A PHYSICALLY BASED METHOD OF COMBINING ADCP VELOCITY DATA WITH POINT SAMPLES TO COMPUTE SUSPENDED-SAND DISCHARGE – APPLICATION TO THE RHONE RIVER, FRANCE

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Abstract

Measuring suspended-sand flux in rivers is a challenge since sand concentrations are highly variable in time and space throughout a river cross section. Most of the present methodologies rely on point or depth-integrated sampling (Nolan et al., 2005, Topping et al., 2016). The standard method estimates mean concentration and multiply it by discharge to compute the suspended-sand discharge. Here, we demonstrate methods of combining point suspended-sediment samples with ADCP (Acoustic Doppler Current Profiler) high-resolution depth and velocity measurements to improve vertical and lateral integration of concentration and flux. A preliminary version of this method is applied to data collected in the Rhône River in Lyon, France, during a 10-year flood in January 2018. Two options for vertically integrating the measured suspended-sediment concentrations were tested whereas lateral integration was based on nearest-neighbor interpolation only, as a baseline option. Sand flux results are similar, thus suggesting that vertical integration options may be less critical than lateral integration options that will be implemented and tested in future work.

Introduction

Estimation of suspended-sand discharge in rivers

Measuring suspended-sediment discharge in rivers is a multi-step process that requires accurate measurement of water discharge and suspended sediment throughout the river cross section. Measuring suspended-sediment concentrations that are representative of sediment conditions in a river is difficult for several reasons and many sources of uncertainties affect the final results. Because the suspended sediment is highly variable in space and time a large number of samples may be required to be representative of the suspended-sediment conditions in the cross section, especially if the suspended load is dominated by sand. Suspended sand (particles with diameter d>63µm) is not homogeneously distributed throughout the cross section; concentrations generally increase toward the river bed (*i.e.* graded suspension). Conversely, washload, which is

made of particles finer than sands (clays and silts, i.e., particles with d<63µm), is mixed more homogeneously throughout the cross-section and may be characterized with relatively fewer samples.
The cross-sectional suspended sediment discharge, Q_s [kg/s], is defined as the mass of suspended sediment passing through a specific river cross section per unit time:

$$Q_S = \int_{y=0}^{B} \int_{z=0}^{H} c(y,z) v(y,z) \mathrm{d}z\mathrm{d}y \quad (1)$$

where v [m/s] and c [g/L] are the time-averaged velocity and suspended-sediment concentration, respectively. B and $H(y)$ [m] are the surface width and vertical depth of flow, respectively.
To compute the suspended-sand discharge in the cross section the standardized method consists of estimating the mean concentration with the sample results and multiplying it by discharge measured or computed in the river reach. The limited number of samples involves interpolating the concentration in the cross section. The aim of the proposed method is to improve vertical and lateral integration of concentrations using high-resolution ADCP depth and velocity measurements.

Methods for computing sand discharge measurement

The most popular method in the USA to compute sediment discharge is to measure the velocity-weighted suspended-sediment concentration in the cross-section using depth-integrating sampling (Edwards and Glysson, 1999) and then to multiply this concentration by the water discharge as:

$$Q_S = C \times Q \quad (2)$$

with Q_s [kg/s] the instantaneous suspended-sediment discharge, C [g/L] the velocity-weighted suspended-sediment concentration in the river cross section and Q [m^3/s] the water discharge at the same time. The method endorsed by the USGS (Porterfield, 1972; Edwards and Glysson, 1999) is described in the ISO 4363 (2002) standard as the “Conventional method” or “discharge-weighted method”. In the rest of this study the method is identified as the standardized method. It is based on the computation of a velocity-weighted suspended-sediment concentration for the cross-section. The method involves dividing the cross-section by verticals into n segments. The verticals are chosen according to two methods: Equal-Width Increment method (EWI) or the Equal-Discharge Increment method (EDI). Using these methods, samples of the water–suspended-sediment mixture are collected at the local velocity in each vertical. Depth-integrated or point integrated sampling methods are used to eliminate the effect of turbulent fluctuations in concentration because they are time-averaged (Topping et al., 2011). The velocity-weighted sediment concentration averaged over the flow depth at each vertical is either that measured by a depth-integrating sampler or, when point-integrating samplers are used, a velocity-weighted spatial average of the concentrations measured at various depths. Depending on the method used to sample the cross section (EWI or EDI), samples are combined or analyzed separately for concentration. Both the mean-section and the mid-section methods from the ISO 748 (2009) standard can be applied to calculate the segmental sediment discharge. For the suspended-sand discharge the standard recommends including in the calculation the percentage of the mass of sediment coarser than a given diameter.

