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Downstream erosion and deposition dynamics of fine suspended sediments due to dam flushing

G. Antoine\textsuperscript{a,b}, B. Camenen\textsuperscript{c}, M. Jodeau\textsuperscript{a,b}, J. Némery\textsuperscript{d}, M. Esteves\textsuperscript{d}

\textsuperscript{a}EDF-LNHE, 6 Quai Watier, 78400 Chatou, France
\textsuperscript{b}LHSV -Laboratoire Hydraulique St Venant-, 6 Quai Watier, 78400 Chatou, France
\textsuperscript{c}INRAE, UR RiverLy, centre de Lyon-Grenoble, 5 Rue de la Dowa, CS 20244, 69625 Villeurbanne Cedex, France
\textsuperscript{d}IGE -Université Grenoble Alpes, CNRS, IRD, Grenoble INP (Institute of Engineering Univ. Grenoble Alpes)-, 38000 Grenoble, France

Abstract

Fine sediment dynamics downstream dams is a key issue when dealing with environmental impact of hydraulic flushing. This paper presents an analysis of six field campaigns carried out during dam flushing events (in June 2006, 2007, 2009, 2010, 2011, and 2012) in the Arc-Isère river system in the Northern French Alps. Suspended sediment concentrations (SSC) and discharges were evaluated using direct measurements or/and 1D hydraulic modelling at up to 14 locations along the 120 kilometres-long river channel. The total suspended sediment flux (SSF) is analysed along the Arc and Isère rivers for each Arc dam flushing event. Uncertainties were quantified based on a propagation method of both measurement and modelling errors. The resulting confidence interval provides elements of discussion on the significance of the sediment mass balance between two consecutive measurement sites. Whereas the discharge time-series of each flushing event is roughly the same, the quantity of fine sediments removed from the reservoirs varied from 10,000 tons in 2007 to 40,000 tons in 2006. Also, a significant erosion is observed in the river system for some events (20,000 tons in 2007) while the SSF barely varied for other events (in 2009 and 2011). This detailed data set allows to identify specific locations in the river network where deposition or erosion occurred. This dynamics is closely related to both the hydrology in the upper Isère River and the morphology of the Arc and Isère rivers, which have been affected by the 2008 and 2010 floods.

Keywords:
1. Introduction

About 1% of the total storage capacity in the world’s reservoirs is lost each year due to sedimentation (Mahmood, 1987; Yoon, 1992; Vörösmarty et al., 2003). This sedimentation rate depends mainly on the size of the reservoir relative to the amount of sediment flowing into it. Since the construction of new dams is rather difficult in developed countries due to stricter environmental regulations and the lack of suitable sites, procedures have been established to sustain the storage capacity of existing reservoirs. In numerous cases, hydraulic flushing has been used successfully to restore lost reservoir storage capacity (Kondolf et al., 2014). The flushing process consists in opening dam outlet gates to produce flows with velocities high enough to flush away the sediments accumulated in the reservoir. Theoretical and numerical studies (Chang et al., 1996; Olsen, 1999; Liu et al., 2004; Khosronejad et al., 2008; Ji et al., 2011), laboratory experiments (Lai and Shen, 1996; Campisano et al., 2004, 2008), and field observations (Jansson and Erlingsson, 2000; Rayan and Iguacel, 2006) have shown that under appropriate conditions, hydraulic flushing can remove both fine (with cohesive material) and coarse (sands and gravels) sediments.

Flushing operations can have a significant impact on the morphology and ecology of the downstream part of a river system (Collier, 2002; Chung et al., 2008; Crosa et al., 2010; Bilotta et al., 2012; Alca yaga et al., 2018). As an example, Crosa et al. (2010) observed a drop in trout density as high as 73% a flushing operation performed in 2006 in an alpine reservoir. In this case, high suspended sediment concentrations (SSC) were measured in the downstream part of the river (peak values up to 80 g/l and event-averaged value equal to 4 g/l). On the other hand, when limits for SSC are adopted, Pe- teuil et al. (2013); Espa et al. (2015, 2019) demonstrated that environmental degradations can be significantly reduced. Also, several studies have focused on the morphological effect of flushing waves on the river bed, which mainly concerns coarse sediments (Kondolf and Wilcock, 1996; Wohl and Cenderelli, 2000; Brandt, 2000; Petts and Gurnell, 2005; Petticrew et al., 2007). These studies identified the direct link existing between the intensity of the flushing operations and the downstream erosion of the river bed (gravel bars or main channel).
However, fine sediments transported by flushing flows can also have a morphological impact on the downstream river system (Smart, 1999; Van Maren et al., 2010). Following a flushing event, Brandt (1999) measured an increase of mean bed elevation of 10 centimetres due to the deposition of fine sediments over a 30 kilometre-long reach downstream of the Cachi dam, in Costa Rica. As an exacerbating factor, vegetation grows more easily on fine deposits, and provides optimal conditions for new deposition of fine sediments due to the local decrease of flow velocities (Newcombe and Macdonald, 1991; Murle et al., 2003; Asaeda and Rashid, 2012; Jourdain et al., 2017). Finally, fine sediments can be the vectors of propagation for particulate pollutants, and the residence time of the contaminated particles in the river channel is an important parameter to evaluate the vulnerability of a system (Frémion et al., 2016).

Fine sediment deposition fluxes often represent a small part of the total suspended sediment flux (SSF) in embanked alpine river for high flow conditions. They have been observed as non-negligible for small braided systems only (Navratil et al., 2010; Misset et al., 2019), where exchanges with the bed can be of the same order of magnitude than upstream input. Therefore, the quantification of the mass of fine deposited sediments, its spatial distribution and its temporal dynamics during one event is rather difficult to assess for large embanked systems. Bathymetric surveys performed before and after a flushing event are expensive, time consuming and highly exposed to uncertainty measurement regarding the possibly small thickness of fine sediment deposits. Some aerial photograph analysis provided an estimate of the deposits but limited to surface measurements and difficult to apply to long reaches (Camenen et al., 2013; Camenen et al., 2016). Furthermore, the measured bed evolution provides an estimation of the volume of sediments deposited or eroded. To be compared to sediment fluxes, an additional hypothesis on the sediment mixture and porosity of the bed is needed to convert the differential volume into a sediment mass.

The method based on SSF consists in estimating the difference between event-integrated SSF for two consecutive positions of the river reach. Such method only provides a reach-averaged behaviour that could be difficult to interpret if the distance between two positions is long. Moreover, the uncertainty is sensitive to the temporal frequency of measurements, and can sometimes become too high to give relevant conclusions (Garcia, 2008). This explains that few studies have focused on fine sediment budgets based on SSF measurements, especially for long embanked systems (López-Tarazón et al.,
2012). None of these studies quantified precisely or examined critically their results with respect to uncertainty values. As an example, the work of Tena et al. (2014) on the Ebro River improves the understanding of the spatial and temporal dynamics of suspended sediment transport during flushing flow but it did not address the issue of fine sediment deposition in the river.

In this paper we raise the following questions: what is the downstream dynamics of SSF during dam flushing events in an impounded river system? Regarding the uncertainty on SSF estimated from a detailed data set, what is the significance of local mass balance between two consecutive measurement sites? How to explain these mass balances with erosion and deposition processes on the river bed? To answer these questions, we analysed the propagation of SSF along the Arc and Isère river system following six hydraulic flushing events of the Upper Arc dams in June 2006, 2007, 2009, 2010, 2011, and 2012. For these six flushing events, measurements of discharges and SSC were performed at fourteen sites along 120 kilometres of the river downstream of the flushed reservoirs (Antoine, 2013).

