Acoustic based assessment of cross-sectional concentration inhomogeneity at a suspended sediment monitoring station in a large river

Flóra Pomázi1 · Sándor Baranya1

Received: 3 December 2021 / Accepted: 27 April 2022 / Published online: 30 May 2022 © The Author(s) 2022

Abstract
Establishing and operating a harmonized sediment monitoring system along large rivers such as the Danube River is a challenging international task. As an element of such a system, a new monitoring site with state-of-the-art instrumentation is currently under development in the Upper-Hungarian section of the Danube River. The monitoring station will consist of a near-bank optical backscatter sensor and a horizontal acoustic Doppler current profiler (H-ADCP). As previous studies showed, the suspended sediment concentration (SSC) that is continuously measured with near-bank sensors can significantly enhance the temporal resolution of sediment transport monitoring. However, sediment plumes from tributary inflows upstream of the monitoring station can alter the detected near-bank concentrations, eventually biasing the sediment load estimation. Such an influence is likely in the cross-section of the planned monitoring station, therefore, a thorough preliminary analysis of the cross-sectional variation of the SSC was performed, based on expeditionary sediment measurement campaigns. Between 2018 and 2021 24 campaigns were carried out at different hydrological regimes, where physical sediment samplings together with fixed and moving boat ADCP measurements were performed. The cross-sectional variability of SSC and its influence on the sediment load estimations were assessed based on the moving boat ADCP measurements, after calibrating the backscatter signal with more than 500 physical samples. Based on the results, we identified different cross-sectional patterns of the SSC which is apparently governed by: (i) the actual hydrological situation considering both the main river and the tributary, and (ii) the local river morphology. Based on our findings, we suggested a correction method that accounts for the above effects, using which the near-bank SSC can be reliably converted into total suspended sediment load.

Keywords Suspended sediment · Danube · Acoustic backscatter · Near-bank monitoring · Tributary influence

Introduction
The role of fluvial sediment transport monitoring has become more and more fundamental in water management, river engineering, and even in multidisciplinary projects (e.g., Landers 2012; Hauer et al. 2018; Nones 2019; Park et al. 2019). Sediment transport is a dynamic process; therefore, an appropriate spatial and temporal resolution is required when studying sediment transport phenomena (e.g., Mossa 1996; Mead et al. 2012; Joshi and Jun 2018). Fluvial sediment transport has two different types, depending on particle size and flow conditions (van Rijn 1984): (i) suspended sediment transport which is the transport of fine (i.e., smaller than 63 μm) sediment particles that are suspended within the water column and are moving with the water flow; and (ii) bedload transport which is the transport of coarse sediment grains that are rolling, sliding or saltating on the riverbed surface. This study focuses on suspended sediment transport.

To describe the suspended sediment transport as reliably as possible, the following characteristics are needed (DanubeSediment 2019b): suspended sediment concentration (SSC; in mg/l or g/m³), total suspended sediment load (SSL; in kg/s or Mt/year), particle size distribution (PSD)
and characteristic particle sizes (e.g., $d_{50}$ median diameter in µm), and the spatial and temporal variability of these parameters.

Without an adequate spatial and temporal resolution, trends cannot be detected, and the sediment balance is hard to assess. Along such long (and international) rivers as the Danube River, it is essential to establish a harmonized monitoring system to maintain the consistency (and quality) of suspended sediment data (DanubeSediment 2019b). For this, a monitoring site should be present at least at each river section where a hydromorphological change (e.g., widening/narrowing channel, bed slope change, tributary confluence, etc.) occurs (DanubeSediment 2019b). Since the actual Hungarian suspended sediment monitoring system lacks the spatial and temporal resolution of sediment data required for sediment balance analysis (DanubeSediment 2019a), the development of the system is proposed. This study presents the case study of a new suspended sediment monitoring station in the Hungarian Danube that is currently under development. In the next part of the introduction, we briefly overlook the suspended sediment measurement methods. A more detailed overview can be found in e.g., Downing (2006); Gray and Gartner (2009); Landers (2012); Rai and Kumar (2015).

SSC measurement methods

Suspended sediment concentration (SSC) is the most important (and most basic) parameter of the fluvial suspended sediment transport. Traditionally, the concentration is determined by a direct approach: first, water samples are taken in the river, and then, the samples are analyzed in the laboratory with a physical method. Different types of physical samplers are used in practice (Gray et al. 2008). Non-isokinetic, instantaneous samplers (i.e., bucket and bottle samplers) are used when a rough estimation is satisfactory enough or under such circumstances where an isokinetic sampler cannot be used (Gray et al. 2008). A non-isokinetic sample is considered a disturbed sample, as it is not granted that the sample has the same SSC as the sampled water volume. In contrast, the design of the isokinetic samplers ensures that the sampling velocity is the same as the flow velocity; thus, the sample will have the same SSC as the river water (Gray et al. 2008). Commonly used isokinetic samplers are the isokinetic samplers of the U.S. Geological Survey (USGS) (e.g., US DH, US D, and US P isokinetic samplers).

The direct method of laboratory analysis means the separation of solid particles from water. The separation can be done by filtration (vacuum or pressure filtration) or evaporation. In both cases, the ratio of the dry mass of the solid particles and the volume of the water–sediment sample is the SSC.

Nowadays, as modern techniques are continuously developing, indirect surrogate methods have become increasingly used (e.g., Thorne et al. 1991; Agrawal and Pottsmith 2000; Downing 2006; Gray and Gartner 2009; Agrawal and Hanes 2015). These methods determine the SSC by an indirect approach: the concentration is not measured but is estimated by empirical, semi-empirical relationships (i.e., calibration) from another parameter like turbidity or backscatter signal. The indirect methods have two main groups: acoustic and optical methods. They are generally in situ sensors, so there is no need for physical sampling and laboratory analysis, however, calibration of the instruments is necessary.

Optical devices emit light into the sample, which scatters, attenuates, or gets absorbed as it passes through the water sample containing suspended sediment particles (Agrawal and Pottsmith 2000; Downing 2006; Agrawal et al. 2008; Gray and Gartner 2009; Landers 2012; Czuba et al. 2015; Boss et al. 2018). SSC is determined via measuring and analyzing light intensity changes. Two main types of optical instruments can be distinguished: laser diffraction and infrared light scattering devices. Laser diffraction devices are mainly used for laboratory analysis (e.g., Malvern Mastersizer 3000, LISST-Portable|XR (Laser In-Situ Scattering and Transmissometry; by Sequoia Scientific)), though there are in situ versions as well (e.g., LISST-200X by Sequoia Scientific). This group of optical instruments has a very valuable advantage in determining the PSD as they also detect the intensity of laser light scattered by given particle size (Agrawal and Pottsmith 2000; Agrawal et al. 2008; Landers 2012; Agrawal and Hanes 2015). The optical devices that are based on the principles of infrared light scattering are submersible optical backscatter sensors (e.g., Solitax ts-line sc, Ponsel NTU) or portable turbidimeters (e.g., Hach TU5, VELP TB1). As they do not consider the particle size, they tend to be sensitive to particle size inhomogeneity (Downing 2006; Czuba et al. 2015; Boss et al. 2018); thus, a distinction should be made based on the particle size when calibrating such a device. Moreover, optical backscatter sensors are sensitive to biofouling and algae formation (Downing 2006; Czuba et al. 2015).