Limitations of the methods: In the standardized method there is no specific focus on the near-bed zone which cannot be sampled, where although sand concentrations are highest, velocities are lowest. In the proposed method the near-bed concentrations are extrapolated using a physically-based vertical profile calibrated with point samples and ADCP velocity profiles. Because the depth-integrating samplers cannot describe vertical gradients in suspended-sand concentration, we use a point sampler in this study. The point-sample method is better suited to compute suspended-sand profiles and to extrapolate concentration throughout the vertical. The estimation of sand concentration might be improved with additional spatial information that can be provided by ADCP measurements and analyses of velocities and concentration profiles, to laterally integrate each ADCP ensemble. One other issue is that the lateral integration is done in the standardized method with a constant concentration integrated on the several segments defined above, with no constraints from depth, velocity and sediment transport along the cross-section.

Objectives

ADCP measurements from a moving boat are today a commonly used method for measuring streamflow (Mueller, 2009). The development of this method allowed a vast reduction in time spent making discharge measurements while providing large datasets with high-resolution measurements of depth, water velocity, and acoustic backscatter. We propose in this study to use this spatial information together with point suspended-sediment samples to work on the estimation of the suspended-sand discharge through the cross section. The velocity field and the bathymetry measured with the ADCP are used for the sediment discharge estimation including the extrapolation in unmeasured zones and interpolations between samples. For each cell of the ADCP, sand concentration is estimated based on a physical interpretation of both flow field and sand-concentration measurements. Some computing options for the vertical integration are tested here and applied to data collected during a flood on the Rhône River (France). We compare these computation options with the standardized method to validate this approach. The lateral integration, which is an important issue, is discussed but not yet implemented in our study.

Methodology

General methodology

The method we propose is based on typical ADCP discharge measurements and point suspended-sediment samples. The calculation procedure is based on an estimation of the concentration on a grid taken from ADCP data exports. The discharge grid from down-looking ADCPs is made of m ensembles of n cells distributed throughout the cross section. The top and bottom discharges (which are unmeasured) are extrapolated during the acquisition. These extrapolations are done according to the measurements and the user settings (Figure 1). The general idea is to assign a concentration for each cell such that, when multiplied by the ADCP discharge in this cell, it yields a good estimate of the sand flux through each cell. The total suspended-sand discharge Q_s [kg/s] can be computed such as:

$$Q_s = \sum_{j=0}^{m+1} \sum_{i=0}^{n+1} C_{ij}\, q_{ij} \quad (3)$$

where C_{ij} [m/s] and q_{ij} [m³/s] are the concentration and discharge at the cell (i,j). The unmeasured zones near the edges ($j = 0, j = m + 1$), the bottom ($i = 0$) and top ($i = n + 1$)

layers are included in the computation. Thus, the interpolation and extrapolation of concentration through the verticals and between them is the main source of error.