In the first part of this paper we describe the field campaigns performed to measure water discharges and SSC at different sites of the river system as well as the method developed to explore this detailed data set. The obtained instantaneous values of SSF are integrated over the flushing time period, in order to compute the local mass balances between two consecutive measurement sites. Then, a model of uncertainty propagation is proposed to estimate the significance of these local mass balances. In the second part of the paper, a global analysis of discharge, SSC and SSF values is provided at the river scale. Also, a discussion is provided on the links between local mass balances and site morphologies and history.

2. Material and method

2.1. Study site

The Arc-Isère river system is a typical example of impounded Alpine river system largely influenced by river management and dam management.

2.1.1. The Arc-Isère River system

The Isère River and its tributary, the Arc River, are located in the Northern French Alps. The respective surface areas of the catchments are 1950 km² and 5570 km² for the Arc River and the Isère River upstream of the city of
Grenoble (Figure 1). Both catchments are characterized by a nival hydro-
logical regime, with an annual mean water discharge of 30 m$^3$/s for the Arc
River at Pontamafrey and 177 m$^3$/s for the Isère River at Grenoble.

In the second part of the 20th century, three dams, with a storage ca-
pacity of 0.8 Mm$^3$, were built on the middle section of the Arc River: the
Freney dam, the Pont-des-Chèvres dam and the Saint-Martin-La-Porte dam
(SMLP dam). Compensation water flows along more than 50% of the to-
tal length of the Arc River due to the water intakes used for hydropower
generation. Nevertheless, tributaries of the Arc and Isère rivers can be very
dynamic, and strong seasonal discharge variations occur in both rivers dur-
ing the year: in the middle of summer, the mean monthly discharges on the
lower Arc River can reach 50 m$^3$/s, and 250 m$^3$/s on the Isère River. In
winter, mean monthly discharges are 10 m$^3$/s on the Arc River and 150 m$^3$/s
on the Isère River. Natural floods usually occur at the beginning of summer
and in autumn. Dams are opened during large floods and have no impact
on the flood dynamics in the downstream part of the valley because of their
low storage capacities (Marnezy, 1999). The discharge for the 10-years flood
on Arc River (Pontamafrey) is estimated at 180 m$^3$/s, and 900 m$^3$/s on the
Isère River (Grenoble).

Because of continuous embankments, the Arc River is strongly constrained
laterally and the mean slope of the river bed varies from 1% at Saint-Jean-
de-Maurienne to 0.2% just upstream of its confluence with the Isère River.
The slope can be locally steeper and supercritical flows are frequently ob-
served on some parts of the river’s course. The slope of the Isère River is
smaller, with values from 0.2% close to the confluence to 0.09% at the end
of the study site. Both Arc and Isère river beds are mainly made of gravels
with a poorly sorted grain size distribution. Both rivers are characterized by
systems of alternate bars that are often vegetated in the Isère River (Serlet
et al., 2018). They are also exposed to snow-melt floods, debris flows and
are greatly affected by deposits of fine sediment on vegetated banks. This
paper focuses on the Arc-Isère river system, from the SMLP dam to the city
of Grenoble. The locations of the measurement sites are defined in this paper
as the distance of the site from the confluence (sites on the Arc River have
negative positions and sites on the Isère River have positive positions).

2.1.2. Flushing of the Arc dams

To maintain storage capacity and electric power production, the three
dams of the middle Arc River (Figure 1) are flushed yearly at the beginning

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of June, except if a larger flood occurs before the planned hydraulic flushing. For example, no flush was performed in 2008 because a 15-years flood occurred in May. During the flushing operation, the successive openings of the dam outlet gates (see Figure 2a) are defined precisely to optimize the hydraulic effect of the flush. As dam operators follow a project hydrograph, similar discharge time series were observed for every flushing event (see Figure 2b) although some differences can be observed because of the natural flow in the Arc and Isère rivers. At the SMLP dam, the different dam opening phases correspond to the following parts of the hydrograph in the Arc River:

1. first a warning wave (for fauna and hydraulic safety precautions) of about 20 m³/s is generated by an overflow of the clear water;
2. then a discharge step is performed, providing a discharge amplitude of approximately 90 m³/s for 3 hours;
3. water is provided by larger reservoirs on the upper Arc watershed (Bis-sorte and Mont-Cenis dam reservoirs mainly, see Fig. 1) to maintain
3. the water discharge value and increase it to its maximum value (from 130 to 150 m$^3$/s) for about 4 hours. The maximum discharge value corresponds to a one-year flood on the Arc River;
4. the discharge returns to the compensation water level.

Figure 2: Photo of the SMLP dam outlet gates during a flushing event (a), and discharge time series of the six studied flushing events at Pontamafrey (b).

In 2012, an additional peak up to 175 m$^3$/s arose during the first discharge step. It resulted from some unexpected problems in the gate management.

2.2. SSC and discharge measurements

To evaluate the suspended load propagation along the reach resulting from dam flushing events, high frequency measurements were performed during June 2006, 2007, 2009, 2010, 2011, and 2012 events. These measurements were anticipated and organization was facilitated by planning the dam flushing several weeks in advance. Measurements consisted in gauging discharges and performing SSC monitoring at several locations along the river reach (Figure 1).

SSCs were estimated from samples taken from surface water (bucket samples from a bridge) or at the riverside (ISCO 4230 automatic sampler) at 14 measurement sites (Figure 1). The samples were filtered and weighed following the ISO 11923 protocol. SSC estimation was also performed thanks to turbidimeters (Hach Lange Solitax SC-Line TS 50 g/l) installed at four monitoring stations (Thollet et al., 2018). In these cases, water samples were used to establish a relation between the measured turbidity and the effective SSC.
As a consequence, it is important to note that the present study excludes coarse particles such as sand since it is poorly measured from surface and/or riverside samples and turbidity. In addition, samples were taken in main tributaries (Arvan, Glandon, Isère restitution, Isère River) to verify that their concentrations were negligible throughout the flushing events. Therefore, the only effect of these tributaries was to decrease the SSC through dilution.

Discharges were estimated at five sites along the Arc-Isère system (A7, A5, A2, I3, and I1) where a hydrometric station is present. At these sites, water level was measured and the discharge was obtained using well documented rating curves and additional discharge measurements (using a classical current meter, LSPIV image analysis technique and/or ADCP measurements Jodeau et al., 2008; Dramais et al., 2011). In addition, pressure gauges (autonomous Diver type and bubbler system pressure gauges) were used to measure water level variations at several locations, giving information on the transfer time of the flushing waves.

One dimensional hydraulic model was built for the whole river system to complete the discharge data set. The 1D hydraulic numerical code MASCARET (Goutal and Maurel, 2002, part of the open-source TELEMAC-MASCARET system) was used for this study. The model geometry was built using topographical data from several river cross-section surveys conducted between 2004 and 2007 on the Arc and Isère Rivers. 56 river cross sections were available to build the Arc River bed, giving an average profile density of about 1 cross section per kilometre. On the Isère River, this density was higher (about one profile every 200 meters). Because local slopes can be very steep, the calculation mesh was fixed at spatial resolution of 20m. Calibration of the Strickler coefficients was performed by comparing measured and computed water level and discharge values. Strickler friction coefficients used to calibrate the model vary from $20 \text{ m}^{1/3}/\text{s}$ in the upstream part to $45 \text{ m}^{1/3}/\text{s}$ in the downstream part.