Acoustic instruments are widely used surrogates in suspended sediment measurements (e.g., Baranya and Józsa 2013; Guerrero et al. 2011, 2012, 2016; Landers 2012; Agrawal and Hanes 2015; Agrawal et al. 2016). The theoretical backgrounds of the acoustic methods are well-known (e.g., Thorne et al. 1991; Gartner 2004; Gray and Gartner 2009; Moate and Thorne 2012). The SSC is estimated from the intensity difference of the sound wave emitted and detected. As the time of backscattering is also known, the distance of the suspended sediment particle from the acoustic sensor can also be estimated; thus, the acoustic instruments can be applied not only for direct but linear or 2D suspended sediment measurements as well (Gray and
Gartner 2009). Moreover, they are less sensitive to biofouling and algae formation than optical instruments (Gray and Gartner 2009; Moate and Thorne 2012). Widely used acoustic devices are, for example, the LISST-ABS (Acoustic Backscatter Sensor; by Sequoia Scientific) or the ADCP (Acoustic Doppler Current Profiler; e.g., by Teledyne RDI), where the latter is, in fact, commonly used for flow measurements and the SSC is only a valuable by-product.

The ABS sensors measure a couple of centimeters from the sensor head, so only near-field effects are taken into account (geometric spreading and water attenuation are fixed, and sediment attenuation is a point value resulting from the detected signal difference in the two measured cell ranges) (Sequoia 2016). On the other hand, in case of the ADCP, the emitted (and backscattered) sound waves travel a more significant distance (i.e., the order of 10–100 m) in the water, so both absorption and attenuation must be accounted for when calibrating the backscatter (Gray and Gartner 2009). The theoretical background of the ADCP backscatter calibration is well-established (Thorne et al. 2011, 2013; Guerrero et al. 2011, 2012, 2016; Sassi et al. 2012; Agrawal and Hanes 2015).

**Monitoring the sediment load in a river cross-section**

When developing a suspended sediment monitoring site in large rivers, recent studies suggest following an integrated concept (Haimann et al. 2012, 2014; DanubeSediment 2019b; Aleixo et al. 2020), consisting of two main elements: (i) a near-bank continuous measurement system that ensures the exploration of the temporal variability of suspended sediment transport, which is needed to be calibrated (and regularly updated) by (ii) supplementary expeditionary measurements. The expeditionary measurements are carried out along the cross-section so the spatial variability of the suspended sediment transport can be better described; moreover, a relationship can be established between the near-bank detected concentration and the total SSL (i.e., the mass of sediment passing the cross section in a unit of time; in kg/s in this study). However, when installing a near-bank sensor, it should be considered whether the near-bank location is representative or it cannot account for the spatial variability properly, and thus, the concentration cannot be extended to the total cross section. For example, Haimann et al. (2012, 2014) found in their study case that in case of the Danube River near Hainburg, the reliability decreases as the flow discharge increases, and a correction should be made. However, they also noted that the increasing scatter towards the higher SSC range might be due to the influence of the upstream hydropower plant.

The near-bank element of the monitoring system generally consists of an acoustic or optical backscatter sensor (or turbidimeter) and a horizontal-looking ADCP (H-ADCP). The primary function of the latter is to measure the flow discharge, but as mentioned before, ADCP backscatter can also be used for SSC estimation. Previous studies have already shown the various aspects of near-bank sensors used for suspended sediment transport monitoring (e.g., installation protocol, calibration procedure, sensitivity, etc.) (e.g., Haimann et al. 2012, 2014). Recent studies (Wall et al. 2006; Moore et al. 2012; Topping and Wright 2016; Landers et al. 2016; Aleixo et al. 2020) presented supporting evidence that not only the near-bank turbidimeters can be successfully calibrated, but ADCPs can also detect the temporal changes of the suspended sediment transport. Moreover, by using an ADCP, the 2D distribution of the suspended sediment transport can be produced, thus enhancing the spatial resolution of monitoring (e.g., Moore et al. 2012; Sassi et al. 2012; Guerrero et al. 2013; Latosinski et al. 2014). By producing the detailed cross-sectional distribution of SSC or SSL, different phenomena can be analyzed, depending on the sampling frequency. For instance, Baranya and Józsa (2013) successfully used acoustic mapping to study a reach of the Danube River that is characterized by significant suspended sediment transport, Haimann et al. (2018) followed the plume of dumped dredged material by means of acoustic mapping, Dwinovantyo et al. (2017) investigated the effect of ebbs and tides in Indonesia, Aleixo et al. (2020) studied single hydrological events (i.e., flood hysteresis) in two very different rivers. These studies, however, have not considered situations where the cross-sectional patterns of SSC at the monitoring site are influenced by upstream tributary inflow. Following the above-described integrated approach, the measured SSC at the near-bank point is likely dependent on the mixing character of the flows in such a case.

The goal of this study is to explore the influence of a nearby upstream, rich-in-sediment tributary inflow under insufficient mixing conditions. In such a case, the sediment plume of the tributary can significantly alter the measured near-bank SSC at a monitoring station. Accordingly, no explicit relationship between the near-bank SSC and the cross-sectional sediment load can be set up, but a correction method needs to be involved. As a case study, we chose the Hungarian section of the Danube River, close to the inflow of the tributary, Mosoni-Duna. At this section of the Danube River, a sediment monitoring station is under development which is going to consist of a near-bank turbidity sensor and an H-ADCP. Before the implementation of the sediment monitoring station, a preliminary assessment has been performed to understand the role of the tributary. For this, we analyzed the cross-sectional patterns of SSC, derived from moving-boat (i.e., cross-sectional) ADCP backscatter signal. Furthermore, we used
the cross-sectional ADCP measurements to illustrate the effects of the tributary on a near-bank fixed monitoring instrument by extracting SSC values in a near-bank point and also along a fixed layer of the cross section. Assessing a series of ADCP measurements, performed under different hydrological conditions, i.e., at different discharge ratios of the main river and the tributary, we suggest a method to account for the tributary’s role in the sediment load calculation.

Materials and methods

Study area

The presented results are based on the data collected within the SEDDON II (Sediment Research and Management at the Danube River, Part II) project. One of the project aims is to improve cross-border sediment management along the Danube River (interreg-athu.eu). Therefore, a sediment monitoring station is under development at river km 1790.61 section of the Danube River. This section is situated in the upper-middle reach transmission of the river, where the riverbed widens, and the bed slope decreases from 37 cm/km to 6 cm/km (DanubeSediment 2020). The mean annual flow discharge is around 2000 m³/s, while the 100-year flood reaches 10,000 m³/s. At the study site (Fig. 1), the mean water depth is around 5–6 m, and the mean cross-sectional width is 400 m. The mean SSL is about 40 kg/s (i.e., approximately 1.3 Mt/yr), while the mean SSC is 20 mg/l (DanubeSediment 2019c). Based on the findings of the recently finished DanubeSediment project (2019c), the ratio of the suspended sediment transport is approx. 70–75% of the total sediment transport. 4 km upstream of the monitoring site, a tributary of the Danube River, the Mosoni-Duna, enters the main channel (Fig. 1), characterized by significant sediment load at high flows. The Mosoni-Duna carries its clay and silt particles and the rich-in-organic content, coarser sediment of the Rába River, a tributary of Mosoni-Duna.

Moreover, the suspended sediment particles of the latter have a different place of origin and, thus, different material, which affects the application of indirect methods. Although the flow discharge of the Mosoni-Duna is seldom above 10% of the Danube River, according to our measurements, the SSC can be six times higher in the tributary compared to the Danube. And still, while the ratio of the total SSL ratio results below 20%, satellite images (Fig. 1) indicate that the rich-in-sediment plume does not mix properly with the Danube’s water for a relatively long distance—including the monitoring cross section. Indeed, the transversal mixing of plumes can last even up to 100 km in such large rivers, enhancing the need for considering the cross-sectional patterns of SSC when quantifying sediment transport.

