sup>-1</sup>, based on daily discharge 124 records for the period 1920 - 2013 from the Beaucaire gauging station located 60 km 125 upstream of the mouth (data available at http://hydro.eaufrance.fr). The Rhone is 126 characterized by large inter-annual flow and sediment flux variability due to highly variable 127 rainfall patterns and lithology within the catchment (Eyrolle-Boyer et al., 2012). This natural 128 variability is enhanced by a series of hydroelectric dams (Provansal et al, 2014). 129

Approximately 50 km upstream of its mouth, the Rhone River separates into two branches – the Petit Rhone and the Grand Rhone (Figure 1a). The dominant branch (Grand Rhone) traverses the city of Arles and transports on average 90% of the flow (Boudet et al,

submitted). Annual floods in Arles have a discharge of approximately 3900 m<sup>3</sup>.s<sup>-1</sup>, and 2-yr 133 and 10-vr return period floods have discharges of 4800 and 7800 m<sup>3</sup>.s<sup>-1</sup> respectively (Boudet 134 et al., submitted). Whatever is the peak discharge, flood durations range from 1 to 34 days 135 with a mean of 5 days (Eyrolle et al., 2012; Boudet el al, submitted). About 90% percent of 136 the alluvial floor in our study area (see below) is covered by sand with a median grain size of 137 0.55-0.50 mm (Arnaud-Fassetta et al., 2003). This sand can be transported by suspension at 138 bankfull discharge (5400 m<sup>3</sup>.s<sup>-1</sup>) according to the Shields diagram (Arnaud-Fassetta et al., 139 2003). 140

In order to improve estimates of total SSF delivered by the Rhone River to the Mediterranean Sea, particularly by large and rapid floods, we equipped a passenger ferry, known as Barcarin, which traverses the Grand Rhone 13 km upstream from the mouth (Fig 1) with an ADCP in order to conduct continuous in-situ measurements.

The Barcarin ferry was equipped with an ADCP - RDI 600 kHz Workhorse Rio Grande 145 (Teledyne RD Instruments, 2007) set to operate with a 0.5 m vertical cell size. The ADCP was 146 mounted on the upstream side of the ferry and conducts measurements each time the ferry 147 crosses the river (Fig. 1b). The distance of the channel at this location is 350 m and it takes 148 the ferry approximately 3 minutes to traverse the full width (Fig. 1b). Approximately two 149 hundred crossings are made per day, resulting in an equivalent number of profiles acquired. 150 The ferry does not run between 2 AM and 4 AM and for discharges higher than 6000  $m^3.s^{-1}$ . 151 The start and end of each profile are automatically determined from GPS positions of the 152 boat, with an error estimated at  $\pm 5m$  due to the width of the docks (Fig. 1b). This error is quite 153 large, sometimes leading successive crossings to be recorded as a single profile; these can be 154 manually separated later on. ADCP data are automatically transferred via Wifi to a computer 155 located in a building near the dock and from there to the CEREGE laboratory. The ADCP is 156 cleaned every few months of biofilm accumulations. 157

Other than short interruptions for technical maintenance and/or improvements, the 158 ADCP has been operating continuously since March 2012. A main advantage of this setup is 159 that the equipment is in place and fully operational when a flood arrives. This eliminates the 160 need of hastily organizing a monitoring trip (equipment and personnel) when flow levels start 161 to rise and ensures that sediment flux is monitored over the full duration of the flood. In 162 addition, the ferry's location, 32 km downstream of the SORA station (Fig. 1), permits 163 comparison between SSF estimates based on the ADCP and those estimated from surface 164 measurements at the station. Finally, as opposed to measurements collected at a single fixed 165 location, the ferry-mounted ADCP collects backscatter data along the full cross-section, 166 167 making it possible to study how suspended sediment is distributed both vertically and horizontally. 168

