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Numerical modelling of the suspended particulate matter dynamics in a regulated river network

M. Launay^{a,b}, V. Dugué^{a,c}, J.-B. Faure^a, M. Coquery^a, B. Camenen^a, J. Le Coz^{a,1}

^aIrstea, UR RiverLy, 5 rue de la Doua CS 20244, 69625 Villeurbanne Cedex, France
 ^bNow at Stucky SA, Rue du Lac 33, 1020 Renens VD, Switzerland
 ^cNow at CNR, Compagnie Nationale du Rhône, 2 rue André Bonin, 69004 Lyon, France

Abstract

Understanding and predicting the propagation, deposition and re-suspension of suspended particulate matter (SPM) in river networks is important for managing water resources, ecological habitat, pollution, navigation, hydropower generation, reservoir sedimentation, etc. Observational data are scarce and costly, and there is little feedback on the efficiency of numerical simulation tools for compensating the lack of data on a river scale of several hundreds of kilometres. This paper aims at exploring the use of a one-dimensional (1-D) hydrodynamical model for understanding the source and fate of SPM during complex events. The numerical model was applied to the May-June 2008 flood in the Lower Rhône River, France. This event was a combination of floods of the Isère (including dam flushing operations in the Lower Isère River) and Durance tributaries over a two-week period. The simulation code was used to model the SPM fluxes at a high spatial and temporal resolution using a multi-class approach. Approximately half of the 4.9 Mt of SPM measured at the outlet at Beaucaire were found to come from the Isère River and the other half from the Durance River, whereas previous studies estimated that most of the SPM flux at the outlet came from the Durance River. The amount of SPM trapped within the river network, mainly behind the first hydropower structure downstream of the Isère confluence, was estimated to be 3.7 Mt due to the deposition of the coarsest

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^{*}Corresponding author

particles. Such a model proved to be able to compute the interaction of various grain size classes with dams and other structures. In turn, the quality of the results of SPM fluxes and deposition is highly sensitive to particle parameters, especially grain size distribution, and to the operational rules of reservoirs. *Keywords:* suspended sediment, suspended solids, 1-D hydrodynamical model, numerical simulation, Rhône River, flood

1 1. Introduction

Monitoring the suspended particulate matter (SPM) dynamics in river systems is crucial for multiple environmental management issues, such as the ecological restoration of aquatic habitats, the sustainable operation of reservoirs, or the management of particle-bound contaminant fluxes (*Walling et al.*, 2003). These questions are generally facing a lack of data available at the watershed scale and at time scales from flood events to several years (*Horowitz et al.*, 2015). The presence of dams significantly affects the SPM dynamics with large deposition in the reservoirs and possible resuspension during specific events when dam gates are opened. Sediment management in dam reservoirs and regulated rivers is indeed one important issue of the 21st century (*Kondolf et al.*, 2014).

The development of station networks measuring SPM and particulate con-12 taminants at large catchment scales remains limited due to the water sampling 13 constraints and the cost of analyses (Horowitz, 2008). Data on SPM concentra-14 tion (C_{SPM}) are mostly derived from discrete water sampling carried out as part 15 of water quality monitoring programs (Walling and Webb, 1985; Phillips et al., 16 1999; Horowitz et al., 2001). The frequency of these measurements, generally 17 performed with a fixed periodicity, is almost never high enough to measure the 18 fine temporal variations in $C_{\rm SPM}$, leading to large uncertainties in flux budget 19 estimation (Moatar et al., 2008). In recent decades, the development of surro-20 gate techniques (Gray and Gartner, 2010) such as Optical Backscatter Systems 21 (OBS, also known as turbidity meters) has allowed the continuous measurement 22 of the SPM concentration, provided that sufficient calibration data are available 23

(Foster et al., 1992; Gippel, 1995; Clifford et al., 1995; Thollet et al., 2013; Dru-24 ine et al., 2018). Hydro-sedimentary stations based on water sampling and/or 25 turbidity measurements at one point of the cross-section rely on the assumption 26 of homogeneous SPM concentration (*Horowitz*, 2008). Nevertheless, the direct 27 measurement of $C_{\rm SPM}$ at the river basin scale remains very expensive, time con-28 suming and in many instances problematic, especially in inaccessible sections 29 and during floods (Ulke et al., 2017). Most of the time, field data are available 30 only for a particular event or over a limited period of time (Mano et al., 2008; 31 Navratil et al., 2012). 32

Together with the deployment of denser measuring networks, hydro-sedimen-33 tary modelling allows the development of operational tools to improve the knowl-34 edge of the fate of suspended sediment in the river network (Wu et al., 2004). 35 Moreover, it allows testing alternative management scenarios and several hy-36 potheses on the water and SPM inputs. The use of numerical hydro-sedimentary 37 models has increased considerably in the last decades in conjunction with the 38 advances in computational techniques. One-dimensional (1-D) codes are admit-39 ted to be suitable for simulation over large temporal and spatial scales as they 40 require less field data and computational resources than 2-D and 3-D codes do. 41 The limited ability of 1-D codes to reproduce fine physical processes is compen-42 sated by the stability of their numerical schemes and their fast calculation speed 43 (Papanicolaou et al., 2008; El Kadi Abderrezzak and Paquier, 2009). Numerous 44 1-D codes have been developed and are frequently used for engineering pur-45 poses. Amongst others, Wu et al. (2004) and Papanicolaou et al. (2008) listed 46 several 1-D codes and their applications to rivers and dam reservoirs. These 47 codes can be classified according to their range of application or their formu-48 lations: steady/unsteady flow, fully coupled/semi-coupled/decoupled flow and 49 suspended sediment modelling, uniform/non-uniform grain size, equilibrium/non-50 equilibrium suspended sediment transport model. 1-D modelling is particularly 51 suitable for calculating SPM dynamics since SPM concentrations are generally 52 assumed to be homogeneously distributed throughout a river cross-section and 53 modelling transverse mixing is not necessary (Garneau et al., 2015). Modelling 54

a flood event at the river basin scale requires i) calibrating the hydraulic and
suspended sediment transport parameters, ii) specifying the water and SPM
inputs (upstream boundary conditions) and iii) validating the results along the
river system, including at the outlet.

The objective of this paper is to explore the use of a 1-D numerical model 59 to better understand the spatial and temporal dynamics of SPM during floods 60 throughout complex river networks. In particular, we test the application of 61 a 1-D numerical model in simulating the SPM dynamics in a river regulated 62 by a series of run-of-the-river dams and other infrastructure. There is indeed 63 very limited feedback in the literature on the following questions. What kind of 64 results is a 1-D model able to provide and what is the added value compared to 65 observational data? What are the most sensitive parameters, hence the main 66 sources of error? What are the most restrictive assumptions and the main 67 perspectives for improvement? 68

The first part of the paper describes the May-June 2008 flood event in the 69 Lower Rhône River. This hydro-sedimentary event was selected for testing the 70 model as it was a typical combination of floods and dam flushing operations and 71 it comes with a complete set of high temporal resolution measurements on the 72 main tributaries and at the outlet. The second part of the paper presents the 73 hydro-sedimentary numerical tools and the Rhône 1-D model used to simulate 74 the May-June 2008 event. The Rhône 1-D model was developed as part of the 75 Rhône Sediment Observatory (OSR) to become an efficient tool for managing 76 SPM at the scale of the river basin. The third part details the results of the 77 modelling and highlights the impacts of grain size distribution and hydropower 78 structures on the simulated SPM concentrations and deposits. The main lessons 79 learnt from the modelling exercise are briefly discussed and summarised in con-80 clusive comments. 81