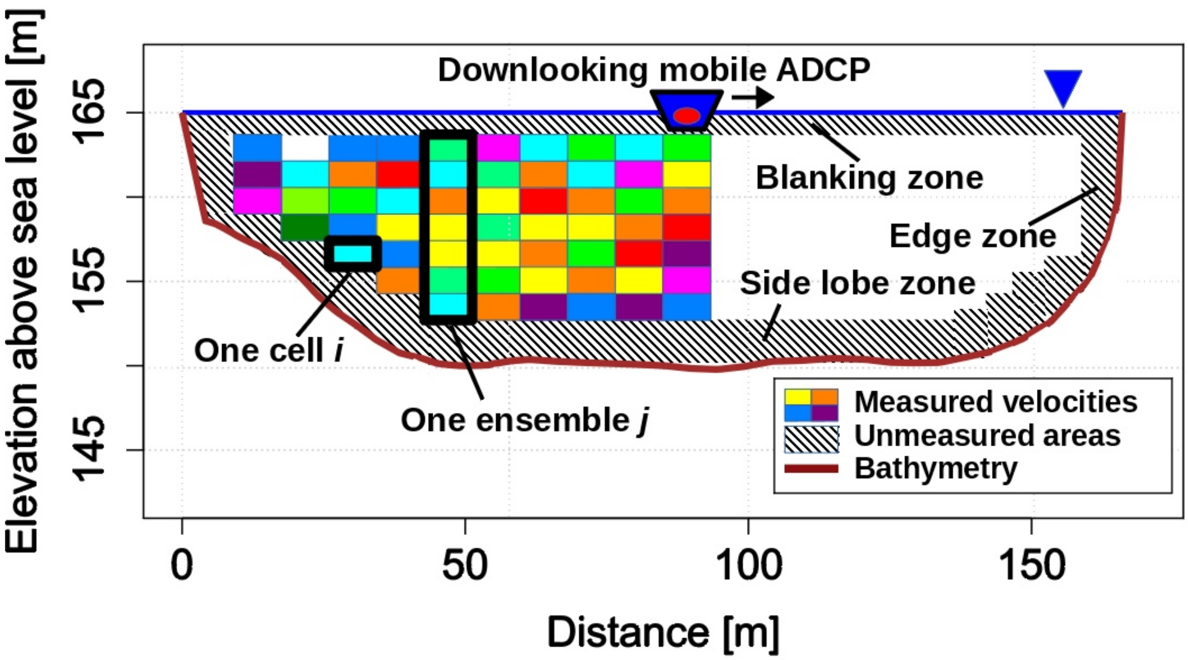


Figure 1: ADCP cross-section measurement sketch

The suspended-sand discharge φ_{ij} [kg/s] through one ADCP cell ij is:

$$\varphi_{ij} = q_{ij} \times C_{ij} = v_{ij} \times w_j \times h_{ij} \times C_{ij} \tag{4}$$

where v_{ij} [m/s] is the normal velocity, w_j [m] is the width, h_{ij} [m] is the ADCP bin size, and C_{ij} [g/L] is the time- and spatial-averaged sand concentration in the ADCP cell ij (j^{th} ensemble, i^{th} vertical cell).

In both processing options presented below, we apply the same lateral integration option, based on the mid-section method, using the concentrations around each vertical within 1/2 distance of the adjacent verticals. As for the measurement of water discharge with ADCPs, the final suspended-sediment discharge is the average of at least 4 ADCP transects computed with the sediment concentration data.

Adaptation of standardized method for depth-integrating point samples

This method is used to convert point-sample suspended-sediment concentrations to velocity-weighted suspended-sediment concentrations at each vertical j.

The flux per unit area φ'_{ij} [kg/m²/s] at each point (i, j) is calculated by multiplying the suspended-sediment concentration at each point C_{ij} [kg/m³] by the time-averaged velocity at each point v_{ij} [m/s] as:

$$\varphi'_{ij} = C_{ij} \times v_{ij} \tag{5}$$

The time-averaged velocity at each point v_{ij} is calculated using the nearest-neighbor method described above.
The velocity-weighted suspended-sediment concentration C_p [kg/m³] is then calculated for sub-section p centered on each vertical j is calculated as:

$$C_p = \frac{\sum_{i=1}^{N_{samples}} \varphi'_{ip} \times (z_{i+1} - z_{i-1})}{\overline{v_p}\,\overline{h_p}} \quad (6)$$

with $\overline{v_p}$ [m/s] and $\overline{h_p}$ [m] being the mean velocity and the mean depth of the sub-section p, respectively.
Finally, the suspended-sand discharge Q_s [kg/s] is calculated as:

$$Q_s = \frac{Q}{W} \sum_{p=1}^{N_{subsections}} C_p w_p \quad (7)$$

with Q being the water discharge [m³/s], W [m] the river width, and w_p the width of sub-section p (computed using the mid-section procedure).

Nearest-neighbor method

In this simple method, the nearest measured suspended-sediment concentration is applied to each ADCP cell. The post-processing steps for the estimation of C_{ij} are as follows:

- Every point suspended-sediment sample and every ADCP cell is located in the cross-section coordinate plane (in an elevation down from the water surface (z) and width (y) scale). In this plane we calculate for each cell (even in the unmeasured zones) with coordinates (y_{ij}, z_{ij}) the distance dm [m] to all the samples with coordinates (y_s, z_s) as:

  $$dm = \sqrt{(y_s - y_{ij})^2 + (z_s - z_{ij})^2} \quad (8)$$

  The concentration of the nearest sample is assigned as the concentration of each cell *ij*. This results in a complete concentration grid including the unmeasured parts.
- As an exception to the rule, the concentration applied on the edge sub-section is the concentration of the nearest surface sample.
- Each cell discharge measurement q_{ij} from the water discharge grid is multiplied by each cell concentration C_{ij} from the concentration grid to obtain a suspended sand discharge, for each cell, according to equation 4.