## 169 3.1 Measurements of in-situ suspended sediment concentrations and grain size 170 distributions

The two annual events that we focus on in this paper occurred in 2012 on November 171 12th (hereafter referred to as the N-12 event) and on November 29th (N-29 event). These 172 events had a peak discharge of 4000 m<sup>3</sup>.s<sup>-1</sup> and 4200 m<sup>3</sup>.s<sup>-1</sup> respectively (Fig 2a). As was 173 previously mentioned, accurate estimation of SSCs from ADCP backscatter data requires a 174 GSD-based correction of the backscatter intensity with SSC calibration. In order to perform 175 this correction, we collected suspended sediment samples during the course of the two floods. 176 Figure 2a shows the hydrograph of these floods with black squares corresponding to the days 177 when in-situ samples were collected. The samples were collected from the ferry itself with a 178 5L horizontal (Niskin) sampling bottle. A multi-parameter probe (Diver CTD) was fixed to the 179 Niskin bottle in order to measure salinity, water temperature, and water depth for each sample. 180 Vertical samples were collected at three lateral locations: left and right banks and channel 181 center (Figure 2b) in order to characterize variations in sediment concentration. On each 182

location, six samples were collected between the surface of the flow and the channel bottom
(flow depths ranged from 7 to 10 m) with the exact depth of each sample recorded with the
probe.

Suspended sediment concentrations (SSC in mg.1<sup>-1</sup>) were determined using a standard 186 filtration method (ISSeP, 2014): 500 ml filtered through 0.45 µm filters and dried at 40 °C for 187 48 h. One liter of sampled water was set aside for measuring GSD and stored at 4°C until it 188 could be analyzed (typically within a few days). The GSD were measured with a Beckman 189 Coulter LS 13 320 laser granulometer, with a range of 0.04–2000 microns in 117 fractions 190 collected on 132 detectors. The calculation model uses Fraunhöfer and Mie theory, water as 191 192 the medium (RI = 1.33 at  $20^{\circ}$ C), a refractive index in the range of that of kaolinite for the solid phase (RI = 1.56), and absorption coefficients of 0.15 for the 780-nm laser wave length 193 and 0.2 for the polarized wavelengths. Ideally, a flow sample is poured all at once into the 1L 194 granulometer cup without the need for pre-treatment or sub-sampling. However, particle 195 concentrations during the floods were too high and exceeded the optimal obscuration 196 windows between 8 and 16% for diffraction and 50% and 70% for diffusion using the PIDS 197 technology (Polarization Intensity Differential Scattering). They were thus subsampled 198 through magnetic stirrer agitation before being injected into the granulometer. Six sub-199 200 samples from a single bottle were measured to define the repeatability of the sub-sampling. The two-sigma errors on the reproducibility were 1.5% on the mean and 0.2 % on the  $D_{50}$ 201 value. The validity of the analyses was also checked routinely using standard including G15 202 (D<sub>50</sub>=15µm), SRM1003C (D<sub>50</sub>=32µm) and SRM1004b (D<sub>50</sub>=78.4µm). The ratio between 203 measured and certified values was respectively -2, +2 and -8% for these standards. 204

### 205 3.2. Backscatter calibration

206 Several methods have been proposed to calibrate the backscatter signal of an ADCP in 207 order to assess sediment flux in fluvial and estuarine environments. While we mention them

here, a detailed explanation of these methods is beyond the scope of this paper. Tessier et al. 208 (2008) proposed a laboratory experiment calibration using optical backscatter sensor (OBS) 209 turbidity measurement. Other researchers have used a post-processing method developed in 210 Sediview (Land and Bray, 2000; Dredging Research Ltd., 2003; Cutroneo et al., 2012), which 211 is based on a simplified version of acoustic theory in order to correct dispersion and 212 attenuation of the acoustic backscatter signal (Defendi et al., 2010). In this study we used the 213 ViSea Plume Detection Toolbox (PDT) developed by Aqua Vision®. Like Sediview, this 214 software uses acoustic theories to correct for signal losses associated with acoustic spreading, 215 water absorption and particle attenuation (Francois & Garisson, 1982; Urick, 1983; Rijn, 216 1993). In the first phase of calibration, the default absorption coefficient of 0.181 dB.m<sup>-1</sup> for a 217 600 kHz ADCP frequency, which is estimated for a water temperature of 4°C and a salinity of 218 35 ppt, is corrected using field temperature and salinity measurements. Next, the absolute 219 backscatter signal is converted to SSC based on direct measurements of SSC in mg.1<sup>-1</sup>. The 220 relationship between Absolute Backscatter (I) and SSC is defined by (*Visea PDT Manual*): 221

222 
$$10 * \log(SSC) = 4.6 + 0.054 * I$$

Where SSC represent the Suspended Sediment Concentration (mg/l) and I the AbsoluteBackscatter Intensity.