⁸² 2. Case study

83 2.1. The Rhône River

The Rhône River flows 810 km from its source in the Swiss Alps to its out-84 let to the Mediterranean Sea in the South of France (Fig. 1). It is the largest 85 single source of freshwater to the Mediterranean Sea (Ludwig et al., 2009). Its 86 hydrological regime is influenced by snow melting in headwater catchments, 87 and by oceanic and Mediterranean rain events (*Pardé*, 1925). The three tribu-88 taries with the largest mean discharges are the Saône, Isère and Durance Rivers 89 (Tab. 1). The Rhône River basin is characterized by a large geological and 90 climatic heterogeneity, and by a dense network of hydropower schemes. From 91 Lake Geneva to the Mediterranean Sea, the Rhône River is equipped with 21 92 hydropower schemes, all of which are run-of-the-river schemes except Génissiat 93 Dam in the Upper French Rhône River (Fig. 1). 94

The Bourg-lès-Valence scheme detailed in Fig. 1 is typical of the other run-of-95 the-river, by-passing hydropower plants (cf. Camenen et al. (2019) for a detailed 96 description and analysis of sand fluxes). The Roche-de-Glun dam controls the 97 discharge distribution between the Old Rhône and the power canal containing 98 the Bourg-lès-Valence hydropower plant. A minimum compensation discharge 99 is maintained in the Old Rhône at any time. During floods, when discharge 100 exceeds the canal capacity, the excess flow is released in the Old Rhône. The 101 particularity of this scheme lies in the confluence between the Isère River and 102 the canal. In case of flood of the Isère River, the so-called Isère dam located 103 between the headrace canal and the Old Rhône (cf. Fig. 1) can derive the excess 104 discharge into the Old Rhône. 105

The Rhône River delivers substantial amounts of SPM to the Mediterranean Sea (*Radakovitch et al.*, 2008; *Launay*, 2014) with a mean inter-annual SPM flux varying between 4.7 and 7.4 Mt/yr (*Pont et al.*, 2002; *Eyrolle et al.*, 2012; *Ollivier et al.*, 2010; *Launay*, 2014; *Copard et al.*, 2018; *Poulier et al.*, 2019) but with huge variations of the annual SPM flux from one year to another. For example, annual SPM flux ranged from 1.2 to 22.7 Mt/yr between 1992 and



Figure 1: River network and hydroelectric schemes of the Rhône River from Lake Geneva to the Mediterranean Sea with a close-up view of the Bourg-lès-Valence hydroelectric scheme at the Rhône-Isère confluence. Monitoring stations of the May-June 2008 flood event in the Rhône, Arc, Isère and Durance Rivers are displayed.

1995 (Pont, 1997). Based on the long-term monitoring of $C_{\rm SPM}$ at Arles near 112 the delta of the Rhône River, Eyrolle et al. (2012) showed that singular events 113 (flood or dam flushing) can represent up to 95 % of the annual SPM budget. The 114 need for a better monitoring of SPM fluxes through the Rhône River motivated 115 the creation of the Rhône Sediment Observatory (OSR) in 2009. As part of the 116 OSR, an SPM monitoring network in the Rhône River and its tributaries from 117 Lake Geneva to the Mediterranean Sea was developed mostly based on turbidity 118 measurements calibrated with frequent SPM samples. 119

	A	Q_a	F_a	$Q_{max,2003}$	$Q_{max,2008}$	$C_{max,2008}$
Station	$[\mathrm{km}^2]$	$[\mathrm{m}^3/\mathrm{s}]$	[Mt/yr]	$[m^3/s]$	$[m^3/s]$	[g/L]
Rhône at Lyon	20 300	600	0.6	813	1 206	-
Saône at Lyon	29 908	475	0.4	$1 \ 262$	568	-
Isère at Beaumont	11 890	333	2.3	$1 \ 513$	1 458	25.2
Durance at Bonpas	$14\ 225$	190	1.7	1 496	1 495	11.1
Rhône at Beaucaire	95590	1 690	4.7 - 6.7	11 500	$5\ 126$	5.0

Table 1: General information on the catchments and hydrological regimes of the Rhône River and its main tributaries.

A = catchment area, $Q_a =$ mean annual discharge, $F_a =$ mean annual SPM flux according to Launay (2014), $Q_{max,2003}$ and $Q_{max,2008} =$ maximum discharges for the events of December 2003 and May-June 2008, $C_{max,2008} =$ maximum C_{SPM} for the May-June 2008 flood event.

According to Launay (2014) and Poulier et al. (2019), the main four tribu-120 taries in terms of SPM contribution to the Rhône River are the Arve River, the 121 Saône River, the Isère River and the Durance River (Fig. 1 and Tab. 1). The 122 SPM output of Lake Geneva is assumed to be negligible due to the large trap-123 ping capacity of the lake. The Isère and Durance Rivers are left bank alpine 124 tributaries of the Rhône River with fast and violent floods. The main SPM 125 contributor of the Isère River is the Arc River, a mountainous river producing 126 fine SPM (Camenen et al., 2016). The six Lower Isère dams located between 127 Grenoble and the Rhône confluence near Valence (Fig. 1) are run-of-the-river 128 dams. Only the lowest Isère dam, Beaumont-Monteux, by-passes the Isère River 129 with a derivation canal. 130

131 2.2. The 2008 hydro-sedimentary flood event

In May-June 2008, a major hydro-sedimentary event occurred in the Lower Rhône River, combining natural floods in its two main tributaries, the Isère

and Durance Rivers, and flushing operations of the Lower Isère dams. All the 134 reservoirs of the Lower Isère and the Lower Rhône are run-of-river dams with 135 very limited storage capacity. They can be partially drained and sediment 136 flushing operations must meet precise regulation requirements. Isère dams can 137 be flushed during flood falling phases in order to evacuate excess deposited 138 sediment. Rhône dams are not expected to be flushed but their operation can 139 be adapted to avoid deposition in critical areas such as around navigation locks 140 or dam gates. This could not be done during the 2008 event presented here due 141 to a lack of understanding and forecasting of the hydro-sedimentary processes, 142 and a lack of real-time coordination between the two distinct companies that 143 operate the Isère dams and the Rhône dams, respectively. 144

The peak discharge recorded at the Beaucaire station during this event was 145 5 125 m³/s, corresponding to a 2-year return period flood. Between May 26th 146 and June 8th 2008, the Arles station recorded a total SPM flux of 4.2 Mt at the 147 Rhône outlet (Eyrolle et al., 2012), equivalent to the SPM output of the 100-year 148 flood in 2003 which had a twice larger peak discharge (Tab. 1). The May-June 149 2008 flood event in the Lower Rhône River was also remarkable because it 150 produced an SPM flux almost equal to the mean annual SPM export of the 151 Rhône River to the Mediterranean Sea recorded since 2005 (Launay, 2014). 152