This nearest-neighbor method splits each sub-section p around a vertical in as many horizontal slices as there are samples. If only one depth-averaged concentration per sampling vertical is available, only one slice is made and the computing method is the same as the standardized method.

Physically based method

To provide a better approach to assigning concentrations to individual cells in each vertical, based on the point suspended sediment sample concentrations, we also developed a physically based method using Rouse mechanics to interpolate sediment concentrations in the z dimension at each vertical. Velocity profiles can be represented by a logarithmic vertical profile in the inner region (Smart, 1999):

$$\frac{u(z)}{U^*} = \frac{1}{k} ln\left(\frac{z}{Z_0}\right) \tag{9}$$

where u is the local, time-average velocity, U^* [m/s] the shear velocity, k the Von Kármán's constant, and z the distance from z_0, the Nikuradse roughness parameter. U^* is computed as a function of the depth-averaged velocity and z_0:

$$U^* = \sqrt{C_D} \times U \tag{10}$$

with the current friction coefficient $C_D = \left\{\frac{k}{(1+\ln(z_0/h))}\right\}^2$

Because $U = q_j/(w_j h_j)$, the only parameter to estimate is z_0. This estimation was based on ensemble-averaging.

An exponential relationship was employed to characterize the Rouse-style reduction in suspended-sand concentration with distance from the bed (Camenen et al., 2008):

$$C(z) = C_R \exp\left(\alpha \frac{z}{h}\right) \tag{11}$$

This equation was fit to the point-sample data at each vertical and then applied to each sub-section p around each vertical, allowing the reference concentration at a z_0 level : C_R [g/L] and the coefficient α to be determined.

Equation 11 was then used to predict the suspended-sand concentration profile over the water column.

The sediment flux at each elevation $\phi_p(z)$ in each sub-section k is then computed by multiplying equations (9) and (11), as follows.

$$\phi_p(z) = C_{p(z)} u_{p(z)} = U_p^*/k \ \ln\left(\frac{z}{z_{0p}}\right) C_{Rp} \exp\left(\frac{\alpha_p z}{h}\right) \tag{12}$$

Equation 12 is then integrated vertically and subsequently laterally to compute the suspended-sand discharge through the cross-section.

As a modification to this method, it is possible to compute a sediment flux for each ADCP vertical j, to improve the lateral integration. Indeed, it is then possible to have a model for the sand flux vertical profile:

$$\phi_j(z) = C_{j(z)} u_{j(z)} = U_j^*/k \ln\left(\frac{z}{z_{0j}}\right) C_{Rj} \exp\left(\frac{\alpha_j z}{h}\right) \tag{13}$$

For each vertical j for the ADCP grid, one can estimate U_j^*, z_{0j}, C_{Rj} and α_j using an interpolation between each measured vertical or assuming on the edge some relationship to water depth with,

$$U_j^* \propto \sqrt{h}, C_{Rj} \propto h \tag{14}$$

The suspended-sand concentration for each cell can then be estimated as:

$$C_{ij} = \frac{1}{q_{ij} w_j h_{ij}} \int_{z_{i,j}}^{z_{i+1,j}} \phi_j(z) dz \tag{15}$$

with $h_{ij} = z_{i,j+1} - z_{i,j}$ and w_j the height and the width of the cell *ij*, respectively

This option is not yet implemented in the code and will be tested to improve the lateral integration.

Application to a flood on the Rhône River, France

Field survey and dataset

The Rhône River is one of the major rivers of Europe, heading at the Rhône Glacier in the Alps, and running through southeastern France (Figure 2). The Rhône river drains a catchment of about 95,000 km². The mean annual discharge is 1700 m³/s. The river has been largely modified since the middle of the 20th century (sediment dredging, levees, dams on the river and on its tributaries). Despite large modifications, the Rhône River remains the main tributary of the Mediterranean Sea by mean sediment flux. It is mostly a gravel-bed river in France. The study site is in the city of Lyon. The dataset results from 4 surveys carried out during a 10-year recurrence-interval flood in January 2018. The range of investigated discharges varied from 1,900 to 2,700 m³/s during the successive phases of the flood (Figure 3).