Since absolute backscatter and therefore SSC depend on the degree of particle attenuation, the second step corrects for this by integrating the grain-size distribution. The ViSea PDT is not limited to only a single  $D_{50}$  value, offering the possibility of taking into account all size fractions ranging from sand (2000 µm) down to clay (0.24 µm). Finally, the software calculates a Total Suspended Sediment Flux (kg.s<sup>-1</sup>) based on the backscatter signal calibration.

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#### 232 **4. Results**

### 233 4.1. Flow velocity and discharge

The structure and evolution of flow velocities across the transect during the N-12 event are 234 shown in figure 3a (mean velocities are indicated in each plot). Figure 3b shows that mean 235 flow velocities (calculated for ADCP profile per day) measured at Barcarin are well correlated 236  $(R^2=0.97)$  with daily discharges measured upstream at the SORA station. The dataset spans a 237 large range of discharges during various days in 2012, for which the estimated mean 238 velocities varied between 0.18 and 1.4 m.s<sup>-1</sup>. Maximum mean flow velocity (1.4 m.s<sup>-1</sup>) 239 corresponded to the flood peaks of both the N-12 and N-29 events. During the flood peaks, 240 velocities were highest within the top 5 meters of the water column and decreased toward the 241 channel bottom and banks (Fig.3a). 242



### 44 4.2. Suspended sediment concentrations and grain-size distributions from direct sampling

Figure 4 shows the SSC measurements for the samples collected at different depths 246 and lateral positions within the channel. The different dates correspond to the black squares 247 shown in figure 2: 7 days and 6 days for the N-12 and N-29 events respectively. There was no 248 statistically significant difference in SSC with lateral position. The SSC was also uniform 249 with depth during low discharges and showed a slight increase with depth during the flood 250 peaks (right bank for the N-12 peak for example). The daily mean SSC (mean of all depths 251 and locations) ranged from a minimum of 40±4 mg.l<sup>-1</sup> on the 27<sup>th</sup> Nov to a maximum of 252  $2853\pm140$  mg.l<sup>-1</sup> on the 12th Nov, corresponding to the peak of the first flood. The mean SSC 253 was clearly lower for the second peak flood on the 29th Nov :  $1100\pm180$  mg.l<sup>-1</sup>. To compare, 254 SSC values in the Grand Rhone typically ranged from 8 to 20 mg.l<sup>-1</sup> during usual flow 255 conditions. 256

Figure 5 shows the distribution of clay, silt, and sand as % of total sample volume for 257 samples collected at 0.5 m from the surface in the center of the channel. The GSD during the 258 N-12 and N-29 floods were very similar and consisted of the following clay-silt-sand 259 percentages respectively based on an average of all samples: 15-81-4 and 15-83-2 (Fig. 5). 260 For both floods, the range of percentage of clay-sized particles was between 11 - 22 % and 261 increased with increasing flow discharge, reaching a maximum value of 22% at the peak of 262 each flood (Fig. 5). Silt-sized particles represented the majority of the suspended sediment 263 load (around 80 %) and the sand fraction never exceeded 10 % (Fig. 5). This last fraction 264 increased during the two days following the N-12 peak. 265

### 266 4.3. Backscatter signal calibration and GSD-based correction

Calibration of the backscatter signal using the ViSea PDT® with SSC and GSD resulted in linear regressions with R coefficients equal to 0.90 and 0.88 for the N-12 and N-29 floods respectively. We used these calibrations to estimate SSC from ADCP backscatter (using the Plum Detection Toolbox) and then used these values to calculate a total SSF in t.d<sup>-1</sup> for each sampling day.