During the 2008 flood event, SPM concentrations were measured at the 153 monitoring stations presented in Fig. 1, either continuously using OBS or the 154 acoustic attenuation method presented by *Moore et al.* (2012), or by sampling-155 filtration method (AFNOR, 2005). All the SPM samples were taken near the 156 free-surface using buckets or automatic samplers. They include the homoge-157 neously distributed suspension ("washload"), not the graded sand suspension. 158 Well mixed cross-sections were chosen for the monitoring of $C_{\rm SPM}$ except for 159 the Rhône station at Valence Bridge, where the Isère and Rhône waters were 160 not fully mixed. Available SPM data cover the Arc-Isère-Rhône river network, 161 the Rhône-Isère confluence with numerous samples, the Durance River network, 162 and some stations along the Rhône River. 163

164

Fig. 2 presents the water discharge times series and $C_{\rm SPM}$ data collected

during the event at the outlet of the Arc, Isère and Durance Rivers, and at four 165 stations of the Rhône River. The Rhône at Ternay station is located upstream of 166 the Isère confluence and monitors the discharge and SPM inputs from the Upper 167 Rhône River. The Rhône at Viviers station provides an intermediate checkpoint 168 to study the Isère River input independently from the Durance input. This is 169 the first monitoring station downstream of the Isère confluence with a complete 170 $C_{\rm SPM}$ time series for the May-June 2008 flood event, while the Rhône at Valence 171 station recorded C_{SPM} only during the third period of the event. The Beaucaire 172 station located near the outlet of the Rhône River gives indication on the SPM 173 fluxes delivered to the Mediterranean Sea. The Beaucaire station is the last 174 discharge monitoring station for the Rhône River before the separation of the 175 two branches of the Rhône Delta. The measurement of C_{SPM} is performed at 176 the Arles station located about 13 km downstream on the Grand Rhône branch. 177 The SPM concentrations are considered to be the same at Beaucaire and Arles 178 for the SPM flux calculation. 179

The measured SPM fluxes were determined by multiplying the instantaneous water discharges and the instantaneous C_{SPM} . For monitoring stations with occasional C_{SPM} measurements (samples), the SPM fluxes were estimated by establishing a power relation between discharge and C_{SPM} to reconstruct a continuous C_{SPM} time series.

The event can be divided into three SPM-producing periods (Fig. 2). The 185 first period covers the dam flushing of the Saint-Egrève dam occurring between 186 26/05/2008 and 29/05/2008 in the Isère River. This dam flushing was trig-187 gered concomitantly with a 1-year return period flood of the Isère River, with 188 discharges up to 1 000 m³/s at the Beaumont-Monteux station. During this pe-189 riod, the Lower Isère dams were operated with high water levels in the reservoirs, 190 and the water overflowing the gates. Meanwhile, a substantial flood occurred 191 in the Durance River, with $C_{\rm SPM}$ greater than 10 g/L on the 27/05/2008. The 192 management of the hydropower schemes of the Durance River during this pe-193 riod led to mitigate the discharge (around $800 \text{ m}^3/\text{s}$) while releasing a large 194 amount of SPM. To account for the flood wave time lag between the upstream 195

part of the catchment and its downstream part, the ending date of the first 196 period was postponed to the 30/05/2008 for the downstream part. During the 197 second period, from 29/05/2008 to 02/06/2008, a large flood of the Arc River 198 was recorded with C_{SPM} greater than 30 g/L, causing a C_{SPM} peak greater 199 than 20 g/L in the Isère at Beaumont-Monteux on the 30/05/2008. This peak 200 propagated in the Rhône River and about 8 g/L were recorded at Viviers on 201 the 31/05/2008. During this period, the Lower Isère dams were not flushed, 202 but the bottom gates were opened. The second period runs from 30/05/2008203 to 03/06/2008 to account for flood propagation delay. During this period, a 204 major flood occurred in the Durance River with discharge up to 1 500 m³/s and 205 C_{SPM} up to 6 g/L. The third period lasted from 02/06/2008 to 10/06/2008, for 206 which the Lower Isère dams were flushed, with low water level in the reservoirs 207 to evacuate the deposited sediments. The cloud of SPM was recorded around 208 04/06/2008 in the Isère at Beaumont-Monteux with maximum $C_{\rm SPM}$ around 209 20 g/L. It was recorded in the Rhône at Viviers with a propagation delay of one 210 day and the peak C_{SPM} was about 2 g/L. 211



Figure 2: Discharges and SPM concentration ($C_{\rm SPM}$) in (a) the Arc and Isère Rivers, (b) the Durance River and (c) the Rhône River during the May-June 2008 flood event. The limits of the three periods are shown with vertical dashed lines: on the 29/05/2008 and 02/06/2008 for the Isère River, on the 30/05/2008 and 03/06/2008 for the Durance River and the Lower Rhône River. Monitoring stations indicated in bold are the upstream boundary conditions of the model.

212 2.3. SPM inputs from the Isère River

A C_{SPM} time series was reconstructed at the outlet of the Isère River since 213 a continuous $C_{\rm SPM}$ time series was not available at the Isère at Beaumont-214 Monteux for the entire event (Fig. 3). The measurements used for the re-215 construction were taken at Tullins (turbidimeter, Rieux, 2008), Romans-sur-216 Isère (side-looking hydroacoustic profiler, Moore et al., 2012), Beaumont-Mon-217 teux (manual water samples, *Rieux*, 2008) and the Rhône at Viviers. Between 218 26/05/08 and 30/05/08, the reconstructed $C_{\rm SPM}$ time series followed the mea-219 surements at Romans-sur-Isère, the closest station upstream of Beaumont-Mon-220 teux, with an estimated time lag of 1 h. Time lag between stations was cal-221 culated based on C_{SPM} peaks. Similarly, between 01/06/08 and 02/06/08, the 222 reconstructed C_{SPM} time series followed the measurements at Tullins with an 223 estimated time lag of 10 h. However data based on Tullins station may be un-224 derestimated if erosion occurs in the Lower Isère reservoirs. Between 30/05/08225 and 01/06/08, those reservoirs were flushed; as no representative measurements 226 were available, the SPM concentration at Beaumont-Monteux was evaluated as 227 the SPM flux in the Rhône at Viviers divided by the water discharge of the Isère 228 at Beaumont-Monteux. The rationale behind this computation is that during 229 that period the SPM flux coming from the Rhône upstream of the Isère junction 230 was negligible with respect to the SPM flux coming from the Isère. This ap-231 proximation is reasonable as discharges and SPM concentrations remained very 232 low in the Rhône upstream of the Isère junction during that period of time. 233 Finally, from 03/06/2008 on, SPM concentrations were measured at Beaumont-234 Monteux. 235



Figure 3: Reconstruction of the SPM concentration (C_{SPM}) time series of the Isère River at Beaumont-Monteux station from SPM measurements at Tullins and Romans-sur-Isère stations from 26/05/2008 to 12/06/2008.