Methodology

Field data collection

A sketch of the field measurement methodology is shown in Fig. 2. For each campaign, we collected physical water samples with a point-integrated US P-61-A1 isokinetic sampler that ensured that the SSC of the collected water samples was the same as that of the flow (Gray et al. 2008). To capture the cross-sectional spatial variability of SSC, the sampling points were determined by using the so-called multi-point method (BMFLUW 2017). Accordingly, samples were taken in 5 verticals along the cross-section, at 5 points per vertical in the following depths: 0.05H, 0.20H, 0.60H, 0.80H, and 0.95H (where H is the total water depth in the vertical). Due to the effects of the local river morphology, i.e. the groyne field along the left bank, the active zone of sediment transport characterizes only the ~ 2/3 of the section, therefore, the sediment sampling verticals were distributed along this zone. To measure the total cross-sectional SSL, the suspended sediment sampling was supplemented by simultaneous flow measurements, using a Teledyne RDI Rio Grande 1200 kHz ADCP. In each vertical, 10-min-long fixed boat measurements were done, providing time-averaged flow velocity profiles for the sediment load calculation. Besides, cross-sectional moving-boat ADCP measurements were also carried out to measure the flow discharge, moreover, the transversal patterns of instantaneous SSC could also be assessed. Using the methodology described above, 24 expeditionary campaigns were performed covering a wide range of flow discharges of the main river as well as of the tributary. A detailed dataset can be found in Table 1 of the Appendix.

Laboratory analysis of sediment samples

The physical samples were analyzed in the laboratory to determine the reference SSC. As a reference, a part of each sample was analyzed by using a positive pressure filtration equipment. With the so-called filtration method, a known volume (V) of the sample was pressured through a membrane filter of 0.45 μm pore size that was previously dried at 105 °C until mass equilibrium and weighed (m(before)). After filtration, the membrane filter was dried and weighed again (m(after); now with the sediment). The SSC was calculated by the following formula (Eq. 1):

\[
SSC = \frac{m_{\text{after}} - m_{\text{before}}}{V}.
\] (1)
Besides determining the reference SSC, particle size analysis was also performed during the laboratory analysis. A laser diffraction-based device, the LISST-Portable|XR was used as an indirect, optical method. The LISST-Portable|XR analyzes low-angle laser scattering. The laser light emitted by the instrument passes through the sample and scatters due to the suspended sediment particles. Then the scattered light is transmitted to the concentric detector rings by a converging lens. Each detector ring receives different amounts of light as the scattering area of the detected light determines the particle sizes in the sample. This way, different particle sizes are detected by different detector rings. Knowing the probability density of the detectable 44 particle size ranges, the volumetric particle size distribution (PSD) can be plotted. The PSD information was very valuable when calibrating the ADCP backscatter as particle size is an important parameter when describing sound attenuation due to sediment particles. The measurement range of the LISST-Portable|XR is 0.34–500 µm (and 10–1900 mg/l, depending on the particle size) (Sequoia Scientific 2018).

Fig. 1 Case study area (source of the satellite image: Sentinel-2). The brownish plume of the rich-in-sediment tributary is evidently not mixing well with the Danube River (middle). The groyne field (bottom) further complicates the sediment transport processes.
The quantification of scattering was done by setting the appropriate optical model (i.e., the Fraunhofer model for spherical particles, or the Mie model for natural, randomly-shaped particles). In this study, the Mie model was chosen as the material of the suspended sediment along the Hungarian section of the Danube is assumed to be quartz (with a specific density of 2.65 g/m$^3$; Bogárdi 1971), and this model proved to be a more accurate model for natural particles (Agrawal et al. 2008; Sequoia Scientific 2018). Other technical settings (e.g., mixing speed and data averaging) granted the stability of measurements (e.g., no particle settling and bubble formation). After setting the operation procedure, the sample was poured into the mixing chamber, and the 2–3 min long measurement could be started. The LISST-PortableXR produced the following results: sediment concentration (volume and – assuming a density – mass concentration), PSD (in volume%), characteristic particle sizes, and other statistical values (e.g., Hazen uniformity coefficient or silt ratio).

Calibration of the ADCP relative backscatter

Following the procedure described by Baranya and Józsa (2013), the calibration of the ADCP backscatter detected in the sampling points along the measurement verticals was done by the method after Gartner (2004), using the following form of the sonar equation (Urick 1983):

$$SSC_{ADCP} = 10^{A + B \cdot RB} = 10^{(A + B \cdot (K_c \cdot (E_l - E_i) + 2 \cdot 10 \log(R)) + (\alpha_w + \alpha_s) \cdot R)},$$

(2)

where $SSC_{ADCP}$ is the calibrated concentration, A and B are calibration coefficients (determined by using the least-squares of the regression between the relative backscatter (RB) and the logarithm of the measured concentration, $K_c$ is the instrument-specific conversion factor, $E_l$ is the echo intensity, $E_i$ is the instrument-specific reference echo intensity (or base-noise), $R$ is the slant range (distance from the instrument), $\alpha_w$ is the water absorption coefficient, and $\alpha_s$ is the suspended sediment attenuation coefficient.
The calibration applied instrument-specific parameters ($K_c = 0.43$, $E_r$) and attenuation coefficients that depend on water ($T_w$ temperature) and suspended sediment characteristics ($d_{50}$ median size and concentration). For the calibration procedure, the time-averaged RB values from the fixed boat surveys and the SSC values resulted from the filtration method were used.

**Calculation of SSL**

The calculation of the total SSL was done after the methods described in BMFLUW 2017. Using the multi-point method, the cross-sectional distribution of suspended sediment transport could be approximated based on single-point SSC and velocity measurements. The product of the coherent velocities and concentrations gives the specific suspended sediment discharge ($q_{ss}$, in g/sm²) in the vicinity of the sampled points. The total SSL (in kg/s) resulted from the integration of this product along the whole cross-section. The integration of such discrete data meant the summation of the areas of triangular, rectangular, and trapezoid objects.

**Analysis of cross-sectional SSC inhomogeneity**

Lastly, we applied the above setup calibration parameters to convert the backscatter from the cross-sectional moving-boat ADCP measurements to 2D, transversal distributions of SSC along the monitoring cross section. These SSC fields were used for the detailed analysis, mimicking the operation of the future sediment monitoring station, in the following manner: (i) 0D near-bank SSC values were extracted at the location of the planned turbidity sensor (i.e., the SSC values derived from the cross-sectional ADCP measurements were averaged in a 1 m × 1 m zone close to the right bank but taking into account the blanking distance of a H-ADCP as well; see Fig. 2); (ii) 1D transversal SSC distributions were extracted along the measurement layer of the planned H-ADCP; (iii) 2D SSC distributions were produced along the whole cross section.

**Results**

**Calibration and sensitivity analysis of ADCP backscatter**

The calibration procedure resulted in a good correlation ($R^2 = 0.75$; Fig. 3) between the ADCP relative backscatter and the logarithm of the measured SSC (determined by the filtration method).

Within the calibration procedure of the ADCP backscatter, we performed a sensitivity analysis on the most uncertain parameters of the equation, to assess the robustness of the calibration. Water temperature is a rather important parameter, so it raises the question of whether it is appropriate to use the surface temperature measured by the ADCP. However, several vertical temperature measurements confirmed that the vertical and cross-sectional temperature distribution is homogeneous in the measurement cross section, so the $\alpha_w$ parameter (see Eq. 2) was used as a constant per measurement. The measurements covered a wide range of water temperature ($T_w = 8–23$ °C), and thus, water attenuation ($\alpha_w = 0.25–0.48$ dB/m). Moreover, using an average value of $\alpha_w$ when calibrating all the samples, the calibration regression was as good ($R^2 = 0.75$) as using the individual values of it.