Figure 6 illustrates the difference in SSC distributions estimated across the channel without 272 (Fig. 6a) and with (Fig. 6b) the correction for the GSD. This example corresponds to the N-12 273 event. When only measured SSC were considered in the calibration, the resulting estimate of 274 total SSF was 825 000 t.d<sup>-1</sup>. When the calibration was based on both SSC and GSD, this total 275 SSF increased to 925 000 t.d<sup>-1</sup> (Fig. 7). For the N-29 event, the total SSF increased from 276 390200 to 431000 t.d<sup>-1</sup> with the correction. This discrepancy in the estimates of SSF 277 highlights the role that fine particles play in attenuating the acoustic signal, inducing here a 278 mean underestimation of about 10 %. During normal discharges, the homogeneity of GSD 279 does not influence so much the estimation of the total SSF. 280

### 282 4.4. Estimated total suspended sediment flux

Once we had estimated SSC from the calibrated ADCP signal (using both measured 283 SSC and GSD) corresponding to each of the samples that were collected, we proceeded to 284 estimate a daily SSF (t.d<sup>-1</sup>) over the course of each flood event (Figures 7 and 8). For that, we 285 assumed that the concentrations estimated from the calibrated signals for one ADCP profile 286 were representative of the daily flux, and thus considered them to be uniform over a 24-h 287 period. We consider this a reasonable assumption since the variability of discharge within a 288 single day was low: the coefficient of variation for hourly discharge measured at SORA over 289 the span of a single day was between 1 and 9 %. The only exception was Nov. 27 when the 290 coefficient reached 22%. Furthermore, when we checked the backscatter profiles measured 291 one hour before and after the sampling, they were very similar to the profiles that were 292 calibrated. We thus assume that the maximum error associated with our daily SSF estimates is 293 ± 10-15 %. 294

Our estimates show that over the course of the N-12 flood, SSF increased from 69000 295 t.d<sup>-1</sup> during the two days prior to peak discharge to 925000 t.d<sup>-1</sup> at the flood peak (Fig. 7A-C) 296 then rapidly decreased to 123000 t.d<sup>-1</sup> and 6700 t.d<sup>-1</sup> for 2 and 7 days post-peak respectively 297 (fig 7 E-G). Maximum daily SSF corresponded to maximum discharge (Fig. 7H). A strong 298 vertical gradient in SSC can be seen on the 11<sup>th</sup> and 12<sup>th</sup> of November – immediately ahead of 299 and during the maximum discharge (Fig. 7 B-C). This maximum vertical gradient did not 300 coincide with the increase in the sand fraction shown in figure 4. SSC was approximately 301  $3000 \text{ mg.l}^{-1}$  near the channel bottom and decreased to  $2500 \text{ mg.l}^{-1}$  at 4 m below the surface. 302 SSC once again became uniform when discharge decreased, stabilizing at a value of 303 approximately 700 mg.1<sup>-1</sup> (Fig. 7E). As discharge decreased during the falling limb of the 304 hydrograph, SSC were high compared to similar discharges during the rising limb. This trend 305 is typical of leading hysteresis in sediment transport during floods and is generally associated 306

with resuspension of sediments from the bed (Horowitz 2008). Similar trends are observed for
the N-29 flood, although vertical gradients in SSC were limited to one day (Fig. 8C&F). As
mentioned earlier, total SSF was twice as high during the N-12 event as in the N-29 event
despite similar daily peak discharges (Fig. 2a).