²³⁶ 3. 1-D modelling of the May-June 2008 flood event

237 3.1. Numerical codes

The 1-D hydro-sedimentary numerical tool used in this study was developed by Irstea. It couples the Mage and AdisTS hydro-sedimentary numerical codes. Mage (*Souhar and Faure*, 2009) is a 1-D hydrodynamic code which simulates transient open-channel flows by solving the 1-D Barré de Saint-Venant equations (shallow water equations):

$$\frac{\partial A_w}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat} \tag{1}$$

243

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\beta \frac{Q^2}{A_w} \right) + g A_w \frac{\partial z}{\partial x} = -g S (J + J_s) + k q_{lat} V \tag{2}$$

where A_w is the wetted area, Q the water discharge, t the time, x the lon-244 gitudinal coordinate, q_{lat} a lateral input/output discharge, β the momentum 245 coefficient, z the water surface elevation, J the energy slope computed using 246 the Manning-Strickler equation, J_s the local energy losses due to sharp varia-247 tion of the cross-section, k a coefficient depending on the sign of q_{lat} (k = 1 if 248 $q_{lat} < 0, \, k = 0$ if $q_{lat} \geq 0$), and $V = Q/A_w$ the cross-section-averaged velocity. 249 Mage describes the real geometry of the river bed as a series of cross-sections, 250 and accounts for compound channel effects using the Debord equations (Nicollet 251

and Uan, 1979). Storage nodes can be defined to model floodplain areas where the water velocity may be assumed to be negligible. No storage nodes were used in the presented simulations. The river network topology may be looped (bifurcations, confluences), with multiple downstream boundary conditions. The 1-D Barré de Saint-Venant equations are solved using a four point semi-implicit finite-difference scheme (Preissmann scheme).

AdisTS (*Guertault et al.*, 2016) is a 1-D code solving mass conservation equations for SPM transport in parallel. The code includes advection-dispersion equations in conservative formulation (Eq. 3) for several SPM classes. SPM grain size distribution (GSD) is reproduced by mixing a fixed number of classes of different proportion. The equations are coupled using source terms that allow modelling erosion and deposition terms:

$$\frac{\partial A_w C_i}{\partial t} + \frac{\partial Q C_i}{\partial x} - \frac{\partial}{\partial x} \left(D_f A_w \frac{\partial C_i}{\partial x} \right) = (E_i - D_i) W_z \tag{3}$$

where C_i is the concentration in SPM class i, E_i and D_i are erosion and deposition fluxes of SPM class i, D_f is the longitudinal diffusion coefficient, and W_z is the river width. The source term combines the *Partheniades* (1965) formula for erosion and the *Krone* (1962) formula for deposition:

$$E_i - D_i = a_{\text{PD},i} (C_{\text{eq},i} - C_i) w_{s,i} \tag{4}$$

where $C_{\text{eq},i}$ is the equilibrium concentration for the SPM class *i*, $a_{\text{PD},i}$ is a recovery coefficient, reflecting non equilibrium sediment transport (*Han*, 1980; *Armanini and Di Silvio*, 1988), and $w_{s,i}$ is the settling velocity of the SPM class *i*. The equilibrium concentration depends on the effective bed shear stress, τ_{eff} as:

$$C_{\text{eq},i} = \begin{cases} C_{0,i} \left(\frac{\tau_{\text{eff}}}{\tau_{\text{cr},i}} - 1 \right) & \text{if } \frac{\tau_{\text{eff}}}{\tau_{\text{cr},i}} > 1 \\ 0 & \text{otherwise} \end{cases}$$
(5)

where $C_{0,i}$ is a calibration concentration specific to SPM class i, $\tau_{cr,i}$ is the critical shear stress for initiation of movement of SPM class i, estimated using the Shields diagram. For fine sediments ($d < 70 \ \mu$ m), since consolidation can be neglected when simulation is performed at event scale, the critical bed shear

stress is assumed independent of the grain size for fine sediments ($\tau_{\rm cr} = 0.15 \, {\rm Pa}$). 277 The effective bed shear stress is computed as $\tau_{\text{eff}} = (K_S/K'_S)\tau$, with K_S the 278 total Strickler coefficient, $K'_S = 24/d_{90}^{1/6}$ the skin-friction Strickler coefficient. 279 The total bed shear stress $\tau = \rho g R_h J$ is computed using the 1-D hydraulic 280 model (ρ water density and R_h hydraulic radius). The calibration of the two 281 AdisTS parameters, $a_{PD,i}$ and $C_{0,i}$, was performed as functions of the grain size 282 by Guertault et al. (2016) on Génissiat hydropower scheme in the Rhône River. 283 The longitudinal diffusion coefficient D_f was calculated using the formula of 284 Iwasa and Aya (1991) as Launay et al. (2015) concluded it was the best suited 28 based on their analysis of tracing experiments and hydro-acoustic measurements 286 in the Rhône River near Lyon. 287

AdisTS is loosely coupled with Mage software. The bed geometry remains 288 fixed over time but the model simulates a potential stock of sediments available 289 over each channel (main channel and floodway) in each cross-section. This stock 290 is spatially distributed using a mean thickness and assuming a constant porosity 291 p = 0.45; it can vary in mass and GSD over time due to erosion and deposition. 292 Indeed, the advection-dispersion equation is solved for each sediment class and 293 the GSD of bed sediment stocks depend on the erosion or deposition simulated 294 along the system for each class independently. It is possible to specify initial 20 sediment stocks along the river system but for the presented simulations no ini-296 tial stock was assumed. Over long timescales, there may be geometric feedbacks 297 that change channel capacity when erosion and sedimentation do not balance. 298 However, the fixed-bed assumption has limited consequences over the timescale 299 of an individual event. It allows a faster calculation which is of particular inter-300 est when dealing with long river reaches and long-term scenarios with limited 301 bed evolution. 302

The 1-D numerical tool can be used to identify the origin of the water flowing at a downstream monitoring station. This identification is done by injecting a numerical tracer in each tributary j with concentration $C_{j,\text{ref}} = 1$ g/L. At a downstream monitoring station where the total water discharge Q is calculated, the proportion of water Q_j/Q coming from the tributary j can be determined

based on the tracer mass continuity equation: $Q_j/Q = C_j/C_{j,\text{ref}}$, where C_j is the concentration of tracer coming from the tributary j calculated at the station. Similarly, each SPM class i from each tributary j can be traced so that concentration $C_{\text{SPM},i,j}$ is computed at each node and at each time of the simulation.

313 3.2. 1-D model of the Rhône River

The Rhône 1-D model, developed by Irstea as part of the OSR program, rep-314 resents the Rhône River from Lake Geneva to the Mediterranean Sea (Fig. 1). 315 Bathymetry surveys of the river cross-sections are available every 500 m stream-316 wise. Lidar data were used to complete some profiles in the main channel and 317 to estimate the extent of the floodway. Additional profiles were included to rep-318 resent dams and hydroelectric plants. In the model, cross-sectional profiles were 319 interpolated every 100 m. Cross-sections of the major tributaries (Arve, Ain, 320 Saône, Isère and Durance Rivers) were also included to represent their lowest 321 sections up to their confluences with the Rhône River. Other tributaries are 322 only represented as local inputs. 323