The upstream boundary condition was built from the most upstream discharge time-series measured on the river (A7, Figure 1) using a time shift based on pressure gauge measurements. The downstream boundary condition is a free water flow boundary condition. Three main water inputs were set at Randens (10 km upstream the Arc-Isère confluence; turbinated water from the Aigueblanche reservoir), at the confluence (upstream part of the Isère River), and at Cheylas (30 km downstream the Arc-Isère confluence; turbinated water from the Flumet reservoir).

Table 1 summaries the measurement methods used at each measurement
site for each flushing event. The position of each measurement site is given by its distance from the confluence (see also Figure 1). Both SSCs and water discharge time series are thus available at 14 measurement sites for the five flushing events.

Table 1: Summary of the methods used for discharge and concentration measurements (Site: code of the measurement point located at the distance $D$ from the confluence). Three methods were used for the concentration values (A.S.: Automatically Sampled, M.S.: Manually Sampled, Tu: Turbidity measurements) and two methods were used for the discharge values (H.S.: Discharge values from Hydrometric Stations, 1D: Discharge values computed with the 1D model).

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<td>-50.4</td>
<td>-</td>
<td>-</td>
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<tr>
<td>A8</td>
<td>-44.7</td>
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<td>M.S. 1D</td>
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<tr>
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<td>M.S. H.S.</td>
<td>Tu. H.S.</td>
<td>Tu. H.S.</td>
<td>Tu. H.S.</td>
<td>Tu. H.S.</td>
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</tr>
<tr>
<td>A6</td>
<td>-37.9</td>
<td>M.S. 1D</td>
<td>M.S. 1D</td>
<td>M.S. 1D</td>
<td>A.S. 1D</td>
<td>-</td>
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<tr>
<td>A5</td>
<td>-33.1</td>
<td>M.S. H.S.</td>
<td>Tu. H.S.</td>
<td>Tu. H.S.</td>
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<tr>
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<td>-</td>
<td>-</td>
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<tr>
<td>A3</td>
<td>-12.2</td>
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<td>A.S. 1D</td>
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<td>A.S. 1D</td>
<td>-</td>
<td>H.S.</td>
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<tr>
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<td>A.S. 1D</td>
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<td>A.S. 1D</td>
<td>Tu 1D</td>
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<tr>
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<td>-</td>
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<tr>
<td>I3</td>
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<td>-</td>
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<tr>
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<td>-</td>
<td>-</td>
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2.3. Suspended Sediment Fluxes

2.3.1. Instantaneous Suspended Sediment Fluxes

At each measurement site located at the position $X_i$, instantaneous flux values $\phi$ are computed using a linear interpolation of both discharges and SSC values:

$$\phi(X_i, t) = Q(X_i, t) \times SSC(X_i, t)$$

Due to a lack of data, three data sets were excluded: site I4 in 2006 and 2007 and site A1 in 2007. SSC data were measured at site A2 with an automatic sampler. However, since this site is located 500 m downstream
the outlet channel of the Randens hydro-power plant, an incomplete lateral mixing was suspected. SSC measurements were performed at several points throughout the river in 2010; the results presented a standard deviation up to 40% due to incomplete lateral mixing, even under low SSC conditions. Consequently, no SSC measurement is made at this site since 2011, and the data from this site will be excluded from the flux estimations.

2.3.2. Suspended Sediment Fluxes integrated over the flushing event

The instantaneous flux computed using Eq. 1 can be integrated over the time period of the event $T_{\text{event}}$, which varies from 12 hours in the Arc River to 16 hours in the Isère River, due to dispersion processes:

$$
\Phi(X_i) = \int_{T_{\text{event}}} \phi(X_i,t)dt
$$

This temporal integration provides the global mass of suspended sediment $\Phi$ transported through a measurement site located at position $X_i$. A formalism was also introduced to study the temporal dynamic. A cumulative transported mass was calculated as a function of the percentage $t\%$ of $T_{\text{event}}$:

$$
\Phi_{\%}(X_i, t\%) = \int_{t\%\times T_{\text{event}}} \phi(X_i,t)dt
$$

2.3.3. Local mass balance

The detailed spatial profiles of the total mass transported at the fourteen measurement sites are used to estimate a local mass balance. This local mass balance $\Delta \Phi$ between two consecutive measurement sites located at positions $X_i$ and $X_{i+1}$, respectively, is expressed such as:

$$
\Delta \Phi(i \rightarrow i + 1) = \Phi(X_{i+1}) - \Phi(X_i)
$$

This integrated approach could mask successive deposition or erosion phases during one event. Then, it is possible to obtain a dynamic local mass balance value using Eq. 3, i.e. a mass balance between two consecutive measurement sites after $t\%$ of $T_{\text{event}}$:

$$
\Delta \Phi_{\%}(i \rightarrow i + 1, t\%) = \Phi_{\%}(X_{i+1}, t\%) - \Phi_{\%}(X_i, t\%)
$$

Note that $\Phi(X_i) = \Phi_{\%}(X_i, 100\%)$ and $\Delta \Phi(i \rightarrow i + 1) = \Delta \Phi_{\%}(i \rightarrow i + 1, 100\%)$. 

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2.4. Uncertainty in the integrated flux estimations

2.4.1. Uncertainty propagation model

As the instantaneous SSC and discharge values are obtained separately, the relative variance of the instantaneous SSF can be expressed as the sum of the relative variances $\sigma_Q^2$ and $\sigma_{SSC}^2$ of these variables:

$$\sigma_\phi = \sqrt{\sigma_Q^2 + \sigma_{SSC}^2}$$  \hspace{1cm} (6)

According to the methodology developed in the GUM (Joint Committee for Guides in Metrology, 2008), the same decomposition of each relative variance $\sigma_Q$ and $\sigma_{SSC}$ is performed to take into account all significant sources of uncertainty. In the proposed error propagation model, $\sigma_Q$ and $\sigma_{SSC}$ are assumed time-averaged.

2.4.2. Uncertainty of the discharge values

Uncertainties in the discharge values of the data set come mainly from three sources: the measurement method ($\sigma_{\text{Q,Meas}}$), the numerical model ($\sigma_{\text{Q,Mod}}$) and, eventually the temporal linear interpolation ($\sigma_{\text{Q,Int}}$).

$$\sigma_Q = \sqrt{\sigma_{\text{Q,Meas}}^2 + \sigma_{\text{Q,Mod}}^2 + \sigma_{\text{Q,Int}}^2}$$  \hspace{1cm} (7)

Measurement method ($\sigma_{\text{Q,Meas}}$). The same measurement method is used at the four measurement sites where discharge values are available. These measurements are performed using the velocity-area method, which consists in sampling flow velocity and depth across the cross-section for the discrete integration of the discharge. Using these isolated measurements, a rating curve is extrapolated to transform the continuously measured water levels into discharge values. The uncertainties resulting from this method are entirely site dependent. Le Coz et al. (2012) proposed a method to estimate the uncertainty of this measurement method at site A2 during dam flushing in 2011. Using these results, the value $\sigma_{\text{Q,Meas}} = 7\%$ was chosen. It is of the same order of magnitude of the uncertainty estimated by Olivier et al. (2008) from well documented rating curves of several mountainous discharge stations.