Based on the laser-based analysis, the particle size range is $d_{50} \approx 10–35$ µm (with a mean of 18 µm; Fig. 5 (left)), and the average sand content of the suspended sediment is ca. 7%. As it can be seen in the distribution of the $d_{50}$ particle size (Fig. 4 (left)), the PSD typically slightly coarsens towards the bottom (here, the average from all the measurements was taken). However, the distribution is quite homogeneous, the standard deviation along the verticals is around 6 µm only (supplementary data is provided in Table 3 of the Appendix). Moreover, the variation along the SSC profiles is also small (Fig. 4 (right)), which presumably means that errors in $\alpha_s$ (per 1 mg/l) will not be further increased when multiplying by the SSC. Furthermore, it also seems that the particle size is not significantly affected by the flow discharge (Fig. 5 (left)). The PSDs in Fig. 5 cover all different flow conditions (rising/falling limb of matching flow discharges at low/medium/high water) and sampling points.

Calculating with an average value of $\alpha_s$ (0.0013 dB/m per 1 mg/l), the goodness of the calibration decreases to $R^2 = 0.71$ as opposed to the final calibration (Fig. 3) using the respective $\alpha_s$ parameters ($\alpha_s = 0.0005–0.0028$ dB/m per 1 mg/l; Fig. 5 (right); see detailed in Table 1 of the Appendix). However, the difference in the two $R^2$ is not significant, thus, the mean particle size was suitable for the estimation when no particle size analysis was performed. On the other hand, according to Fig. 5 (right), attenuation due to sediment...
particles (DRL Software Ltd 2003) changes rapidly with particle size in the detected range. To illustrate the effect of particle size changes (Fig. 6), we calculated the cross-sectional SSC distribution for a flow regime close to the mean \((Q = 2579 \text{ m}^3/\text{s})\) with three different \(\alpha_s\) values based on the \(d_{10,\text{min}} \approx 1 \mu \text{m}, d_{50,\text{avg}} \approx 18 \mu \text{m},\) and \(d_{90,\text{max}} \approx 120 \mu \text{m}\) particle sizes \((\alpha_s = 0.005, 0.001, \text{and } 0.0006 \text{ respectively}; \text{note that } \alpha_s \text{ for } d_{50,\text{avg}} \approx 35 \mu \text{m} \text{ is also } 0.0006).\) Even considering these large differences in the particle diameter, the results indicated a maximum difference of 15\% in the near-bank SSC, average cross-sectional SSC, and total SSL values—which we found satisfactory for the purposes of this study.

**Fig. 4** Typical \(d_{50}\) (left) and SSC (right) profiles in the measurement verticals

**Fig. 5** Typical PSD curves of the suspended sediment (left) and attenuation due to sediment particles as a function of particle size and instrument frequency (DRL Software Ltd 2003) (right) where the orange dots note the measurements of this study

**Fig. 6** Effect of sediment attenuation on the cross-sectional SSC distribution and its investigated parameters (near-bank SSC, average cross-sectional SSC, and total SSL)

\[
\begin{array}{l|l|l|l}
\text{Parameter} & \text{Value} & \text{Value} & \text{Value} \\
\hline
\alpha_s & 0.005 & 0.001 & 0.0006 \\
\text{SSC}_{\text{near-bank}} & 51.05 \text{ mg/l} & 51.93 \text{ mg/l} & 60.63 \text{ mg/l} \\
\text{SSC}_{\text{avg}} & 47.50 \text{ mg/l} & 48.42 \text{ mg/l} & 54.78 \text{ mg/l} \\
\text{SSL} & 69.36 \text{ kg/s} & 67.91 \text{ kg/s} & 78.76 \text{ kg/s} \\
\hline
\end{array}
\]
As acoustic (and optical) methods are quite sensitive to particle size, a further differentiation was made between the fines and the coarser particles based on the sand content of the physical samples. Excluding the samples containing more than 10% (~150% of average sand content) of sand resulted in a significant improvement in the calibration, which is presented as the final calibration.

Although the 5-point method is a good way to measure the suspended sediment transport, the top and bottom points are usually in the blanked zone of the ADCP (i.e., there are no data). Deines (1999) suggested that for the used instrument, data should not be included below \( R = 1.34 \). In this study, only a slight decrease (\( R^2 = 0.74 \) instead of 0.75) was experienced when including data closer to the ADCP than recommended by Deines (1999). Although it makes serious assumptions about the near-bed PSD and SSC, we studied the effect of EI profile extrapolation towards the bottom in the blanked zone of the ADCP, just to illustrate the more significant aspect. Including the estimated EI values in the bottom points (using the equation of the polynomial curve fit on the measured EI profiles), the regression between RB and the logarithm of the measure SSC is less than satisfactory (\( R^2 = 0.39 \)).

**Near-bank SSC vs. cross-sectional mean values**

If following the integrated monitoring approach for the suspended sediment introduced in the previous section, the cross-sectional sediment load determination relies on the SSC measured at the bank. Accordingly, a strong relationship has to be set up between these two parameters—this way ensuring that the near-bank value can reliably describe the cross-sectional variations of suspended sediment transport (see e.g. Haimann et al. 2012, 2014). To see how well the near-bank SSC (detected in a 1 m × 1 m cell in this study) can represent the total cross-sectional sediment transport at the proposed monitoring station, we revealed the relationships between the calibrated (i.e., obtained from the cross-sectional ADCP measurements as described in 2.2.5) near-bank concentration and the measured cross-sectional sediment load (Fig. 7). Apparently, the SSC measured in one point (or cell) of the cross-section, does not adequately describe the sediment load. The section-integrated load values vary significantly, especially at higher SSC values, yielding differences of more than an order of magnitude. As shown in Fig. 7, the same near-bank SSC can belong to even a ±50% wide range of total SSL, which, for example, means a ±500 kg/s difference at SSC = 100 mg/l.

To understand how the same near-bank SSC value can result in a completely different sediment load, we studied the variations of SSC along a fixed layer (i.e., at the location of the monitoring instruments to be installed in the future; see Fig. 2) and the whole cross-sectional area. As for the layer-wise distribution (Fig. 8a–d), we can find hydrological situations where: (i) the same near-bank concentrations correspond to different SSC pattern but similar sediment load values (see Fig. 8a and d); (ii) the same near-bank concentrations correspond to different SSC patterns and significantly different, even two times higher, sediment load values (Fig. 8b); (iii) different, two times higher, near-bank concentrations correspond to similar sediment load values (Fig. 8c).

Analyzing the 2D distribution of the SSC, clear patterns could be identified within the monitoring cross-section. In normal water regimes, when the contribution of the tributary is negligible, the highest concentration characterizes the middle of the channel (Fig. 9 top). This is, in fact, in accordance with theory, showing the highest sediment transport capacity in the mainstream. Here, the typical SSC is 2–5 times higher compared to the near-bank regions. On the other hand, when higher flow characterizes the rich-in-sediment tributary, the approaching plume could be well observed at the monitoring site, indicating a well-separable patch at the right bank of the river (Fig. 9 bottom). Indeed, as the list of figures in the Appendix (Table 2) shows, these two kinds of patterns can be detected in all the SSC maps of the 24 measurement campaigns. Consequently, it can be confirmed, that operating a sensor at the near-bank point of the river, the point-wise SSC cannot represent adequately the cross-sectional sediment transport. Instead, a correction method, which takes the discharge ratio of the main river and the tributary into account, can likely contribute to setting up a sediment rating curve. Besides the influence of the tributary, the effect of river morphology can also be noticed in the maps. As a matter of fact, a groyne field is located along the left bank in the vicinity of the monitoring site (Fig. 1) which contracts the flow here. The flow recirculation zone, approximately the one-third of the whole section, in low water regime is characterized by very low SSC. On the other hand, at water regimes above the mean flow discharge (\( Q_{\text{mean}} = 2200 \text{ m}^3/\text{s} \)), when the groyne field becomes submerged, the distribution of SSC is much more homogeneous.
However, the ratio of the SSL in this area is only 2% at low water, and 7% at high water.