Flow resistance coefficients of the main channel (30 $\leq K_S \leq 42 \text{ m}^{1/3}/\text{s}$) 324 were calibrated and validated over each reach using longitudinal water profiles 325 measured over a wide range of discharges from low water to flood conditions 326 $(1500 \leq Q \leq 4500 \text{ m}^3/\text{s})$. It was not necessary to vary the flow resistance 321 coefficients with discharge to achieve an acceptable calibration, i.e. stage errors 328 lower than 0.1 m, typically. Flow resistance coefficients of the floodways (over 329 bars, islands, etc.) were assumed to be equal to 20 $m^{1/3}/s$ everywhere. The 330 floodways of the Rhône River are narrow due to the presence of dykes and 331 overbank flows are limited. Therefore, the results are not much sensitive to the 332 values of the flow resistance coefficient defined for the floodways. The model 333 does not include floodplains and cannot be used to simulate flooding over dikes. 334 The model includes the operation rules of the 21 run-of-the-river hydropower 335 schemes (Dugué et al., 2015). All the Rhône dams included in the model have 336 a bypass channel (remember that no Isère dams are included in the computa-337

tional domain). The operation rules of the run-of-the-river hydropower schemes 338 impose a minimum compensation discharge in the bypassed channel and a max-339 imum discharge in the power canal as allowed by the hydropower plant (Duqué 340 et al., 2015). Also, the maximum water level at a regulation point in each reser-341 voir is prescribed through legal dam operation rules which the operator has to 342 follow, especially during floods, whatever the initial storage is. Such run-of-343 river dams actually have a limited storage capacity and the water level in the 344 reservoir can be regulated by opening the dam gates, typically. The legal dam 345 operation rules are specific to each dam and relate the maximum allowed water 346 level as a function of inflow, usually. 347

For the specific study of the May-June 2008 flood event, the 1-D numerical 348 model was restricted to the Lower Rhône River, starting from Ternay station. 349 Eleven hydropower schemes are present in the study area. In this configuration, 350 the model has three main upstream boundary conditions: the Rhône at Ternay, 351 the Isère at Beaumont-Monteux (i.e. just downstream of the last dam of the 352 Lower-Isère chain of dams) and the Durance at Bonpas (see Fig. 1). The smaller 353 tributaries located between Ternay and the Mediterranean Sea are considered 354 as local water inputs. Both discharge and $C_{\rm SPM}$ time series for the three main 355 upstream boundaries are indicated as thick lines in Fig. 2. The discharge of the 356 smaller tributaries were also simulated. The downstream boundary conditions 357 on the Rhône Delta are the water levels measured in the Grand Rhône branch 358 and in the Petit Rhône branch (cf. Fig. 1). 359

Upstream of the Isère confluence, the SPM concentration in the Rhône River 360 at Ternay was lower than 0.2 g/L typically (cf. Fig. 2c), which is much lower 361 than the SPM concentration of the Isère and Durance tributaries during the 362 flood event. As the discharge time series at Ternay does not indicate any flood, 363 the SPM input at Ternay was set to zero for the simulations. The $C_{\rm SPM}$ time 364 series used as input for the Isère River at Beaumont-Monteux was reconstructed 365 as discussed in section 2.3. For the Durance River, SPM time series was recorded 366 at Bonpas turbidity station (Fig. 2b). SPM inputs from smaller tributaries were 367 considered to be negligible during the May-June 2008 flood event compared to 368

³⁶⁹ the inputs of the Isère and Durance Rivers.

370 3.3. Grain size distributions

The 1-D numerical model requires information on the grain size distribution (GSD) of the SPM. Numerical simulations on the Rhône River were performed using six SPM classes with variable grain sizes from clay to medium sand, and assuming grain size distribution of each class to be log-normal of parameters $d_{50,i}$ and σ_i (see Tab 2). $d_{50,i}$ and σ_i are assumed constant in time; only the relative proportion of the class *i* (in the total SPM concentrations and stocks) may vary in time.

The three classes with the finest SPM were determined based on grain size 378 analysis of Rhône SPM samples (Launay, 2014) and the three classes with the 379 coarsest SPM were defined by *Guertault* (2015). These classes were defined 380 so as to best represent main groups of particles that systematically show up 381 in the measured grain size distributions. Eventually, only the first four finest 382 classes will be used for this study, the two coarsest sand classes being easily 383 trapped by dam reservoirs (*Camenen et al.*, 2019). The representative settling 384 velocity $w_{s,i}$ for each class of sediment *i* was calculated using *Camenen* (2007) 38 formula and assuming the grain size distribution of each class to be log-normal 386 (cf. Tab. 2). Cohesion is neglected since organic content is very low (< 5%, 387 typically) as well as cohesiveness (Legout et al., 2018). The impact on settling 388 velocity (flocculation) is thus relatively low, and there is actually no possible 389 validation of any flocculation model for this specific case. 390

No GSD was measured in the Isère or Durance Rivers during the May-June 391 2008 flood event. Grain size analysis of the SPM of the Isère River in 2008 and 392 during a similar hydrological event in 2015 showed that the particles of the Isère 393 River and the SPM collected in the Rhône River during the 2012 dam flushes 394 have similar grain size distributions. Therefore, the parameters calibrated by 39 Guertault et al. (2016) were kept to simulate the 2008 flood event. The same 396 assumption was made on Durance SPM although no grain size analysis was 397 performed on SPM samples of the Durance River. 398

Table 2: Physical properties of the elementary SPM classes and AdisTS coefficients $a_{PD,i}$ and $C_{0,i}$, as proposed by *Guertault* (2015). Proportions of the SPM classes in the three SPM mixtures tested with the numerical model for the Isère input.

Name	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Median diameter: $d_{50,i}$ (µm)	4	15	45	90	200	400
Standard deviation of $\ln(d_i)$: σ_i (-)	0.32	0.24	0.17	0.17	0.20	0.20
Settling velocity: $w_{s,i}$ (m/s)	$2.8 10^{-5}$	$2.3 \ 10^{-4}$	$1.4 10^{-3}$	$7.5 10^{-3}$	$2.6 \ 10^{-2}$	$5.8 \ 10^{-2}$
Critical shear stress: $\tau_{\mathrm{cr},i}$ (Pa)	0.153	0.154	0.155	0.158	0.174	0.232
Recovery coefficient: $a_{\text{PD},i}$	1	1	1	1	1	1
Calibration concentration: $C_{0,i}$ (g/L)	1	1	0.5	0.2	0.2	0.2
% in Mixture A - Fine	31	44	25	0	0	0
% in Mixture B - Medium	23	28	31	18	0	0
% in Mixture C - Coarse	12	18	40	30	0	0

Samples collected in other occasions in the Arc-Isère network were used to determine three possible GSD for the SPM transported by the Isère River in May-June 2008, named Mixtures A, B and C (see Fig. 4 and Tab. 2). The measured GSD were approximated using a mixture of log-normal distributions, as explained by *Masson et al.* (2018).

Two surface water samples were collected during floods of the Arc River 404 (June 2015, documented by Camenen et al. (2016)) and the Isère River (May 405 2015). The Arc River is the main natural SPM input to the Isère River. The 406 SPM usually transported by the Arc River represent the finest SPM transported 407 during a flood in the Arc-Isère river network (classes 1 and 2 composed of clay 408 and fine silt). They were averaged to give Mixture A - Fine GSD (Fig. 4). 409 Two samples of riverbed sediment were collected in the Rhône River after the 410 May-June 2008 flood event. One sample was collected downstream of the Bourg-411 lès-Valence (BLV) plant (06/08/2008), and the other sample was collected in 412 the garage of the BLV lock (23/06/2008). Additionally, one sample was taken 413 after the flood of May 2015 from a deposit near the right bank of the Isère 414 River downstream of Beaumont-Monteux. Bank deposit and riverbed sediment 415

samples correspond to the coarsest SPM transported during a flood. They were
averaged to compose Mixture C - Coarse GSD, which is considered as an extreme
scenario for which most of the SPM would be made of that coarsest fraction.
Finally, one sample taken in the water column close to the bottom at the Rhône
and Isère confluence during the May 2015 flood contained particles from clay to
coarse silt in equal proportions. This intermediate sample constitutes Mixture
B - Medium GSD.