Numerical modelling ($\sigma_{\text{Q,Mod}}$). For each flushing event, the simulated instantaneous discharges were compared to those observed on the four measurement sites. The time transfer of the water wave is well reproduced by the model for
each flushing, as are the maximum discharge values. The standard deviation between the measured and modelled discharge was estimated systematically using the following equation:

$$\sigma_{M_i} = \frac{1}{N} \sum_{j=1}^{N} \left| \frac{Q_{\text{mod}}(j) - Q_{\text{meas}}(j)}{Q_{\text{meas}}(j)} \right|$$  

(8)

The $\sigma_{M_i}$-values vary from 2% to 7% with an averaged value around 5%. Larger values correspond generally to low flow discharges, which are not as accurately modelled. However, these low flow discharges are not significant in term of overall fluxes.

Effect of temporal sampling frequency ($\sigma_{Q,\text{Int}}$). Water levels are measured continuously or calculated numerically with a small time step, so the temporal effect of the linear interpolation (used to compute the instantaneous suspended sediment flux at every time step) is neglected for the discharge values. As this assumption is not correct for the SSC measurements, this source of uncertainty is taken into account in the following part.

2.4.3. Uncertainty of the SSC values

Four main sources of uncertainty are identified concerning the SSC values: the vertical ($\sigma_{\text{SSC,VH}}$) and transversal heterogeneity ($\sigma_{\text{SSC,HH}}$) of the SSC in a river cross-section, the different measurement methods used (sampled-filtered-wetted ($\sigma_{\text{SSC,Spl}}$), or from turbidity measurement ($\sigma_{\text{SSC,Tu}}$)) and the effect of linear interpolation ($\sigma_{\text{SSC,Int}}$).

$$\sigma_{\text{SSC}} = \sqrt{\sigma_{\text{SSC,HH}}^2 + \sigma_{\text{SSC,VH}}^2 + \sigma_{\text{SSC,Spl}}^2 + \sigma_{\text{SSC,Tu}}^2 + \sigma_{\text{SSC,Int}}^2}$$  

(9)

Spatial heterogeneity ($\sigma_{\text{SSC,HH}}$ and $\sigma_{\text{SSC,VH}}$). SSC values are measured assuming a homogeneity throughout river cross-section. Vertical homogeneity depends on the degree of turbulence of the river flow, the grain size distribution of the suspended sediments and the geometry of the river bed. Some studies (Ryan and Boufadel, 2006; Horowitz et al., 1990) have shown that the homogeneity of suspended sediment is highly site dependant. Vertical SSC distribution has never been estimated on the Arc and Isère Rivers, because of the high flow velocities during flushing events. However, the Rouse-Schmidt number $Z = W_s/(\kappa u_*)$ (with $W_s$: settling velocity of the suspended sediments, $\kappa = 0.41$: Von Karman constant, and $u_*$: friction velocity) gives
information on the potential vertical heterogeneity of the suspension (Garcia, 2008). Very low values of the Rouse-Schmidt number \( Z \ll 1 \) indicate that the suspended sediments are well distributed over the vertical dimension of the river cross-section. Such vertical homogeneity was also verified on a secondary channel of the Arc River (Camenen et al., 2018). Antoine et al. (2012) measured the settling velocity of suspended sediments during the flushing event of 2011 and observed a maximum value \( W_s = 2 \) mm/s. Using the numerical hydraulic model to estimate \( u_* \), the maximum value of the Rouse-Schmidt number calculated is thus \( Z = 3 \times 10^{-2} \), which yields theoretically a relative standard deviation of 3% from the mean value on the SSC profile. As a consequence, we assume hereafter that \( \sigma_{SSC,VH} = 3\% \). It should be noted that this value would be higher while including the sand fraction.

Lateral homogeneity is mainly function on the lateral variability in turbulence, and so on the lateral variability in bed roughness. It was studied during the flushing of 2006 (Némery et al., 2013) on the Isère River at site I1, where the river slope is the mildest (0.1 %) and the river cross-section is the widest (100 meters). The measurements were performed at three sampling positions at the surface (left, middle and right side of the section). The average value of the standard deviation was \( \sigma_{SSC,HH} = 5\% \) between the middle of the section and the left and right sides, and the error occurred mainly during the lowering phase of the flushing event.

These two values (\( \sigma_{SSC,VH} = 3\% \) and \( \sigma_{SSC,HH} = 5\% \)) are used at every measurement site, for every flushing event. These uncertainty values may be locally higher near confluences. Indeed, in case of a confluence, the lateral homogeneity also depends on the longitudinal mixing and the distance to the confluence. However, since all measurement sites are far enough from confluences (except A2, which has been skipped), this local effect is neglected.

**Measurement method** (\( \sigma_{SSC,Spl} \) and \( \sigma_{SSC,Tu} \)). The SSC measurement method plays a key role in error production. For this study, two different methods were used to measure the SSC: a direct method, using automatic or manual samples, and an indirect method, using a turbidimeter.

The error produced by the first method was studied in laboratory (Mano, 2008). The repeatability of the measurement was tested 40 times on several samples, over a range of SSCs from 0.02 to 1 g/l. This experimental study showed that the relative standard deviation decreased rapidly with SSCs from 20.1% to 5.5%. Another experiment was performed with higher...
concentrations (about 10 g/l), and confirmed the decrease of the mean standard deviation to 2.5%. Since most of the measured concentrations during a flushing event vary from 1 to 30 g/l, the relative standard deviation from the direct sampling method was assumed equal to $\sigma_{SSC, Spl} = 2.5\%$.

Navratil et al. (2011) gave a global uncertainty value resulting from the turbidimeter sampling method. The authors estimated a relative standard deviation of 5% at high concentrations (more than 10 g/l) and 10% at lower concentrations (between 1 and 10 g/l). In the data set presented in Table 1, most of the SSC values obtained from a turbidimeter were lower than 10 g/l. Thus the relative standard deviation is fixed at $\sigma_{SSC,Tu} = 10\%$. However, for the specific cases of flushing event, turbidity measurements were generally combined with regular ISCO sampling; as a consequence, we reduced the error to 5%.

**Effect of temporal sampling frequency ($\sigma_{SSC,Int}$).** The term $\sigma_{SSC,Int}$ has to be estimated due to the heterogeneity of the sampling frequencies for the SSC measurements. A simple formula is proposed to estimate this term: between two measured SSC values $SSC_i$ and $SSC_{i+1}$ separated by the time interval $\Delta t$, the local relative error could be estimated as the product $|SSC_i - SSC_{i+1}| \times \Delta t$, normalized by the averaged SSC value $(SSC_i + SSC_{i+1})/2$ and the time period $T_{event}$ of the flushing event. Finally, the relative standard deviation resulting from the interpolation can be expressed for a whole instantaneous SSC signal of N values as:

$$\sigma_{SSC,Int} = \frac{1}{N} \sum_{i=1}^{N} \frac{|SSC_i - SSC_{i+1}| \times \Delta t}{T_{event} \times \frac{SSC_i + SSC_{i+1}}{2}} \quad (10)$$

As observed in Figure 3, $\sigma_{SSC,Int}$ decreases with the number of sampled SSCs during the event. This result allows defining a sampling strategy during the flushing event. This indicator varies from about 0.004% for a very high frequency signal (turbidimeter) to 24% for a low frequency signal (manual sampling with a frequency lower than one sample per hour). Whatever the case, uncertainties due to sampling frequency become negligible as soon as there is at least one sample every 30 mn ($\sigma_{SSC,Int} \approx 3\%$). The high frequency obtained thanks to turbidimeters is therefore not so beneficial in terms of overall uncertainty since $\sigma_{SSC,Tu} = 10\%$.