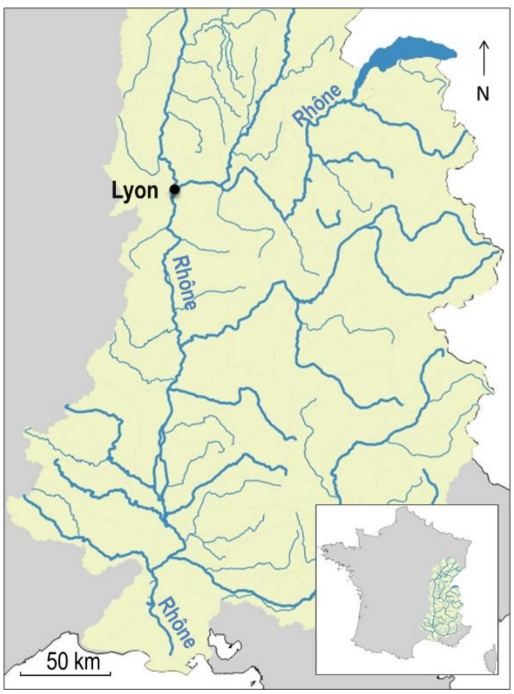


Figure 2: The Rhône River catchment

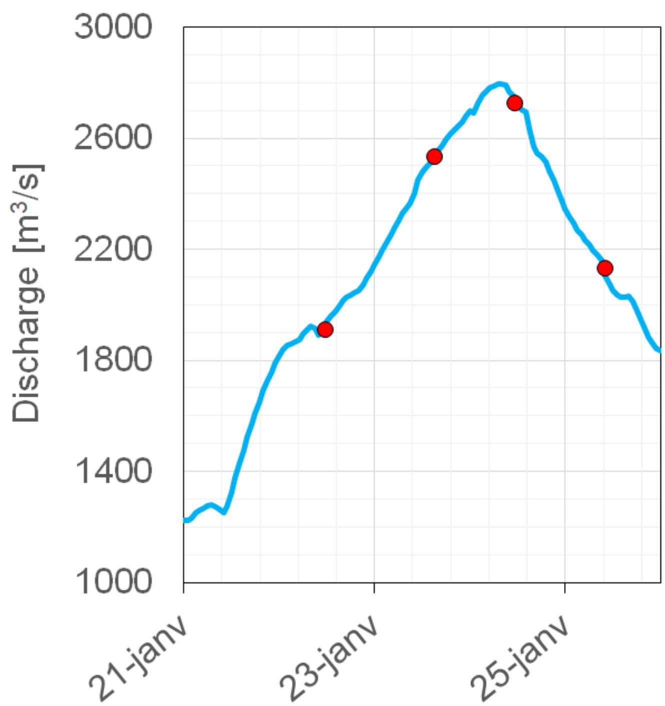


Figure 3 : Discharge during the 2018 flood (blue line) and sampling surveys (red dots)