Figure 4: Three possible grain size distributions for the SPM transported by the Isère River during the May-June 2008 flood event.

The SPM of the Durance River was assumed to be composed of clay only (class 1), with a median diameter d_{50} of 4 μ m. This hypothesis relies only on field observation of the very fine aspect of the washload transported by the Durance River.

427 4. Results

428 4.1. Origin of water discharge during the May-June 2008 flood event

The contributions of the Isère and Durance Rivers to the Rhône River water discharge during the May-June 2008 event were evaluated using the 1-D model. The hydrograph decomposition results are presented for the Rhône at Valence

Bridge, Viviers and Beaucaire stations (Fig. 5). Overall, the simulated discharge
is within 10% of the measured discharge, except for short transient phases. This
is less than the expected level of uncertainty of hourly discharge measurements
(*Horner et al.*, 2018), which suggests that the main sources of water and their
propagation through the river network are correctly simulated by the model.



Figure 5: Decomposition of the flow hydrographs of the May-June 2008 flood event at the hydrometric stations of the Rhône at Valence, Viviers and Beaucaire using the 1-D hydrodynamic model. The three periods (see section 2.2) are separated by the vertical dashed lines.

At Valence Bridge station (Fig. 5a), two water sources can be distinguished: 437 the Upper Rhône River (upstream of Ternay) and the Isère River. The contri-438 bution of the tributaries between Ternay and Valence was very small during the 439 event. The Upper Rhône River was not in flood during the period of the May-440 June 2008 flood event, so the shape of the hydrograph at Valence Bridge was 441 mainly influenced by the Isère River contribution. At Viviers station (Fig. 5b), 442 the contribution of the tributaries other than the Isère is increased by water 443 inputs from the Eyrieux, Drôme, Right-bank Ouvèze and Roubion Rivers. The 444

discharge contribution of these tributaries is higher than that of previous tributaries between Ternay and Valence but remains small. At Beaucaire (Fig. 5c),
most of the water came from the Upper Rhône (from 20 to 40 %), the Isère
(around 25 %)and the Durance (around 25 %) Rivers, with smaller inputs from
the Ardèche and other tributaries.

450 4.2. Impact of grain size distribution on simulated SPM concentrations

During the May-June 2008 flood event, one can expect different sources of 451 SPM for the three distinct periods described in section 2.2, with dam flushing 452 operation during the 1st and the 3rd periods and natural floods during the 2nd 453 period. As a consequence, one can expect different GSD for each of these pe-454 riods. As the GSD of SPM transported by the Isère River were not measured 455 in 2008, simulation tests were run using the three hypothetical mixtures de-456 fined in Tab. 2 from samples collected in the Isère River during other events 457 (Section 3.3). Results from these three simulations are presented in Fig. 6. 458

Simulated concentrations C_{SPM} obtained at Viviers station are compared with measured concentrations in Fig. 6. Simulated SPM concentrations are sensitive to grain size due to erosion/deposition and transport processes. Concentrations C_{SPM} at Viviers using the coarse GSD (Mixture C) are half the C_{SPM} simulated using the fine GSD (Mixture A). This is explained by the more intense deposition of the coarsest particles within the four hydropower schemes between the lowest Isère dam and Viviers.

For the flood period, although concentrations at Beaumont-Monteux were 466 evaluated based on Viviers concentrations, the model yields an underestimation 467 of the peak concentrations whatever the choice of GSD. This results from dis-468 persion processes. The concentration peak at Beaumont-Monteux should thus 469 have been higher and narrower to take into account this effect. The difference 470 between measured and simulated $C_{\rm SPM}$ could also be partly due to an overes-471 timation of the C_{SPM} measured at Viviers by the acoustic attenuation method, 472 particularly when fine particles are highly concentrated, which increases the 473 acoustic attenuation (Moore et al., 2013). 474



Figure 6: Simulated and measured SPM concentration (C_{SPM}) at Viviers station for the three hypothetical GSD defined in Tab. 2: (a) Mixture A - Fine, (b) Mixture B - Medium and (c) Mixture C - Coarse.

475 Simulation tests also confirm that the GSD of the SPM transported was
476 different during the three periods of the May-June 2008 flood event. During the

St Egrève Dam flushing period, the model using medium or coarse GSD (Mix-477 tures B or C) yields C_{SPM} -values in relatively good agreement with measured 478 data. Mixture B was eventually preferred since it corresponds to measured data 479 during the flood period of a similar event (in 2015). Also, it yields a better es-480 timation of peak concentrations. Flushing operation evacuated the coarse SPM 481 from the St Egrève reservoir, but they were partially stored into the Lower Isère 482 reservoirs, as the Lower Isère dams were operated with high water levels during 483 this period. This could explain why the medium GSD is consistent with this 484 situation. 485

During the Arc-Isère flood period, the $C_{\rm SPM}$ peak measured at Viviers 486 reached about 9 g/L. Mixture A yielded the best agreement between simu-487 lated and measured $C_{\rm SPM}$ time series. Such very fine washload material, poorly 488 represented in the bed, is brought from the Isère basin by the flood wave. Nev-489 ertheless, the simulated $C_{\rm SPM}$ peak reached only 6 g/L. As discussed above, 490 the concentration peak at Beaumont-Monteux should have been higher and 491 narrower. Using a finer GSD could also increase the simulated C_{SPM} peak. 492 However, as discussed in section 3.3, a finer GSD would no longer correspond 493 to the samples measured in the Isère River during floods of the Arc River. 494

For the third period of the event, corresponding to the Lower Isère dams flushing, Mixture C yields C_{SPM} at Viviers station that are in best agreement with measurements. This is consistent with the opening of the dam gates and the resuspension of coarser particles previously settled in the reservoir.

According to these observations, the GSD was parametrized as follows for the simulation of the May-June 2008 flood event: the medium GSD of Mixture B for the first period, the fine GSD of Mixture A for the second period and the coarse GSD of Mixture C for the third period.