2.5. **Significance of the local mass balance**

Knowing the uncertainty in the integrated flux estimations, the signifi-
cance of the local mass balance $\Delta \Phi(i \to i + 1)$ can be evaluated regarding the confidence interval of the integrated fluxes calculated at two consecutive measurement sites. The condition for a significant erosion or deposition rate between two consecutive measurement sites is thus the following:

$$|\Phi(X_{i+1}) - \Phi(X_i)| > \sigma_{\Phi}(X_{i+1}) + \sigma_{\Phi}(X_i)$$  \hspace{1cm} (11)

3. Results

3.1. Total fluxes and global uncertainty

The calculated values of $\Phi(X_i)$ and their associated relative uncertainties $\sigma_{\Phi}$ are presented in the Table 2. Measurements were not achieved every year at the 14 sites generally due to experimental difficulties.

The uncertainty values of the integrated fluxes vary between 9.2% and 25.9%, with a mean and median values of 11.5% and 10.7% respectively. Figure 4 shows an example of the global uncertainty profile for the 2010 dam flush, with the SSC, discharge and global uncertainty profiles (Figure 4a), and the resulting confidence interval $\Phi(X_i) \pm \sigma_{\Phi}(X_i)$ (Figure 4b). The global uncertainty stems in almost equal proportions from the uncertainties on discharge and SSC. The results are similar for the other flushing events, except for the case of very scattered SSC samples. In these cases the contribution of the SSC uncertainties is predominant (e.g. in 2006).
Table 2: Summary of the global uncertainty $\sigma_\Phi$ (in %) associated with the flux $\Phi$ at the 14 sites (in $10^3$ Tons).

<table>
<thead>
<tr>
<th>Site</th>
<th>2006 $\Phi$</th>
<th>$\sigma_\Phi$</th>
<th>2007 $\Phi$</th>
<th>$\sigma_\Phi$</th>
<th>2009 $\Phi$</th>
<th>$\sigma_\Phi$</th>
<th>2010 $\Phi$</th>
<th>$\sigma_\Phi$</th>
<th>2011 $\Phi$</th>
<th>$\sigma_\Phi$</th>
<th>2012 $\Phi$</th>
<th>$\sigma_\Phi$</th>
</tr>
</thead>
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<td>A10</td>
<td>-</td>
<td>-</td>
<td>11.7 13.1</td>
<td>-</td>
<td>20.1 10.9</td>
<td>29.1 10.2</td>
<td>14.5 11.0</td>
<td>51.6 12.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A9</td>
<td>39.5 13.4</td>
<td>-</td>
<td>16.5 13.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A8</td>
<td>36.6 13.3</td>
<td>21.3 13.1</td>
<td>24.9 11.2</td>
<td>36.3 10.3</td>
<td>13.0 11.1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>A7</td>
<td>44.4 13.1</td>
<td>22.2 13.1</td>
<td>16.9 12.6</td>
<td>25.2 12.6</td>
<td>14.7 12.6</td>
<td>57.5 12.6</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>A6</td>
<td>63.6 26.1</td>
<td>23.6 13.1</td>
<td>20.3 11.0</td>
<td>32.2 10.7</td>
<td>19.2 11.4</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A5</td>
<td>39.1 11.1</td>
<td>18.5 9.9</td>
<td>21.7 9.9</td>
<td>33.6 9.8</td>
<td>19.5 9.9</td>
<td>48.4 9.9</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A4</td>
<td>-</td>
<td>-</td>
<td>21.8 12.7</td>
<td>17.5 12.5</td>
<td>31.9 11.0</td>
<td>19.2 13.0</td>
<td>53.3 10.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>39.0 13.8</td>
<td>24.9 12.3</td>
<td>17.4 12.3</td>
<td>33.8 10.8</td>
<td>21.3 12.9</td>
<td>71.9 10.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td>-</td>
<td>-</td>
<td>38.7 15.8</td>
<td>16.9 12.2</td>
<td>33.0 10.5</td>
<td>28.8 14.5</td>
<td>65.6 10.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I4</td>
<td>-</td>
<td>-</td>
<td>15.8 12.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>33.1 12.7</td>
<td>17.5 12.6</td>
<td>79.6 9.8</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I2</td>
<td>40.9 12.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>52.9 10.3</td>
<td>17.9 11.0</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I1</td>
<td>56.6 13.5</td>
<td>42.0 12.6</td>
<td>20.2 12.6</td>
<td>46.6 12.6</td>
<td>19.7 12.6</td>
<td>68.1 12.8</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 4: Spatial variation of the uncertainties in fine sediment concentration, discharge, and fine sediment flux estimations for the 2010 dam flushing event (a) and confidence interval resulting from the estimation of global uncertainties (b).

3.2. Spatial evolution of total fluxes

As the first measurement site A10 is located only one kilometre downstream to the SMLP dam, it gives the mass output from the three Arc River
dams. In Figure 5, we can see that this total input of sediment from dams varied from 12,000 tons in 2007 to 40,000 tons in 2006 (at A9) and 52,000 tons in 2012. These variations in the storage and removal of fine sediment from the reservoirs depend on the upstream watershed incomes and dam management operations during the year separating two consecutive flushing events. It should be noted that in Figure 5, a decrease (respectively increase) in $\Phi(X_i)$ indicates deposition (respectively erosion). For the 2012 flushing event, a larger erosion was observed due to the much larger discharge during the first step of the flushing event that led to a much significant erosion of the dam reservoirs.

![Figure 5: Spatial profiles of the integrated suspended sediment fluxes $\Phi(X_i)$.](image-url)

Over the whole river system, the values of $\Phi(X_i)$ vary widely depending on the flushing event with some clear difference on the Arc and Isère rivers, respectively:

- On the Arc River, between A10 (-50 km) and A1 (0 km), $\Phi(X_i)$ was conserved in 2006, 2009, and 2010, whereas it increased between these two measurement sites by almost 12,000 tons in 2011 ($\approx +60\%$), and 20,000 tons in 2007 and 2012 ($\approx +50\%$ and $+40\%$, respectively), indicating a large and significant erosion regarding the confidence interval, especially in the downstream part of the Arc River.
- On the Isère River, between A1 (0 km) and I1 (63 km), $\Phi(X_i)$ did not vary significantly in 2007, 2009; it increased by more than 10,000 tons in 2006 and 2010 ($\approx +40\%$). In 2011 and 2012, some variations were observed but on the upstream Isère reach only.

- Eventually, apart from the 2009 and 2011 events corresponding to the lowest total fluxes, one can observe a net erosion over the whole river system from approximately 10,000 tons in 2006 and 2012 to 20,000 tons in 2007 ($\approx +30\%, +40\%, \text{ and } +50\%$, respectively).

This indicates that the river bed responds differently to very similar flushing hydrographs depending on the year. A more detailed analysis of the $\Phi$ spatial evolution shows that even if the value $\Phi(X_i)$ remained the same, conserved or increased along the entire studied area, specific local variations may occur especially around St-Jean-de-Maurienne ($X \approx -40$ km) and in the Isère River straight after the confluence with the Arc River ($0 < X < 15$ km). Strong positive or negative gradients of $\Phi(X_i)$ can be observed, which indicate potentially strong local deposition or erosion processes.