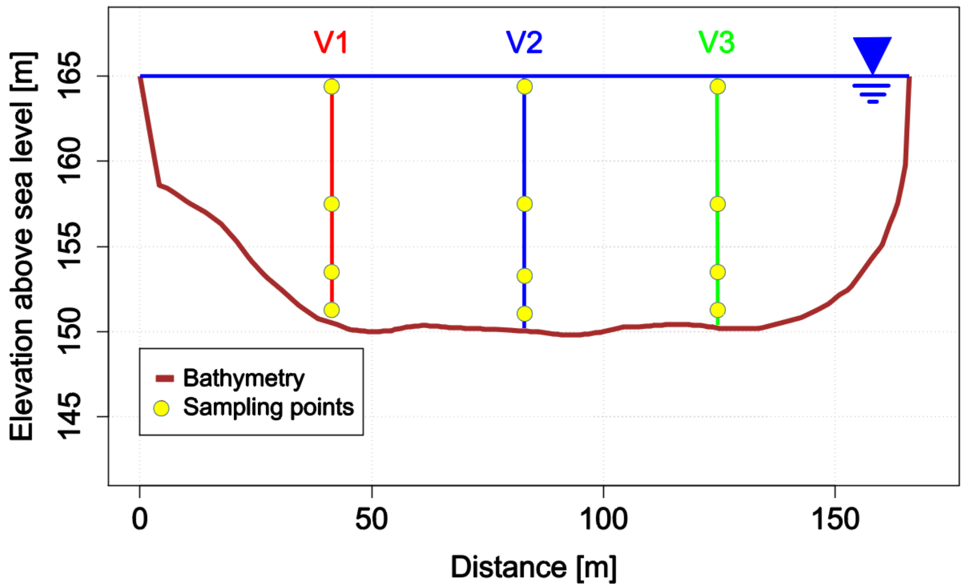


Figure 4 : Samples and verticals position sketch

Each suspended-sediment sampling survey consisted of a set of 12 point-samples distributed throughout a cross-section. Three verticals were sampled following the EWI option. The sampler was a 2-liter Van Dorn bottle that could be opened at both ends. This sampler was deployed as follows. Upstream from the sampled cross section, the open bottle was lowered from a boat into the river on a cable until it reached the target depth. During this phase the boat drifted downstream to the cross-section where the cable became vertical. To achieved the verticality of the cable, the boat's drifted velocity must be higher than the sampler's drifted. Sampling commenced by closing the bottle by sending a weighted trigger (messenger) down the cable. We also took ADCP velocity and discharge measurements (600 and 1200 kHz) at the same time according to our standard procedure.

Sediment characteristics

Analyses of the suspended-sediment samples were conducted in the laboratory by sieving and filtering according to the ASTM D3977 (2013) standard. Both sand and silt concentrations were measured on each point sample in each set. Our analyses on the Rhône samples showed that silt and clay-sized sediment (d<63µm) were well mixed in the cross section during the surveys and could be considered as washload. We observed substantial gradients in the profiles of sand concentration (Figure 5) and grain size. The amount of sand in suspension was relatively small compared to most sandy rivers, but it was substantial for the Rhône River. The median grain-size (d50) of the sand-size sediment was between 100 and 350 µm and the grain size first fined and then coarsened during the event.

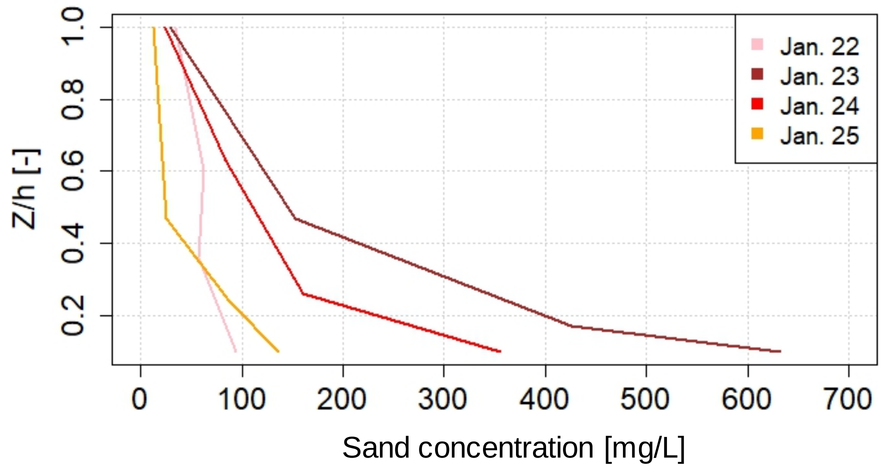
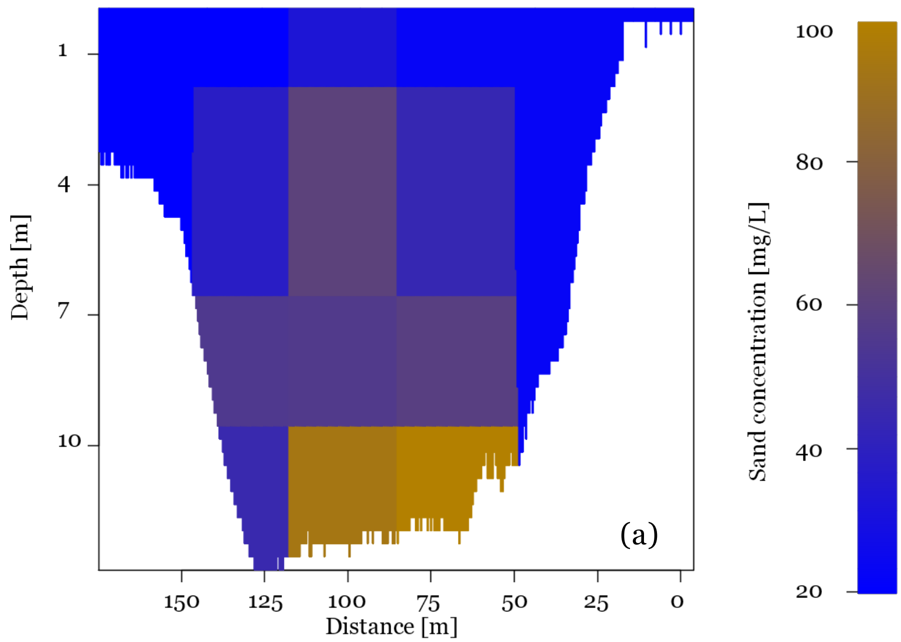