⁵⁰³ 4.3. Interaction of SPM with hydropower schemes

The objective of this section is to study the SPM dynamics in interaction of SPM with hydropower schemes between the lowest Isère dam and Viviers station (Fig. 1). Five additional simulations were carried out to study the de-

position/erosion processes occurring in each hydropower scheme of the reach. 507 The first simulation was run without activating deposition/erosion within the 508 entire river system. In the other four simulations, deposition/erosion was suc-509 cessively activated in the four hydropower schemes of the system, which led to 510 the decrease of the C_{SPM} simulated at Viviers (Fig. 7). Simulation of deposition 511 is necessary to reproduce the $C_{\rm SPM}$ measured at Viviers. The simulated $C_{\rm SPM}$ 512 peak decreased from 4 to 2 g/L, 9 to 6 g/L, and 8 to 2 g/L in the first, second, 513 and third period, respectively. This confirms that hydropower schemes are an 514 obstacle to SPM transport due to the decreased flow velocity in dam reservoirs, 515 which enhances deposition particularly for coarse SPM. Deposition is particu-516 larly intense during the dam flushing periods (first and third periods), as coarser 517 GSD was parameterized for these periods (see section 4.2). These simulations 518 also suggest that the largest decrease of $C_{\rm SPM}$ occurred in the Bourg-lès-Valence 519 (BLV) scheme, between the lowest Isère dam and BLV dam. SPM also settled 520 down within the next three hydro-electric schemes, but to a lesser extent since 521 most of the coarsest particles settled down in the first scheme. 522



Figure 7: Measured and simulated SPM concentration ($C_{\rm SPM}$) at Viviers station during the May-June 2008 flood event, with deposition/erosion processes successively activated in the four hydropower schemes located between the lowest Isère dam and Viviers. BLV = Bourg-lès-Valence, BCT = Beauchastel, BLN = Baix-Le Logis Neuf, MTL = Montélimar. Coloured areas represent the cumulative SPM trapped in successive reservoirs.

⁵²³ The numerical model provides detailed information on the quantity and grain

size distribution of the SPM present in each branch of the river system at any 524 time of the simulation. In order to better understand the deposition processes 525 between the lowest Isère dam and the BLV dam observed in Fig. 7, the cumu-526 lative amounts of SPM settled in the area are presented in Fig. 8. At the scale 527 of the entire event, the Isère River produced a total amount of 7.7 Mt of SPM, 528 of which 2.8 Mt deposited at the Isère-Rhône confluence (Fig. 8d). The SPM 529 deposition occurred mainly within three branches of the network: 60% in the 530 lowest Isère branch, and 30% in the BLV and Beauchastel (BCT) power canals. 531 Deposition mainly occurred during the second and third periods with a segre-532 gation in the grain size of the particle deposited, as also observed by *Camenen* 533 et al. (2019). The Isère River produced 2.8 Mt during the second period, and 534 80 % of this input, mainly composed of fine SPM, travelled through the BLV 535 and BCT schemes. The remaining 20%, mainly composed of class 3 particles, 536 were trapped in the BCT and BLV power canals, and not in the lowest Isère 537 branch. But most of the deposition occurred during the third period when the 538 Lower Isère dams were flushed. The SPM flux during this period was 3.8 Mt, i.e. 539 half of the total input of the Isère during the event. SPM of class 4 represented 540 30 % of the Isère River input, and these particles massively deposited within 541 the Isère branch, and to a lesser extent within the BLV and BCT power canals. 542 The deposits simulated in the downstream Isère reach are mainly composed of 543 classes 3 and 4, which is consistent with available observations and with the 544 choice of Mixture C as a coarse GSD representative of a deposit collected after 545 the May 2015 flood. 546



Figure 8: Mass and grain size composition of SPM deposited in the Isère-Rhône confluence system during the May-June 2008 flood event: first period (a), second period (b), third period (c) and entire event (d). See section 2.2 for definition of periods and Tab.2 for definition of grain size classes. The mass and grain size composition of SPM fluxes at boundaries are also shown. The thickness of the lines is proportional to the mass of SPM deposited in each reach. BLV = Bourg-lès-Valence scheme and BCT = Beauchastel scheme.

547 4.4. Cumulative SPM fluxes

Measured and simulated SPM cumulative fluxes are presented in Tab. 3 and Fig. 9 for the three periods (see section 2.2) and for the entire May-June 2008 flood event at the monitoring stations in the Rhône River. In Fig. 9, the lefthand graphs display the cumulative fluxes estimated from observations whereas the right-hand graphs display the cumulative fluxes specified or simulated in the numerical model.

The relative deviation between the simulated and measured SPM cumulative 554 fluxes was between +15 % and +36 % (see Tab. 3), except for the first period for 555 which larger values are observed since measured cumulative fluxes are small. At 556 Viviers station, the absolute deviation was around +0.8 Mt for the entire event 557 for a total measured SPM flux of 3.6 Mt at this station. This relatively small 558 deviation validates the reconstruction of the C_{SPM} time series at Beaumont-559 Monteux described in section 2.3, and the choice of the varying GSD for the 560 three periods (see section 4.2). At Arles station, the measured SPM flux for the 561 entire event was 4.2 Mt, and the simulated SPM flux was 5.7 Mt. Eyrolle et al. 562 (2012) estimated this flux to be 4.7 Mt \pm 30 %. These results are of the same 563 order of magnitude and confirm the exceptional nature of the May-June 2008 564 flood event. 565

As for the Durance River, the model highlighted the weakness of the hy-566 pothesis made of a very fine grain size distribution for the entire event. During 567 the first week of the event, the relative deviation between measured and simu-568 lated fluxes increased from +50% to +133% between Viviers and Beaucaire (see 569 Tab. 3). This is explained by the transfer of the SPM of the Durance directly 570 to Beaucaire without deposition because of a too fine grain size distribution as-571 sumed for the Durance River SPM input during this first period. The measured 572 SPM flux of 0.5 Mt only at Beaucaire during the first week indicated a large de-573 position of around 1.0 Mt at the Durance confluence. For the second and third 574 periods, the hypothesis of a fine GSD for the Durance SPM input appeared 575 more realistic although still a little bit too fine as the measured and simulated 576 fluxes at Beaucaire were in better agreement. The fine SPM coming from the 577

Rhône at Viviers Rhône at Beaucaire Rhône at Arles RD Model RD RD Meas. Model Meas. Meas. Model Mt Mt % % %

Mt

1.4

3.0

2.1

6.5

+133

+15

+24

+33

Mt

0.5

2.2

1.5

4.2

Mt

1.2

2.6

1.9

5.7

+140

+18

+27

+36

Mt

0.6

2.6

1.7

4.9

Period 1

Period 2

Period 3

Total

0.4

1.9

1.3

3.6

0.6

2.2

1.6

4.4

+50

+16

+23

+22

Table 3: Measured and simulated SPM cumulative fluxes for the three periods (see section 2.2) and for the entire May-June 2008 flood event at the monitoring stations in the Rhône River, and relative deviations (RD) of the simulated fluxes to the measured flux.

Durance River during these two periods seemed to have travelled through the 578 downstream Durance reach and Rhône River down to the Delta with limited 579 deposition. For the downstream Durance reach, this also could be explained 580 during the second period because of the much higher discharges and velocities. 581 The model was also useful for estimating the amount of SPM transported 582 in the Petit Rhône at Fourques, where no $C_{\rm SPM}$ measurement were available. 583 The SPM flux of the Petit Rhône represented from 10 to 15 % of the SPM 584 fluxes measured at Beaucaire station. This is in good agreement with the water 585 discharge distribution between the Petit Rhône and the Grand Rhône observed 586 in long-term discharge time series (source CNR). 587



Figure 9: Monitored and simulated SPM cumulative fluxes (in Mt) along the Rhône River during the first, second and third periods of the 2008 flood event. Line thickness is proportional to SPM flux at the corresponding station.