**Discussion**

The results introduced in the previous points built on two main pillars. First, the calibration and sensitivity analysis were performed of the ADCP relative backscatter-based suspended sediment concentration estimation, and second, a thorough assessment of the spatial behavior of the SSC at the planned sediment monitoring station was done. For the calibration, we collected more than 500 physical samples which were analyzed in laboratory using the conventional filtration method. Moreover, a laser-based analysis provided information about the characteristic particle sizes that were used during the calibration. As introduced earlier, it is mainly particle size-dependent that acoustic or optical instruments operate better under given circumstances (Agrawal et al. 2016). When an instrument has a constant response, the signal intensity changes only with concentration, and particle size should not affect the detected values (Agrawal et al. 2016). Optical sensors see fine (clay and silt) particles very well but have a firm limit in the coarser range. Acoustic instruments have the opposite tendency: a more considerable variance is expected in fines but have a constant response to sand load. Of course, the response is also instrument-specific. In fact, it depends on the operating frequency of the device: the higher the frequency, the smaller the particle size from which the response is constant. This particle size is ~400 µm in case of the 1200 kHz ADCP (Guerrero et al. 2011). Numerous recent studies can be found that distinguish between silt-and-clay and suspended sand when assessing sound attenuation and backscatter (e.g., Wright et al. 2010; Latosinski et al. 2014; Venditti et al. 2015). The so-called form function (Thorne and Hanes 2002; Thorne and Meral 2008) that describes the scattering properties of the suspended particle decreases progressively for particles smaller than 0.8 mm, and due to the small value of the form function in case of silt-and-clay (i.e., washload), some scattering can be present in the calibration curve (Latosinski et al. 2014). According to Latosinski et al. (2014), in case of the applied 1200 kHz ADCP, “scattering and viscous losses account for a little attenuation unless particle size is very small.”

Fig. 8 Layer-wise variations (in the position of the planned H-ADCP) of SSC at different hydrological situations (Note: 1. the near-bank SSC is to be measured at the right bank, 2. the illustrated distance represents the typical maximum sampling range (ca. 225 m) of a 300 kHz H-ADCP (Teledyne 2013))

QD=2890 m³/s
Qt=98 m³/s
QD=1953 m³/s
Qt=152 m³/s
QD=1594 m³/s
Qt=87 m³/s

Fig. 9 Cross-sectional SSC distributions: (i) at water regime when $Q > Q_{\text{mean}}$ (top), (ii) at high flow in the tributary (middle), and (iii) at water regime when $Q < Q_{\text{mean}}$ (bottom)
small, or SSCs are very high”. As the median particle size \((d_{50} = 18 \mu m)\) of the suspended sediment in the study area is significantly smaller than the approximate particle size of the constant response, the scatter in the presented calibration curve seems to be appropriate. However, low SSC conditions can further reduce the reliability of the calibration as the nonuniformity that develops in the vertical distribution of SSC is reflected in the acoustic profile (Haught et al. 2016).

Recently, successful attempts have been made to use various indirect methods as means of continuous suspended sediment monitoring (e.g., Curtis 2008; Rasmussen et al. 2009; Haimann et al. 2014, 2018; Felix et al. 2018). This study followed the more recent trend of using the commercial ADCP instruments for SSC assessment in rivers (e.g., Moore et al. 2012; Dwinovantyo et al. 2017; Aleixo et al. 2020). The applied calibration procedure of ADCP RB had been previously tested at different sections of the Hungarian Danube (Baranya and Józsa 2013; Guerrero et al. 2016, 2017; Pomázi and Baranya 2020a,b). Similarly, strong relationships could be established between the SSC and ADCP RB. Comparison of the calibration curves supports the supposition of Pomázi and Baranya (2020a,b) that the ADCP RB calibration relationships cannot be combined along the Hungarian Danube due to the large number of calibration parameters that must be adjusted to the local situations and thus, calibration procedures must be done individually at each measurement site.

The strength of the calibration correlation \((R^2 = 0.75)\) suggests that the produced 2D maps of SSC can be reliably used for detecting spatial trends in such a dynamic phenomenon. So, an attempt was made to analyze not only individual vertical (e.g., Thorne and Hurther 2014), cross-sectional (e.g., Latosinski et al. 2014) or longitudinal (e.g., Haimann et al. 2018 in the Danube River, in Austria, or de Oliveira et al. 2021 in the Guamá River, in Brazil) measurements or short-term changes (i.e., studying single hydrological events such as floods; e.g., Moore et al. 2012; Aleixo et al. 2020), but a long-term campaign of 24 ADCP measurements that covered a wide range of flow discharge \((Q_D \approx 1100–5600 m^3/s)\), concentration \((SSC \approx 10–200 mg/l)\) and load \((SSL \approx 5–3000 kg/s)\). Although the applied ADCP measured vertically, through the horizontal, layer-wise analysis at the elevation of a H-ADCP to be installed here in the future, we showed a significant variance in the SSC distributions. The findings of this paper greatly contribute to the calibration of the future suspended sediment monitoring station by assessing the significance of the tributary’s effect. It could be confirmed that a simple point-wise measurement of SSC at a near-bank location cannot representatively account for the spatial inhomogeneity of the sediment transport, even with applying cross-sectional corrections as suggested by Haimann et al. (2012, 2014). On the other hand, we found that both the nearby tributary inflow and the river morphology, the groyne field actually, play relevant role in the SSC patterns and eventually in the sediment load calculation.

In order to quantify the influence of the tributary inflow we introduced a parameter, the so-called relative difference between the flow discharge of the Danube River \((Q_D)\) and that of the tributary \((Q_t)\):

\[
\Delta_r = \frac{|Q_D - Q_t|}{\min(|Q_D|, |Q_t|)}.
\]

(3)

Considering the ratio of the SSC measured at the bank and the mean SSC \((SSC_{mean})\), calculated from the total sediment load \((SSL/\bar{Q}_D)\), a strong relationship (Fig. 10) can be set up. Furthermore, a separation of the points, introducing the effect of the river morphology could also be done. As explained earlier, the groyne field along the left bank of the study section has a substantial influence on the flow features. At low flows, i.e., lower than \(\bar{Q}_D\) \((\approx 2200 m^3/s)\), the contracted channel transports all the fine sediments, whereas at flow regimes higher than the mean, an intensive mixing, with submerged groyne field, characterizes the river. Accordingly, at high flows, the influence of the tributary is almost negligible. The ratio of the near-bank and cross-sectional mean SSC is actually constant \((0.86)\). This finding supports the identified patterns in the 2D SSC maps, namely, that the near-bank detected SSC value is lower than the mean values. On the other hand, below \(\bar{Q}_D\) the significant effect of the rich-in-sediment tributary inflow is apparent. Here, a strong exponential relationship \((R^2 = 0.71)\) could be established between the investigated parameters. Depending on the relative difference between the two rivers, the near-bank concentration could be up to 3 times higher than the average SSC.

![Fig. 10 The ratio of near-bank and cross-sectional mean SSC vs. the relative difference between the discharges of the Danube River and the tributary](image)
This, in fact, means that the estimation of suspended sediment load at the planned monitoring site might be feasible by measuring continuously the SSC at the monitoring point, and having continuous information about the approaching flow discharges. The effect of extreme flood conditions was not considered here due to the lack of such measurements; however, one would expect a complete mixing in case of a Danube flood. Moreover, the return probability of flood in the tributary and low flow in the Danube is reasonably low.