### 3.3. Local mass balance

Regarding the confidence interval, some local variations of $\Phi(X_i)$ appear to be not significant. As an example, the magnitude of the local variations observed between A4 ($X = -24$ km), A5 ($X = -33$ km) and A6 ($X = -38$ km) is not high enough to be significant regarding the confidence interval for most flushing events. Fig. 4b shows on the opposite a strong positive variation between I3 ($X = 14$ km) and I2 ($X = 27$ km) in 2010, which is significant regarding the confidence interval.

Table 3 presents the values of the local mass balance $\Delta\Phi(i \rightarrow i + 1)$ (expressed in $10^3$ tons) along the study area. If $\Delta\Phi(i \rightarrow i + 1) > 0$, this means that resuspension occurs between two consecutive measurement sites located at positions $X_i$ and $X_{i+1}$. If $\Delta\Phi(i \rightarrow i + 1) < 0$, this means that deposition occurs between the two consecutive measurement sites. The local mass balance values which are confirmed by the confidence intervals are given in bold font in Table 3 following Eq. 11. It should be noted that depending on the year, some intervals have been aggregated due to the absence of data in some sites. It does not affect the results since the condition proposed (Eq. 11) does not depend on the distance between the two consecutive measurement sites.
Table 3: Local mass balance ($\Delta \Phi(i \rightarrow i + 1)$, in $10^3$ tons) distribution in the Arc-Isère river system for the six studied dam flushing events (bold values correspond to significant values regarding the global uncertainty value, positive values correspond to erosion whereas negative values correspond to deposition).

<table>
<thead>
<tr>
<th>Reach</th>
<th>2006</th>
<th>2007</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>A9-A10</td>
<td>-</td>
<td>+4.8</td>
<td>+4.7</td>
<td>+7.2</td>
<td>+3.5</td>
<td>+5.9</td>
</tr>
<tr>
<td>A8-A9</td>
<td>-2.9</td>
<td>+4.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A7-A8</td>
<td>+7.8</td>
<td>+0.8</td>
<td>-7.9</td>
<td>-11.1</td>
<td>-3.3</td>
<td></td>
</tr>
<tr>
<td>A6-A7</td>
<td>+19.1</td>
<td>+1.4</td>
<td>+3.3</td>
<td>+7.0</td>
<td>+4.5</td>
<td></td>
</tr>
<tr>
<td>A5-A6</td>
<td>-24.5</td>
<td>-5.1</td>
<td>+1.5</td>
<td>+1.4</td>
<td>+0.2</td>
<td></td>
</tr>
<tr>
<td>A4-A5</td>
<td>-0.1</td>
<td>+3.3</td>
<td>-4.2</td>
<td>-1.7</td>
<td>-0.2</td>
<td>+4.8</td>
</tr>
<tr>
<td>A3-A4</td>
<td>+3.1</td>
<td>-0.1</td>
<td>+1.9</td>
<td>+2.1</td>
<td></td>
<td>+18.7</td>
</tr>
<tr>
<td>A2-A3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1-A2</td>
<td>+1.2</td>
<td></td>
<td>-1.0</td>
<td>+0.1</td>
<td>-11.3</td>
<td>+14.0</td>
</tr>
<tr>
<td>I4-A1</td>
<td></td>
<td>+13.9</td>
<td>-0.5</td>
<td>-0.8</td>
<td>+7.4</td>
<td>-6.3</td>
</tr>
<tr>
<td>I3-I4</td>
<td></td>
<td>+3.3</td>
<td>-1.0</td>
<td>+0.1</td>
<td>-11.3</td>
<td>+14.0</td>
</tr>
<tr>
<td>I2-I3</td>
<td></td>
<td>+4.4</td>
<td>+19.8</td>
<td>+0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I1-I2</td>
<td>+16.4</td>
<td></td>
<td>-6.3</td>
<td>+1.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3 indicates that only 14 of the 52 local mass balances are significant for the proposed uncertainty model propagation: 5 of the 19 negative mass balances, and 9 of the 33 positive mass balances. However, significant local mass balances highlight different behaviours of the river bed evolution: in 2010, a significant deposition is observed just upstream a strong re-suspension, even if the two successive river reaches (separating A8, A7 and A6) have almost the same mean slopes (about 1%) and reach lengths are smaller than 5 kilometres. More generally, we can see that flushing events produce significant dynamics in terms of exchange with the river bed, with values of re-suspension or deposition of fine sediments up to 20,000 tons.

Despite this relatively low significance of the local mass balance values, meaningful tendencies may explain why local variations can be significant for one flushing event but not significant for the next one. More generally, the responses of the river bed can be divided into two groups: the river bed gave similar responses for 2009, 2010 and 2011 (group 1), and similar responses for 2006 and 2007 (group 2). The difference observed between the mass balance distributions of groups 1 and 2 is particularly evident for upstream sites in
the Arc River, where the slope of the river bed is high: for example, high erosion of the bed was observed between measurement sites A8 and A7 before the year 2008, whereas systematic deposition was observed after this year. The same behaviour was observed between sites A5 and A4, whereas the opposite was observed between sites A6 and A5. The two groups of flushing events were separated by a major event: in May 2008 a natural flood flowed from the upper Arc catchment (15-year return period). Regarding previous results, the bed changes due to this flood significantly modified the local mass balance distribution. Jaballah et al. (2015) showed evidences on these large effect of the 2008 flood on the river morphology on a 5 km long reach (located between A6 and A5), which confirms its impact on SSF dynamics. The flood that occurred in May 2010 (the second highest in intensity during the study period), and which affected in similar proportions all the sub-catchments of the Isère watershed, did not change this local mass balance distribution. The difference of behaviour between flushes could also be partly explained by the settling properties of sediments that can change depending on the storage duration in dam reservoirs (Legout et al., 2018). Indeed, most deposits in dam reservoirs form during the spring period. Depending on the exact date of the dam flushing, their storage duration can vary from a few days to a few months depending on the hydrology.

4. Discussion

4.1. Spatio-temporal dynamics of discharge and SSC

The analysis of SSC and discharge signals gives information on their variability along both rivers and could provide some clues about the differences in flux dynamics from one flushing event to another. In Figure 6, the discharge and concentration measurement are presented for the dam flushes of 2007 and 2009 at Pontamafrey (A7) and Grenoble (I1), respectively. On site A7, the SSC patterns resulting from the 2007 and 2009 flushing events differ in shape and magnitude. In 2007 the peak SSC value (16.7 g/l) was measured during the first discharge step of the flushing hydrograph, whereas the peak value of the 2009 SSC signal (10.9 g/l) appeared during the second discharge step. These differences may be explained by the availability of the fine sediments and the erosion processes in the three dam reservoirs of the Arc River. In 2007, the SSC peak value corresponds to sediments that are easily removed from the reservoirs, while the second part of the SSC signal is related to sediments removed due to higher bed shear stresses
Figure 6: Water discharge and concentration time-series at sites A7 (Pontamafrey, a and c) and I1 (Grenoble, b and d) for the 2007 (a and b) and 2009 (c and d) flushing events.