588 4.5. Origin of the SPM

606

The origin of the SPM transported during the three periods of the event 589 and measured at Arles was clarified. In particular, the Isère River input that 590 was not measured during the first period could be quantified with the model. 591 Fig. 10 shows the evolution of the measured and simulated C_{SPM} at Arles and 592 the proportion of SPM coming from both the Isère and the Durance Rivers. 593 The simulated C_{SPM} are close to the measured C_{SPM} , except the C_{SPM} peak 594 recorded on 01/06/2008. The maximum recorded C_{SPM} was about 5 g/L while 595 the maximum simulated C_{SPM} was 4 g/L, being a difference of 20 %. Fig. 10 596 highlights the high contribution of the Durance River during the first days of 597 the event, and the increasing contribution of the Isère River during the rest of 598 the event. Approximately 50 % of the SPM fluxes came from the Durance River 599 and the remaining 50 % came from the Isère River. Marion et al. (2010) and 600 Eyrolle et al. (2012) discussed the origin of the SPM transited and deposited 601 in the Grand-Rhône pro-delta during the May-June 2008 event. They assumed 602 that most of the SPM came from the Durance River, therefore they investigated 603 the origin of the SPM within the Durance river basin and ignored the equally 604 large contribution of the Isère River. 605



Figure 10: Simulated and measured C_{SPM} in the Rhône at Arles during the May-June 2008 flood event with decomposition of the Isère and Durance Rivers SPM inputs.

Nearly 50 % of the SPM flux brought by the Isère River to the Rhône

River system deposited in the river network before reaching Viviers. Although the model confirmed that the Rhône reservoirs acted as sediment sinks during the May-June 2008 flood event, they can turn to act as sediment sources due to resuspension during other floods. In the annual SPM fluxes computed by *Poulier et al.* (2019), there is evidence that the SPM deposited and stored during the 2008 event were later re-suspended and exported during floods.

5. Conclusive comments

This paper explores the potential of numerical simulation to predict the 614 sources and fate of SPM in regulated river networks. The main questions on 615 numerical simulation tools addressed through this case study were: What is 616 the added value of 1-D modelling of SPM fluxes? What are the most sensitive 617 parameters? What are the main limitations and perspectives for improvement? 618 A 1-D hydrodynamical model was built and applied to a major hydro-619 sedimentary event in May-June 2008 in the Lower Rhône River, France. Such 620 model would be the simplest and fastest possible hydrodynamical model that 621 could be constructed and some physical processes that may be important are 622 neglected in exchange for that simplicity. The Rhône River has a complex river 623 network with confluences, bifurcations and hydropower schemes. The simula-624 tion code (AdisTS) was able to model the SPM fluxes at a high spatial and 625 temporal resolution, which is useful to understand the SPM dynamics over the 626 whole river system on time scales ranging from hour to decades, thanks to fast 627 computational times. Especially, SPM supplies from the main tributaries and 628 deposition of the coarsest particles behind hydropower structures could be quan-629 tified precisely, at any time and at any cross-section of the river network. The 630 model provides insights that are not available from observational data alone. Es-631 pecially, the model simulates the continuous dynamics and spatial distribution 632 of deposits, which would have allowed a better anticipation and management of 633 sedimentation in critical areas of the Rhône reservoirs. 634

635

In the presented study case, approximately half of the 4.9 Mt of SPM mea-

sured at the outlet of the Rhône River catchment during the event were found 636 to come from the Isère River and the other half from the Durance River whereas 637 previous studies estimated that most of the flux at the outlet came from the 638 Durance River. Also, the model confirmed that a large amount of the SPM de-639 livered by the Isère River was trapped behind the first hydro-electric scheme in 640 the Rhône River, a cause of conflicts between dam operators. The high temporal 641 and spatial resolution of fluxes computation is highly valuable for reconstruct-642 ing past events and also for managing future events like natural floods or dam 643 flushing operations, by testing multiple dam operation scenarios. If forecasts 644 of water discharges and SPM inputs are available, such a model can be used 645 to compute real-time forecasts of SPM concentrations, fluxes and deposition 646 throughout the river network. 647

As a basis for hydraulic simulation, an accurate description of the channel geometry and of the artificial structures is necessary, along with a conventional 649 calibration of the friction coefficients along the river stretches. This was easily 650 achieved in our case study. As for SPM simulation, the quality of the numeri-651 cal results was found to be highly sensitive to suspended sediment parameters, 652 especially grain size, and to the operational rules of artificial structures. This 653 may lead to substantial errors because accurate information on grain size distri-654 bution is often difficult to obtain, grain size varies spatially and temporally, and 655 the coarsest particles may not be homogeneously distributed throughout the 656 river cross-section. In this study, sensitivity tests made on the grain size dis-657 tribution of the SPM improved our knowledge of the Isère River input, despite 658 the lack of measurements. Finer SPM particles were mostly transported during 659 the natural flood period while coarser SPM were transported during the dam 660 flushing periods. The simulation of deposition and erosion processes within the 661 hydropower schemes was necessary to reproduce the strong deposition of SPM 662 at the Isère confluence and further downstream. Deposits were mainly com-663 posed of the coarsest SPM (cf. *Camenen et al.*, 2019), while finer SPM travelled 664 through the hydropower schemes without settling down. 665

⁶⁶⁶ Of course, observation and modelling supplement each other: dense and

precise SPM observational data measured at key points of the river system 667 are necessary to specify the boundary conditions of numerical models, and to 668 calibrate and validate them. An extended sensitivity analysis could be done 669 to better infer upstream sediment supply, i.e. input concentrations and GSD. 670 In the present paper, we constrained the tests to prior knowledge based on 671 actual measurements and uncertainties. Another perspective of this work is to 672 compare 1-D numerical modelling with chemical fingerprinting for quantifying 673 SPM sources in the Rhône River for various hydrological conditions. 674

The 1-D numerical model applied in this study is typical of modern simu-675 lation tools used in river engineering applications. While the principles of 1-D 676 hydrodynamical codes have virtually not changed for fifty years or so, their 677 computation performance and the power of the available computers have been 678 greatly improved. Compared to 2-D or 3-D hydrodynamical codes, 1-D hydro-679 dynamical codes offer much faster computational times allowing for real-time 680 or long-term simulations and uncertainty analysis through Monte Carlo sim-681 ulation or sensitivity analysis (Souhar and Faure, 2009), which is practically 682 challenging with higher level codes. The spatial resolution of 1-D hydrodynam-683 ical codes is sufficient for studying SPM dynamics on the river network scale, 684 while 2-D or 3-D hydrodynamical codes would be required for studying local 685 processes, in the close vicinity of artificial structures for instance. However, most 686 1-D hydrodynamical codes still come with restrictive assumptions that call to be 687 improved through future research. Computing the flow and suspended sediment 688 flux interactions between the main channel and the floodways, or floodplains, 689 is still motivating active research. More generally, the spanwise distribution of 690 velocities, SPM concentrations and deposition/erosion fluxes throughout cross-691 sections has to be predicted from 1-D, i.e. cross-sectional average results. A 692 major limitation of 1-D hydrodynamical codes is the usual assumption of full, 693 instantaneous mixing of water and SPM downstream of confluences. In the case 694 of the Rhône River, full mixing after a confluence is actually seldom reached 695 before the next bifurcation between the navigation canal and the by-passed 696 channel of the Old Rhône. Formulas for predicting the degree of mixing and the 697

 $_{\tt 698}$ $\,$ spanwise distribution of SPM concentrations still have to be elaborated, based

⁶⁹⁹ on tracing experiments conducted in the laboratory and in the field.

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