The influence of tributary inflow on the sediment pattern in a river cross-section should be considered not only on short distances as introduced in this study. In fact, the longitudinal distance to reach a complete transversal mixing of any sort of passive tracer can be estimated using semi-empirical approaches. Fischer et al. (1979), for instance, suggested the following formula to estimate the mixing distance ($L_m$):

$$L_m = \frac{\alpha \bar{u} W^2}{\epsilon_t},$$

where the $\alpha$ dimensionless coefficient is a function of e.g., geometry and the position of the inflow, $\bar{u}$ is the mean flow velocity (in m/s), $W$ is the channel width (in m) and $\epsilon_t$ is the transverse mixing coefficient (in m$^2$/s). After Lane et al. (2008), $\alpha = 0.18$ for the case when the position of the inflow is approx. at the fourth of the channel width. Using characteristic mean values for the Danube River, a longitudinal distance of 286 km has resulted. Indeed, satellite images, similarly to the one introduced in Fig. 1, indicate long-lasting sediment plumes from tributaries in the Danube River. In fact, similar incomplete mixing occurs also in other large rivers, e.g., Orinoco River (100 km < $L_m$; Weibezahn 1983; Stallard 1987), Rio Negro (120 km < $L_m$; Matsui et al. 1976), Paraná River (375 km < $L_m$; Lane et al. 2008), Mackenzie River (480 km < $L_m$; Mackay 1970). Consequently, the effect of tributaries on cross-sectional SSC inhomogeneity in the main river can be major, but detailed sediment analysis, as introduced in our study, can strongly support the quantification of this phenomenon.

**Conclusion**

This study assessed the inhomogeneity of suspended sediment concentrations at a planned sediment monitoring station in the Hungarian section of the Danube River, using a high number of cross-sectional acoustic mappings. Good correlation ($0.70 < R^2$) was found between the analyzed sediment concentrations from the conventional direct (filtration) method and the ones from the calibrated ADCP relative backscatter, well establishing the acoustic-based assessments. The study showed that tributary inflows upstream of the monitoring site can strongly alter the cross-sectional distribution of the SSC by carrying a significant amount of suspended sediment in the form of a plume. This phenomenon has to be considered when setting up sediment monitoring stations which, conventionally, are based on continuous near-bank SSC measurements. Following the results of this study, we suggest performing expeditionary calibration measurement campaigns to relate the near-bank SSC to the cross-sectional sediment load, taking the discharges of both the main river and tributary into account. To have a better understanding of the transversal patterns of the sediment features, applying horizontal ADCPs at the monitoring site is also recommended.

**Appendix**

See Fig. 11 and Tables 1, 2 and 3.

---

**Fig. 11** Water stage time series and measurements from 01/06/2020 to 30/09/2021
Table 1 Basic information about the expeditionary suspended sediment measurements and individual parameters of ADCP backscatter calibration (Notes: \(^1\) samples were taken also in the left third of the cross section; \(^2\) in the absence of particle size analysis the \(d_{50}\) median particle size (and thus, the \(\alpha_s\) sediment absorption coefficient) was estimated by the average; \(^3\) data is only for estimation as only three samples could be taken due to poor weather conditions on 17/08/2020)

| #   | Date    | Flow discharge, \(Q\) (m\(^3\)/s) | Average (min./max.) suspended sediment concentration from physical samples, SSC (mg/l) | Number of physical samples (points x verticals) | Water temperature, \(T_w\) (°C) | Water absorption coefficient, \(\alpha_w\) (dB/m) | Median (min./max.) particle size, \(d_{50}\) (μm) | Sediment attenuation coefficient, \(\alpha_s\) (dB/m; per 1 mg/l) |
|-----|---------|---------------------------------|---------------------------------------------------------------------------------|-----------------------------------|----------------|----------------|---------------------------------|----------------|
| 1   | 19/06/2018 | 1815                           | 31 (16/63)                                                                       | 50 (10×5)                      | 21.18          | 0.28           | 10.86 (7.94/15.59)              | 0.0022          |
| 2   | 30/08/2018 | 1087                           | 10 (3/22)                                                                         | 30 (5×6)\(^1\)                | 21.99          | 0.27           | n.a                             | 0.0013\(^2\)    |
| 3   | 15/07/2020 | 1753                           | 39 (20/81)                                                                        | 20 (5×4)                      | 21.08          | 0.28           | 19.80 (12.38/32.50)             | 0.0011          |
| 4   | 05/08/2020 | 4302                           | 220 (152/318)                                                                     | 25 (5×5)                      | 20.56          | 0.29           | 19.00 (16.47/20.98)             | 0.0011          |
| 5   | 17/08/2020 | 1849                           | 68 (n.a.)\(^3\)                                                                  | 3 (3×1)                        | 22.71          | 0.27           | 15.55 (n.a.)\(^3\)             | 0.0013          |
| 6   | 22/09/2020 | 1114                           | 14 (9/21)                                                                         | 25 (5×5)                      | 18.52          | 0.32           | 14.19 (9.42/20.31)              | 0.0016          |
| 7   | 06/10/2020 | 1953                           | 66 (19/107)                                                                        | 25 (5×5)                      | 15.23          | 0.36           | 13.47 (10.36/18.68)             | 0.0017          |
| 8   | 19/10/2020 | 2750                           | 68 (56/79)                                                                         | 25 (5×5)                      | 10.65          | 0.44           | 14.52 (12.91/17.17)             | 0.0016          |
| 9   | 13/11/2020 | 1594                           | 44 (12/115)                                                                        | 25 (5×5)                      | 9.26           | 0.47           | 20.17 (12.30/35.21)             | 0.0010          |
| 10  | 20/11/2020 | 1323                           | 17 (10/26)                                                                         | 25 (5×5)                      | 8.74           | 0.48           | 14.86 (9.80/18.14)              | 0.0015          |
| 11  | 10/02/2021 | 2890                           | 48 (39/61)                                                                         | 19 (5×3 and 2×2)              | 4.75           | 0.57           | 18.97 (17.54/21.55)             | 0.0011          |
| 12  | 11/03/2021 | 1408                           | n.a                                                                               | 0                              | 6.41           | 0.53           | n.a                             | 0.0013\(^2\)    |
| 13  | 26/03/2021 | 1423                           | n.a                                                                               | 0                              | 7.65           | 0.50           | n.a                             | 0.0013\(^2\)    |
| 14  | 15/04/2021 | 1616                           | 14 (11/18)                                                                        | 25 (5×5)                      | 9.06           | 0.47           | 19.90 (16.22/23.96)             | 0.0010          |
| 15  | 29/04/2021 | 1485                           | 25 (6/58)                                                                          | 15 (3×5)                      | 12.91          | 0.40           | 31.44 (20.46/50.26)             | 0.0006          |
| 16  | 13/05/2021 | 2770                           | 39 (30/47)                                                                         | 25 (5×5)                      | 15.06          | 0.37           | 29.47 (25.78/32.27)             | 0.0006          |
| 17  | 27/05/2021 | 2579                           | 27 (23/32)                                                                         | 25 (5×5)                      | 14.80          | 0.37           | 22.74 (20.23/25.44)             | 0.0009          |
| 18  | 10/06/2021 | 2645                           | 33 (28/37)                                                                         | 25 (5×5)                      | 20.11          | 0.30           | 23.60 (21.96/26.33)             | 0.0008          |
| 19  | 24/06/2021 | 2570                           | 33 (26/39)                                                                         | 25 (5×5)                      | 24.29          | 0.25           | 15.28 (12.74/17.87)             | 0.0015          |
| 20  | 08/07/2021 | 1752                           | 16 (9/19)                                                                          | 25 (5×5)                      | 23.44          | 0.26           | 15.83 (9.79/19.58)              | 0.0014          |
| 21  | 19/07/2021 | 4969                           | 613 (437/794)                                                                      | 15 (5×3)                      | 20.22          | 0.29           | 18.02 (16.76/19.32)             | 0.0012          |
| 22  | 20/07/2021 | 5621                           | 502 (448/550)                                                                      | 10 (5×2)                      | 19.15          | 0.31           | 13.77 (13.05/14.21)             | 0.0017          |
| 23  | 22/07/2021 | 4239                           | 376 (289/500)                                                                      | 30 (5×6)\(^1\)               | 19.24          | 0.31           | 9.11 (8.68/9.89)                | 0.0025          |
| 24  | 01/09/2021 | 3802                           | 138 (88/185)                                                                       | 25 (5×5)                      | 16.75          | 0.34           | 13.20 (12.35/13.91)             | 0.0018          |