Figure 5: Evolution of the sand concentration profiles on the middle vertical (V2) during 4 days of the flood

Estimation of sediment fluxes

33 ADCP transects were computed for the flood event. Figure 6a shows an example of the concentration grid computed with ADCP and sand-concentration data using the nearest-neighbor interpolation method applied to individual point samples. The figure 6b shows an example of the velocity-weighted sand concentration grid computed for each ADCP cells.



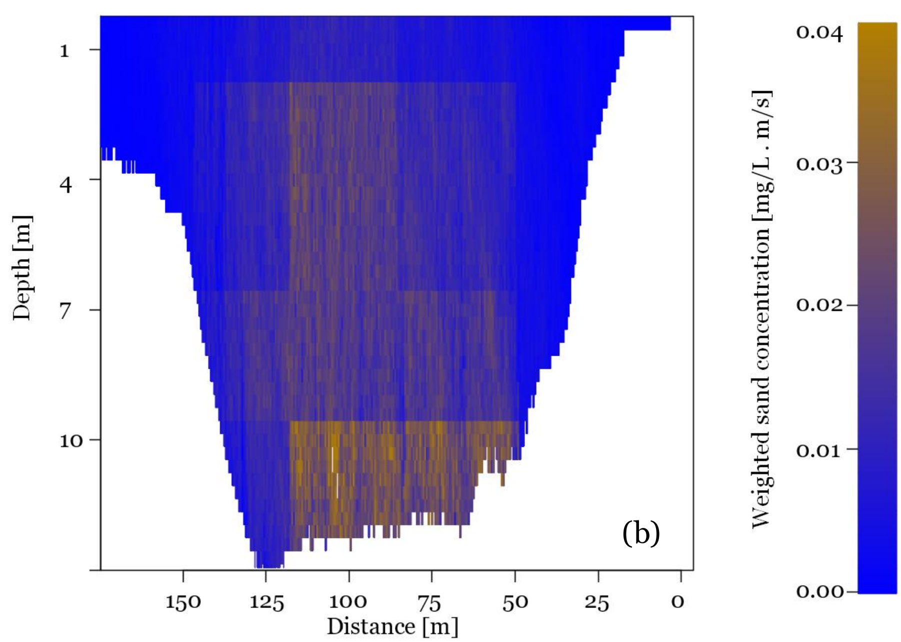


Figure 6: The nearest-neighbor method applied to individual point samples in the Rhône River at Lyon: (a) Sand concentration assigned to sub-sections according to the sample positions and ADCP data; (b) Velocity weighted sand concentration calculated for each ADCP cell.

Results from using the physically based method to estimate sand fluxes, highlighting the three main steps of this method, are illustrated in Figure 7: the logarithmic velocity law fit to the ADCP velocity data (Figure 7a), the Rouse-based exponential fit to the point-sample sand concentrations (Figure 7b), and the flux profiles (Figure 7c) resulting from the combination of the velocity and concentration profiles.