discharge values, super-critical flows in the dam reservoirs). In 2009 the sediments of the dam reservoirs were more difficult to remove, and the SSC signal increased only from the increasing part of the second discharge step. As a consequence, the sediment input is highly function of the hydrology during the months preceding the flushing event, and so the accumulation of fresh fine sediments in dam reservoirs during the spring period. On site I1, the SSC signals are smoothed, because of the long distance travelled along the river and the dispersion processes; the differences between the SSC peak values are attenuated. One should note that the SSC peak is measured systematically after the discharge peak of the hydrograph since the flood wave travels faster than flow velocity.
4.2. Hydrology influence on SSC dynamics

In order to understand the possible influence of the hydrology on the fine sediment dynamics, we define an average discharge for the spring season before the flushing event \(Q_{m,\text{spring}}\) (i.e. from the 1st April to the day before the flushing event) at both A7 and I1 location, as well as a base discharge \(Q_{m,\text{base}}\) during the flushing event on the Isère River at I1 location (averaged discharge on the day before the flushing event). Indeed, the \(Q_{\text{max}}\) values are almost the same whatever the event on the Arc River; they increase only with the input from tributaries, i.e. at the Isère restitution \((X = -8 \text{ km})\), the Isère confluence \((X = 0 \text{ km})\), and at the Cheylas restitution \((X = +20 \text{ km})\).

Results are presented in Tab. 4 together with the concentration peak values measured at A7 location for both discharge step.

Table 4: Mean discharges at Pontamafrey (A7) and Grenoble (I1) during the spring period before flushing events \((Q_{m,\text{spring}})\) and at the restitution near A2 site \((Q_{m,\text{rest}})\), peak concentrations for the first \((C_{p1})\) and second \((C_{p2})\) plateau of the event, and cumulative SSF \((\Phi_{\text{tot,\text{spring}}})\) measured at site I1 during the 3 months preceding each flushing event.

<table>
<thead>
<tr>
<th>Site</th>
<th>A7</th>
<th>A2</th>
<th>I1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>(Q_{m,\text{spring}}) (m^3/s)</td>
<td>(C_{p1}) g/l</td>
<td>(C_{p2}) g/l</td>
</tr>
<tr>
<td>2006</td>
<td>30.0</td>
<td>9</td>
<td>24</td>
</tr>
<tr>
<td>2007</td>
<td>33.5</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>2009</td>
<td>36.0</td>
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<tr>
<td>2010</td>
<td>35.5</td>
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<td>12</td>
</tr>
<tr>
<td>2011</td>
<td>33.5</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td>2012</td>
<td>27.0</td>
<td>12*</td>
<td>42</td>
</tr>
</tbody>
</table>

*: a third intermediate peak concentration at 20 g/L was observed because of the unexpected peak discharge in the middle of the first plateau.

In general, the second peak of concentration during the 2nd plateau is higher than the first one since bed shear stresses are higher in the dam reservoirs. However, in 2007, a lower value is observed indicating a smaller stock of fine sediments in the reservoirs. It could be explained by the flood event in September 2006 \((Q_{\text{max}} \approx 150 \text{ m}^3/\text{s})\). Only two other significant floods, for which dam gates were opened, were observed during the period between 2005 and 2012: the May 2008 flood \((Q_{\text{max}} \approx 450 \text{ m}^3/\text{s})\) and the June 2010 flood \((Q_{\text{max}} \approx 160 \text{ m}^3/\text{s})\). Similarly, the following flushing event
in 2009 and 2011 yielded a low total flux $\Phi$ just after dam reservoirs, i.e. $\Phi < 20,000$ tons. The initial total flux from dam reservoir is thus function of the duration without dam operation. On the other hand, the hydrology during the spring period does not appear to influence significantly the amount of fine sediment to be eroded. No correlation could be found between the average flow $Q_{m, spring}$ on the two month prior to the flushing event and the initial total flux.

Also, we note that erosion generally occurred in the Isèrere River when the base discharge $Q_{m, base}$ in the Isère River is the highest (2006, 2010, and 2012). This could be explained as the gravel bar were then flooded and fine sediment stocks over gravel bars could be resuspended. However, for the 2012 event, which reached the largest discharges (close to 500 m$^3$/s), highest vegetated part of gravel bars have been flooded and have enhanced deposition. We expect to relate erosion on the downstream part of the Arc River observed in 2007, 2011, and 2012 with the additional flow discharge coming from the restitution ($Q_{m, rest}$). However, no clear correlation could be made.

### 4.3. Initial quantity of erodible sediments in the river bed

Continuous SSF measurements at site I1, which integrate the whole study area, are available over the whole period of the study (with a sampling step of 30 minutes). More specifically, the cumulative SSF measured at site I1 during the 2-3 months preceding each flushing (from 1st April) event showed large variations as a function of the event (Tab. 4): from 125,000 tons in 2011 to 1,000,000 tons in 2010. The large amounts of sediment mass in 2006 and 2010 were mostly due to a very active spring period but also due to some engineering works on the Isère dikes in 2010. Also, a large compensation reservoir directly connected to the Arc River just upstream A7 ($X = -40$ km) was cleaned out over a three month period in 2010 and 2011. In 2006 and 2010, the 2-month integrated SSF at I1 reached very large values that have potentially led to large deposition over gravel bars. Significant re-suspension have been observed on the Isère River during the flushing events performed these two years, and on the Arc River during the 2006 event, which appears consistent with the hydrology during the spring period. The cleaning of the compensation reservoir in 2011 could also explain the large re-suspension observed in the Arc River during the following flushing event, just upstream the confluence with the Isère River.

In any case, the sediment mass transported during a flushing event does not represent more than 5% of the annual suspended sediment mass transiting
at site I1. These results corroborate previous estimations of the contribution of hydraulic flushes to annual SSF of the Isère River (Némery et al., 2013).

Our results confirm the importance of the suspended sediment dynamics before the event (during the spring period). Indeed, the spatial distribution of sediment deposits strongly affects the possible resuspension of sediment during the flushing event. Some studies (Droppo et al., 2001) have shown the effect of sequential bed depositions under several flow conditions in the bed erosion process, especially if the proportion of cohesive sediments in the total suspended load is non-negligible.

4.4. Dynamic mass balance

Table 3 gives spatial information on the local mass balances per river reach. For example, the river bed between the two consecutive measurement sites A4 and A3 was systematically eroded as was the river bed between A3 and A1. Furthermore, the lengths of these two reaches are almost equal ($\approx 12$ km). However, the values of the dynamic and time-normalized mass balance $\Delta \Phi \%_{(i \rightarrow i+1, t\%)}$ (Eq. 5) on these parts of the river bed show very different mass transport dynamics during the flushing events. In Fig. 7 c and d, the values of $\Delta \Phi \%_{(A3 \rightarrow A1, t\%)}$ and $\Delta \Phi \%_{(A4 \rightarrow A3, t\%)}$, respectively, are plotted as a function of the time made dimensionless with the duration of the event $T_{event}$. Although the two reaches of the river were globally eroded at the end of the flushing event, the A3-A1 reach endured first some large erosion and then some deposition. This succession of erosion and deposition could be explained by an easily erodible mass of sediment on the river bed that was removed by the first discharge step of the flush hydrograph. During the second discharge step, the water level became high enough to flow on gravel bars implying significant deposition. On the other hand, the A4-A3 reach endured successively considerable deposition and then even larger erosion during the same event (Fig. 7 d). On this reach, two large, easily submersible banks and a small dam reservoir were the only remarkable sites. They could indeed explain the following mass balance dynamics from 2009 to 2011 events: before the first discharge step, the reservoir was emptied, removing a small proportion of the fine deposited sediments. This first release generated nevertheless a SSC peak at a relative low discharge value and did not influence the global mass balance value. The first discharge step led to considerable deposition on the easily submersible banks which were eventually easily re-suspended by the second discharge step. Furthermore, the second discharge step involved sufficiently high water levels to remove the
upper layer of sediment deposited in the small reservoir. The global mass balances calculated for all the events were in this case not representative of the temporal dynamics of this reach, where the exchange processes with the river bed were significant.