Total number of samples: 517
Number of samples used for calibration: 289
Table 2  The calibrated 2D SSC distributions (sorted in ascending order by the value of $Q_D$)

| $Q_D$ | $Q_t$ | $\Delta Q$ | $Q_D$ | $Q_t$ |
|-------|-------|-------------|-------|-------|
| 1087  | 55    | o           | 1114  | 60    |
| 1323  | 85    | o           | 1408  | 64    |
| 1485  | 65    | o           | 1594  | 87    |
| 1616  | 72    | o           | 1752  | 51    |
| 1753  | 85    | o           | 1801  | 72    |
| 1815  | 137   | o           | 1849  | 113   |
| 1953  | 152   | o           | 2570  | 59    |
| 2579  | 89    | $\Delta$    | 2645  | 56    |
| 2750  | 226   | o           | 2770  | 66    |
| 2890  | 98    | $\Delta$    | 3802  | 107   |
| 4239  | 69    | $\Delta$    | 4302  | 107   |
| 4969  | 67    | *           | 5621  | 90    |

| $Q_D$ | $Q_t$ |
|-------|-------|
| 2579  | 89    |
| 2750  | 226   |
| 2890  | 98    |
| 4239  | 69    |
| 4969  | 67    |
| 5621  | 90    |

- $Q_D$: water discharge of the Danube River (m³/s)
- $Q_t$: water discharge of the tributary (m³/s)
- $\Delta$: pattern i) outstanding SSC in the middle of the cross section
- $o$: pattern iii) high SSC both in the near-bank zone and the thalweg
- $\ast$: special scenario: extreme mixing in the rising limb of a flood
Authors’ contributions F.P. participated in the field data collection and performed all the laboratory analysis and post-processing of the sediment data. F.P. prepared the relevant part of this manuscript. S.B. leads the related part of the funding project, designed the field measurement protocol, participated in the field measurements, and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by Budapest University of Technology and Economics. SEDDON II—Interreg AT-HU project. Bolyai János fellowship of the Hungarian Academy of Sciences (S.B). The research reported in this paper and carried out at BME has been supported by the NRDI Fund TKP2021 based on the charter of bolster issued by the NRDI Office under the auspices of the Ministry for Innovation and Technology (project id: BME-NVA-02).

Data availability The data and material that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

Table 3 Statistical data of the d50 particle size

| Sampling point | d50 statistics | Measurement vertical |
|----------------|----------------|----------------------|
|                |                | I        | II        | III       | IV        | V         |
| 0.05H          | Min            | 8.73     | 8.88      | 9.24      | 9.13      | 9.07      |
|                | Average        | 16.89    | 17.09     | 16.98     | 16.20     | 15.74     |
|                | Max            | 29.45    | 31.16     | 30.51     | 30.68     | 25.78     |
|                | Std            | 4.91     | 4.89      | 4.98      | 5.26      | 4.93      |
| 0.20H          | Min            | 8.71     | 9.39      | 9.19      | 9.06      | 9.02      |
|                | Average        | 17.64    | 16.86     | 16.44     | 16.47     | 16.70     |
|                | Max            | 29.60    | 29.74     | 30.09     | 29.02     | 32.27     |
|                | Std            | 5.36     | 5.10      | 5.46      | 5.34      | 5.40      |
| 0.60H          | Min            | 9.89     | 8.98      | 9.10      | 8.68      | 8.89      |
|                | Average        | 17.87    | 17.79     | 16.40     | 17.08     | 16.58     |
|                | Max            | 26.62    | 29.61     | 29.80     | 31.08     | 30.05     |
|                | Std            | 4.66     | 5.62      | 5.18      | 5.80      | 5.18      |
| 0.80H          | Min            | 9.48     | 9.10      | 8.95      | 8.88      | 9.49      |
|                | Average        | 18.87    | 19.64     | 19.04     | 18.60     | 17.03     |
|                | Max            | 32.49    | 32.50     | 30.96     | 29.41     | 27.37     |
|                | Std            | 6.40     | 6.53      | 5.96      | 6.09      | 4.84      |
| 0.95H          | Min            | 9.82     | 9.32      | 9.10      | 9.24      | 9.15      |
|                | Average        | 18.83    | 19.36     | 19.97     | 18.52     | 16.57     |
|                | Max            | 29.65    | 32.60     | 35.21     | 30.33     | 27.00     |
|                | Std            | 5.63     | 6.20      | 6.64      | 5.48      | 5.26      |
| Total:         | Min            | 8.71     | 8.88      | 8.95      | 8.68      | 8.89      |
|                | Average        | 18.02    | 18.15     | 17.37     | 17.37     | 16.52     |
|                | Max            | 29.56    | 32.60     | 35.21     | 31.08     | 32.27     |
|                | Std            | 5.37     | 5.82      | 5.72      | 4.52      | 5.01      |

References

Agrawal YC, Pottsmithe HC (2000) Instruments for particle size and settling velocity observations in sediment transport. Mar Geol 168:89–114. https://doi.org/10.1016/S0025-3227(00)00044-X

Agrawal YC, Hanes DM (2015) The implications of laser-diffraction measurements of sediment size distributions in a river to the potential use of acoustic backscatter for sediment measurements. Water Resour Res 51:8854–8867. https://doi.org/10.1002/2015WR017268

Agrawal YC, Whitmire A, Mikkelsen OA, Pottsmithe HC (2008) Light scattering by random shaped particles and consequences on measuring suspended sediments by laser diffraction. J Geophys Res 113:871. https://doi.org/10.1029/2007JC004403
Agrawal YC, Slade W, Pottsmith HC, Dana D (2016) Technologies and experience with monitoring sediments for protecting turbines from abrasion. IOP Conf Ser: Earth Environ Sci 49:122005. https://doi.org/10.1088/1755-1315/49/12/122005

Aleixo R, Guerrero M, Nones M, Ruther N (2020) Applying ADCPs for long-term monitoring of SSC in rivers. Water Resour Res 56(1):812. https://doi.org/10.1029/2019WR026087

Baranya S, Józsa J (2013) Estimation of suspended sediment concentrations with ADCP in Danube river. J Hydrol Hydromech 61:232–240. https://doi.org/10.2478/johh-2013-0030

BMF/LUW (2017) Schwebstoffe im Fließgewässer – Leitfaden zur Erfassung des Schwebstofftransports. Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft. 2. Auflage, Vienna, Austria. https://info.bmlrt.gv.at/jcr:479ff2f0-b143-4560-a9a9-36c464c25125/Leitfaden_Schwebstoffmessung_2te-Auflage.pdf. Accessed 14 October 2021

Bogárdi J (1971) Sediment Transport in Alluvial Streams, 1st ed., Vienna, Austria. https://info.bmlrt.gv.at/jcr:479ff2f0-b143-4560-a9a9-36c464c25125/Leitfaden_Schwebstoffmessung_2te-Auflage.pdf. Accessed 14 October 2021

Boss E, Sherwood CR, Hill P, Milligan T (2018) Advantages and limitations to the use of optical measurements to study sediment properties. Appl Sci 8(12):2692. https://doi.org/10.3390/app8122692

Curtis JA (2008) Summary of Optical-Backscatter and Suspended-Sediment Data, Tomales Bay Watershed, California, Water Years 2004, 2005, and 2006; U.S. Geological Survey Scientific Investigations Report 2007–5224, 16 p.