311

### 312 5. Discussion

Estimates of SSC and SSF from ADCP measurements conducted over the course of two 313 flood events from the Barcarin ferry near the mouth of the Rhone River showed good 314 correlation with their respective flood hydrographs (Fig. 7H & Fig. 8F). Furthermore, the SSF 315 estimates are very similar to those obtained from the automated sampling station SORA 316 located 32 km upstream (Fig. 9). This comparison shows a strong linear relationship (y =317 0.6803x + 67067;  $R^2 = 0.6$ , n = 12; p > 0.05, not shown), a relation further improved (y = 318 0.8719x + 26252;  $R^2 = 0.9$ ; p>0,001) when we correct for the time-lag between the two 319 locations (approximately 10 h for a mean flow velocity =  $1 \text{ m.s}^{-1}$ ). This strong relationship is 320 likely due to the fact that the vertical gradient in SSC was weak for the two monitored floods 321 (fig 3), and confirms that surface samples at SORA are representative of SSC over the entire 322 vertical flow column for annual return floods, such as the two events monitored here. It 323 remains unknown how SSC is distributed vertically for larger floods, but our data indicate that 324 a suspended gradient may develop at higher discharges. This in agreement with Arnaud-325 Fassetta et al (2003) who shown that Shields diagram indicates that transport of sand can be 326 common (and in suspension) at bankfull discharge (5400  $\text{m}^3.\text{s}^{-1}$ , higher than our peak 327 discharges). 328

The two consecutive floods had very similar peak discharges and hydrograph shapes, but estimates of daily SSF were twice as high in the first event. This difference does not appear to be related to the relative contributions of different tributaries during each event.

Indeed, the major tributaries of the Rhone contributed in a similar manner to the total 332 discharge during both events as follows: 10-15% from the Durance, 15-20% from the Isere, 333 25-30% from the Saone and 40% from the Rhone upstream of Lyon (estimates are based on 334 daily discharges reported at http://hydro.eaufrance.fr). Therefore, the difference in SSC is 335 likely explained by a difference in the amount of material eroded in the tributary basins and 336 the channel banks, and/or a decrease of sediment available for resuspension from the riverbed 337 between the first and second flood. Zebracki et al (2015) have demonstrated the role of 338 remobilized sediment as a significant secondary source, based on a fingerprinting approach 339 using plutonium activity ratios associated with particles. 340

The estimated total solid flux transported during these two events (8 days in total) was 341 2.7  $10^6$  tons. This value represents 50 % of the annual SSF in 2012 (5.6  $10^6$  tons) estimated 342 from measurements at the SORA station (unpublished data, SORA station database). In 343 addition to the November floods, high discharges occurred in January and December 2012 344 (average daily discharges were between 2900 to 3800  $\text{m}^3.\text{s}^{-1}$  from January 2 – 10, and 3100 to 345  $3600 \text{ m}^3.\text{s}^{-1}$  from December 16 – 30.). The cumulative total SSF transported by these four 346 events represents 82 % of the annual suspended sediment flux, a typical value for the flux 347 transported by annual floods in the Rhone (Eyrolle et al, 2012). 348

A synthesis of SSF transported by the floods since 2005 based on data from SORA 349 station showed that fluxes are influenced by factors other than maximum discharge such as 350 location of precipitation in the catchment area and sometimes dam management (Eyrolle et al, 351 2012). The results of this study support these observations and highlight the role of sediment 352 available for resuspension in the riverbed, as well as the role of antecedent conditions (i.e. 353 flood succession). Continuous monitoring is therefore necessary to accurately quantify long-354 term trends and to estimate SSF contributions from individual events. In addition to informing 355 coastal management, this type of data is important to constrain the flux of various 356

hydrophobic pollutants including metals, PCBs and other organic contaminants (Ollivier etal., 2011).

359

### 360 Conclusion

a. In this study we used the Plum Detection Toolbox to calibrate suspended sediment
concentrations (SSC) from ADCP acoustic backscatter and used this to estimate suspended
sediment flux for two annual floods on the lower Rhone River.

b. The ADCP in this study was mounted on a ferryboat that traverses the dominant branch of
lower Rhone River (Grand Rhone) multiple times a day. This setup has enabled continuous
acquisition for more than 4 years up to now and ensures that the equipment is in place when a
flood arrives.

c. We showed that ADCP backscatter provides a viable method for estimating SSC during
floods when the signal is properly calibrated using SSC and Grain-Size Distribution (GSD)
data from measured samples. Our results show that vertical SSC distributed over the river
section is necessary to obtain a good calibration of the backscatter signal. When GSD was not
accounted for, Suspended Sediment Flux (SSF) was underestimated by 10% (Fig. 2b).