Figure 7: Dynamic cumulative mass balance between A8 and A7 (a), A5 and A4 (b), A4 and A3 (c) and A3 and A1 (d) (a positive value means erosion whereas a negative value means deposition).

This cumulative method is also applied to confirm the effect of the flood in May 2008, as it appears in Table 3 (i.e. different river bed responses before and after the flood). On the two previous examples from Fig. 7 c and d, we can see that deposition and erosion dynamics suddenly changed between 2007 and 2009. Even if the mass balance at the end of the events remain positive, the dynamics changed from significant exchanges with the river bed to simple transfer of sediment mass (and vice versa). After 2009,
the dynamics tend back to the one observed before the 2008 flood.

The dynamic cumulative mass balance for the more upstream reaches A8-A7 and A5-A4 are presented in Fig. 7 a and b, respectively. If the overall impact of the dam flushes on these reaches was generally deposition, they presented a first step of erosion followed by a large deposition on the second part of the event. These two additional examples also confirm the 2008 flood impact on SSF dynamics in these two other reaches linked to the large modifications of the river morphology (Jaballah et al., 2015). Indeed, the opposite behaviour was observed in 2007 compared to the events after 2008, the global mass balances changing global erosion into global deposition (b) or inverse (a).

The four examples presented in Figure 7 show that the river reaches have not the same ability to recover the prior-flood equilibrium: reaches like the ones between A5 and A4 or A3 and A1 show in 2011 very similar dynamics than the one observed in 2007. For the two other reaches, the prior dynamics were still not recovered in 2011. It also shows the dominating influence of river morphology on SSF dynamics.

4.5. Physical characteristics of the transported sediments

Sediments parameters like grain size and/or settling velocity but also suspended concentration are fundamental for predicting deposition processes (Legout et al., 2018). Their variability could also explain observed differences between flushing events or river reaches (Garcia, 2008). In 2011, grain size distribution (GSD) have been measured for every sediment samples at A5, A1 and I1 sites. Grain size characteristics, averaged over the flushing period, are presented in Table 5.

Table 5: Time-averaged values of $D_{10}$, $D_{50}$ and $D_{90}$ ($\mu$m) measured at sites A5, A1 and I1 during the 2011 flushing event.

<table>
<thead>
<tr>
<th>Site</th>
<th>2011 flushing event</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$D_{10}$</td>
</tr>
<tr>
<td>A5</td>
<td>3.4</td>
</tr>
<tr>
<td>A1</td>
<td>3.4</td>
</tr>
<tr>
<td>I1</td>
<td>3.1</td>
</tr>
</tbody>
</table>

These grain size measurements show that few differences are observed between the three measurement sites for this event even if a small fining
is observed. Only the percentile $D_{90}$ changed significantly between A1 and I1. In 2011, one observed a significant local erosion between A5 and A1 and a significant local deposition between A1 and I3 this year. The local deposition between A1 and I3 could be related to the decrease of $D_{90}$ values with a position of the coarsest particles downstream the confluence with the Isère River. During the flushing event of June 2011, the additional discharge coming from the upper Isère River was low, and the flow velocity could have decrease significantly downstream the confluence where the river width is larger.

Despite the significant local erosion observed between A5 and A1, no change were measured in terms of grain size distributions. Fig. 7 b, c and d shows the local dynamics of erosion and deposition between A5 and A1. In 2011, the flux was globally transferred between A5 and A4 with a first period of deposition followed by a period of erosion. In this case, one can conclude that the freshly deposed sediments during the first part of the event have been re-suspended during the second part of the event explaining the constant GSD. However, between A3 and A1, the opposite behaviour is observed. Previous sediments deposits on the river bed were replaced by the suspended sediments coming from upstream. However, a similar GSD is observed indicating a certain consistency of the long term dynamics of the fine deposits in these reaches.

5. Conclusion

Six field campaigns were analysed to evaluate the impact of dam flushing events on suspended sediment dynamics downstream of the dams. SSC and discharge measurements were performed on the Arc and Isère Rivers, France, at 14 sites in June 2006, 2007, 2009, 2010, 2011, and 2012. These intensive measurement campaigns allowed an estimation of suspended sediment fluxes along the reaches of both rivers as well as the local mass balance.

To estimate the significance of the observed local variations, a propagation model for the uncertainty on the global flux was built, taking into account the main sources of error for both SSC and discharges. The mean calculated uncertainty value was $\sigma_\Phi = 11.5\%$. These uncertainty values confirm the global tendency of suspended sediment flux propagation, whereas only 14 out of 52 local mass balances between two consecutive measurement sites were significant. Also, a dynamic time-normalized method was developed
to evaluate and discuss temporal variations of the mass balance during one flushing event.

Even if the dam flushing operating protocol was identical over the years (except for 2012), the suspended sediment mass removed from the reservoirs varied from 10,000 tons in 2007 to 40,000 tons in 2006. The hydrology on the Upper Arc River during the previous spring period significantly affected the efficiency of these flushing events. On the other hand, the global fine sediment mass balance along the studied river segment varied from zero in 2011 and 2009 to 30,000 tons in 2007 indicating also a strong effect of the initial state: stock of fine sediments in the river but also river geometry.

We showed that the bed morphology significantly modified the fine sediments dynamics. Indeed, the May 2008 flood, a 15-year return period flood on the Arc River that largely modified both Arc and Isère river morphologies yielded major changes in fine sediment dynamics during flushing events. Indeed, opposite behaviour were observed for many reaches in terms of global mass balance (after the flushing event) but also in terms of temporal dynamics during the event (erosion followed by deposition or the opposite).

Another point to be addressed is the quantity and quality of the fine sediment stocks in the river bed, i.e. surface deposits and stocks infiltrated in the bed matrix. Indeed, our knowledge of the stocks remains very limited. It would be important to evaluate the quantity of available sediments as deposits but also stocked in the river bed that could be re-suspended as soon as coarse particles are mobilized (Navratil et al., 2010; Misset et al., 2019). More continuous monitoring of SSF, but also direct measurements on the river bed and in dam reservoirs are necessary to estimate the initial state of the river bed and the availability of the fine sediments in reservoirs.

To better predict the effect of dam flushing, investigations must now focus on combining the analysis of local morphodynamics and global hydrological aspects more in detail. It could be eventually made in the future thanks to repeated Lidar surveys, assuming that topographic changes are only due to fine sediment dynamics and only occur on gravel bars. An important issue is the sand fraction. It corresponds indeed to approximately 50% of the deposit volume (Camenen et al., 2016) whereas sand flux are not captured by the turbidimeters nor by the surface sampling network. Also, the use of a numerical model to calculate downstream sediment propagation would help dam operators to optimize dam flushing scenarios.
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