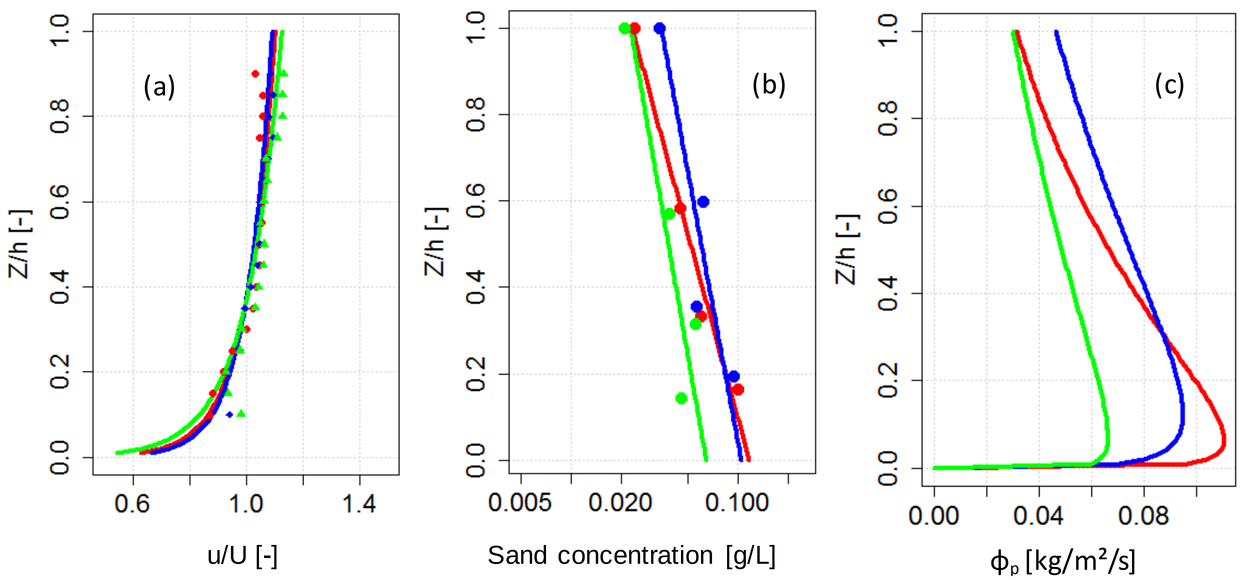


Figure 7: "Physically based method" applied to the Rhône River dataset (2018/01/22) (a) fitted ADCP velocities, (b) exponential profile (semi log scale), (c) Flux profile. Colors represent verticals numbers according to **Figure 4**.

Table 1 shows a summary of the results for the different post-processing options. For each day, the sand-flux and water-discharge results are the average of the computation of several ADCP transects. The same dataset (ADCP measurements and point sample concentration) is used for all the computations. The standardized method is considered as the reference. Results are quite similar. The nearest-neighbor method gave results that were only slightly lower than the standardized method, about -14% for the largest difference. The physically based method gave results close to the standardized method, with the largest difference also being -11%. The farthest right Q_s column is a simplified case with a single vertical in the middle of the river, which produced mostly overestimations owing to the higher concentrations and velocities in the center of the river cross section, thus illustrating the need for multiple verticals.

Table 1. Results of the different computation options for suspended-sand discharge

Date	Qwater [m³/s]	**Qs** Standard **[kg/s]**	Qs Nearest neighbor [kg/s]	Deviation versus Standard [%]	Qs Physically-based [kg/s]	Deviation versus Standard [%]	Qs Standard Single vertical [kg/s]	Deviation versus Standard [%]
2018/01/22	2000	**104**	102	-2	108	4	130	25
2018/01/23	2650	**505**	482	-5	510	1	587	16
2018/01/24	2720	**378**	333	-14	338	-11	368	-3
2018/01/25	2150	**87**	82	-6	87	0	104	20

This comparison shows that the same dataset and different computing methods yield results that are only slightly different. Although the physically based method is very sensitive to the velocity and sediment-concentration profile calibrations, it provides a better estimate of the concentration through the entire water column at each vertical, especially near the bed where it is difficult to measure velocity and suspended-sediment concentration.

Conclusions

In this study, we developed a method to combine ADCP data with suspended-sediment-concentration data to compute the suspended-sand discharge. We applied this method to field surveys carried out on the Rhône River during a 10-year flood. This method is a reliable procedure to estimate suspended-sand discharge through the cross section. The nearest-neighbor and physically based methods provided us with results consistent with the standardized method. The results show that little difference is found among vertical integration, but they lay the groundwork for the next step on lateral integration, which is what will really take advantage of the resolution of ADCP data for lateral integration as already done for vertical integration. Our study site of Perrache on the Rhône River is quite simple with a quasi-trapezoidal cross-section. To test our method in more complicated channel geometries, we need to conduct further tests of our method at other sites. Our results suggest that the computed suspended-sand discharge is relatively insensitive to the method used for vertical integration. We expect more difference with the lateral integration options we plan to test in the future. A first step in improving the lateral integration in our method will be to combine the suspended-sand concentration profiles from the physically-based method with each ensemble of the ADCP grid to improve the concentration estimations. We then propose to further improve the lateral integration by using the fluid-corrected backscatter from the ADCP (Boldt, 2015; Topping and Wright, 2016) to better interpolate the suspended-sand concentrations between the locations of the point samples.

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