d. ADCP allows to understand the structure of the solid flow throughout the channel sectionand to better assess SSF, particularly during flood events.

e. Suspended sediment for the two floods investigated was dominated by silts and clays whichhave an effect on the acoustic signal in water.

f. Analysis of the sediment transported in suspension from samples collected at different
vertical depths showed uniform concentrations and GSD with depth. A vertical gradient was
visible only at peak discharge.

g. Estimates of SSF based on ADCP data were similar to those based on surface samples
collected at the automatic SORA station, located 32 km upstream. This similarity is linked to
the weak vertical gradient in SSC for the two floods.

h. The two flood events analyzed for this study, separated by only a few days, showed clear differences in suspended SSC and SSF, with twice more suspended sediment transported during the first event. We attributed this decrease to the amount of sediment available from hillslope and bank erosion or more probably from resuspension within the riverbed. These differences in fluxes for similar magnitude events highlight the difficulty in estimating sediment fluxes precisely in the absence of continuous measurements.

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### **CAPTIONS**

Figure 1. a). The Rhone River Delta highlighting the location of the Barcarin ferry crossing 530 on the Grand Rhone and the city of Arles where the SORA station is located. b) An aerial 531 photo of the Barcarin ferry landing. The white dotted line shows the average trajectory of the 532 ferry between the right and left banks of the Grand Rhone. The white dots mark the locations 533 where the ADCP measurements automatically start and stop. 534

535

Figure 2. a) Mean daily discharge  $(m^3 s^{-1})$  of the Rhone river for the month of November, 536 2012 highlighting the two annual events N-12 (12<sup>th</sup> Nov.) and N-29 (29<sup>th</sup> Nov) that were 537 monitored in this study. The black squares indicate the days on which the flow was sampled. 538 Discharge measurements were conducted at the SORA station in Arles (32km upstream) and 539

- provided by the CNR. b) a cross-sectional view of the channel showing in red the locations 540
- where samples were collected at different depths in the water column. 541

Figure 3. a) Distribution of flow velocities measured with the Barcarin ferry ADCP during 542 the N-12 flood. The date and mean current speed are indicated in each panel. b). Relationship 543 between mean Barcarin ADCP flow velocities and corresponding discharge measured at the 544 SORA station at Arles. 545

546

547 **Figure 4.** Suspended sediment concentrations  $(mg.1^{-1})$  with depth at the three sampling locations (left and right

banks and middle channel) for the N-12 (black) and N-29 (white) floods. The legend refers to the sampling date, 548 and the measurements associated with each flood peak are highlighted. 549

Figure 5. The relative grain-size fractions: clay, silt, and sand, for each of the suspended samples collected at 0.5 550 551 m from the surface of the flow throughout the two monitored floods. During the two flood events, there are no daily vertical variation of sediment grain size. 552

Figure 6. An example of SSC distribution along the cross section based on ADCP backscatter 553 calibrated (a) without accounting for GSD and (b) with GSD correction included. 554

Figure 7. A - G) Suspended sediment flux based on corrected ADCP measurements across the 555 river for the N-12 flood. The date and total flux (t.d<sup>-1</sup>) are indicated in each panel. H) Mean 556 daily discharge measured at Barcarin and mean daily suspended sediment flux estimated from 557

ADCP measurements for the N-12 flood. 558

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Figure 8. A - Z) Suspended sediment flux based on corrected ADCP measurements across the 562 river for the N-29 flood. The date and total flux (t.d<sup>-1</sup>) are indicated in each panel. H) Mean 563 daily discharge at Barcarin and mean daily suspended sediment flux estimated from ADCP 564 565 measurements for the N-29 flood.

566 Figure 9. Comparison of suspended sediment flux (tons/day) during the rising and falling limbs of the 2 monitored floods (N-12 and N-29) based on measurements from automated 567 surface samples at the SORA station in Arles and calibrated ADCP backscatter at the Barcarin 568 569 crossing.

















### b). Signal correction with grain size distribution







Figure 7.