Czuba JA, Straub TD, Curran CA, Landers MN, Domanski MM (2015) Comparison of bivalve suspended-sediment concentrations and particle-size distributions measured with in-stream laser diffraction and in physical samples. Water Resour Res 51:320–340. https://doi.org/10.1002/2014WR015697

DanubeSediment (2019a) Sediment Monitoring in the Danube River. Approved project report. http://www.interreg-danube.eu/approved-projects/danubeSediment/output. Accessed 14 Oct 2021

DanubeSediment (2019b) Handbook on Good Practices in Sediment Monitoring. Approved project report. 2019. http://www.interreg-danube.eu/approved-projects/danubeSediment/output. Accessed 14 Oct 2021

DanubeSediment (2019c) Analysis of Sediment Data Collected along the Danube. Approved project report. http://www.interreg-danube.eu/approved-projects/danubeSediment/output. Accessed 14 October 2021

DanubeSediment (2020) Long-term Morphological Development of the Danube in Relation to the Sediment Balance. Approved project report. http://www.interreg-danube.eu/approved-projects/danubeSediment/output. Accessed 14 Oct 2021

Deines KL (1999) Backscatter Estimation Using Broadband Acoustic Doppler Current Profilers. Oceans 99 MTS, IEEE Proceedings, San Diego, California. https://doi.org/10.1109/CMM.1999.755249

de Oliveira PA, Blanco CJC, Mesquita ALA, Lopes DF, Filho MDCF (2021) Estimation of suspended sediment concentration in Guanã River in the Amazon region. Environ Monit Assess. 193:79. https://doi.org/10.1007/s10661-021-09891-w

Downing J (2006) Twenty-five years with OBS sensors: the good, the bad, and the ugly. Cont Shelf Res 26:2299–2318. https://doi.org/10.1016/j.csr.2006.07.018

Dredging Research Limited (2003) The Sediview Method – Sediview Procedure Manual.

Dwinovantyo A, Manik HM, Prartono T, Susilohadi S (2017) Quantification and analysis of suspended sediments concentration using mobile and static acoustic doppler current profiler instruments. Adv Acoust Vib 4890421:1–14. https://doi.org/10.1155/2017/4890421

Felix D, Albayrak I, Boes RM (2018) In-situ investigation on real-time suspended sediment measurement techniques: turbidity, acoustic attenuation, laser diffraction (LISST) and vibrating tube densimetry. Int J Sediment Res 33(1):3–17. https://doi.org/10.1016/j.jscr.2017.11.003

Fischer HB, List EJ, Koh RCY, Imberger J, Brooks NH (1979) Mixing in inland and coastal waters. Elsevier

Gartner JW (2004) Estimating suspended solids concentrations from backscatter intensity measured by acoustic Doppler current profiler in San Francisco Bay. California Mar Geol 211(3–4):169–187. https://doi.org/10.1016/j.margeo.2004.07.001

Gray JR, Gartner JW (2009) Technological advances in suspended-sediment surrogate monitoring. Water Resour Res. https://doi.org/10.1029/2008WR007063

Gray JR, Glysson GD, Edward TE (2008) Suspended sediment samplers and sampling methods. In Sedimentation Engineering – Processes, Measurements, Modeling, and Practice, M. Garcia (eds), American Society of Civil Engineers Manual 110, ch. 5.3., American Society of Civil Engineers, Reston, Virginia, pp. 318–337.

Guerrero M, Rüther N, Haun S, Baranya S (2017) A combined use of acoustic and optical devices to investigate suspended sediment in rivers. Adv Water Resour 102:1–12. https://doi.org/10.1016/j.adwatre.2017.01.008

Guerrero M, Szupiany RN, Amsler ML (2011) Comparison of acoustic backscattering techniques for suspended sediments investigations. Flow Meas Instrum 22:392–401. https://doi.org/10.1016/j.flowmeasinst.2011.06.003

Guerrero M, Rüther N, Szupiany RN (2012) Laboratory validation of acoustic Doppler current profiler (ADCP) techniques for suspended sediment investigations. Flow Meas Instrum 23:40–48. https://doi.org/10.1016/j.flowmeasinst.2011.10.003

Guerrero M, Szupiany R, Latosinski F (2013) Multi-frequency acoustics for suspended sediment studies: An application in the Parana River. J Hydrol Res 51(6):696–707. https://doi.org/10.1080/00221686.2013.849296

Guerrero M, Rüther N, Szupiany R, Haun S, Baranya S, Latosinski F (2016) The acoustic properties of suspended sediment in large rivers: consequences on ADCP methods applicability. Water 8:13. https://doi.org/10.3390/w810013

Haimann M, Liedermann M, Naderer A, Lalk P, Habersack H (2012) Integratives Schwebstoffmonitoringkonzept – Innovativen Ansätze auf Basis direkter und indirekter Methoden. Österr Wasser- Und Abfallw 64:535–543. https://doi.org/10.1007/s00506-012-0038-2

Haimann M, Liedermann M, Lalk P, Habersack H (2014) An integrated suspended sediment transport monitoring and analysis concept. Int J Sediment Res 29:135–148. https://doi.org/10.1016/S1001-6279(14)0030-5

Haimann M, Hauer C, Trithart M, Prehner D, Leitner P, Moog O, Habersack H (2018) Monitoring and modelling concept for ecological optimized harbour dredging and fine sediment disposal in large rivers. Hydrobiologia 814:89–109. https://doi.org/10.1007/s10750-016-2935-z

Hauer C, Leitner P, Unfer G, Pulg U, Habersack H, Graf W (2018) The Role of Sediment and Sediment Dynamics in the Aquatic Environment. In Riverine Ecosystem Management, 1st ed., Schmutz, S., Sendzimir, J., Eds., Springer: Chami, Switzerland, Volume 8, pp. 151–169.

Haught D, Venditti JG, Wright SA (2016) Calculation of in situ acoustic sediment attenuation using off-the-shelf horizontal ADCPs in low concentration settings. Water Resour Res 52:5017–5037. https://doi.org/10.1002/2016WR019695

Joshi S, Jun XY (2018) Recent changes in channel morphology of a highly engineered alluvial river – the Lower Mississippi River. Phys Geogr 39(2):140–165. https://doi.org/10.1080/02723646.2017.1340027
Landers MN (2012) Fluvial Suspended Sediment Characteristics By High-Resolution, Surrogate Metrics of Turbidity, Laserdiffraction, Acoustic Backscatter, and Acoustic Attenuation. Ph.D. Thesis, Georgia Institute of Technology, Atlanta, GA, USA.

Landers MN, Straub TD, Wood MS, Domanski MM (2016) Sediment acoustic index method for computing continuous suspended-sediment concentrations: U.S. Geological Survey Techniques and Methods, book 3, chap. CS, 63 p. https://doi.org/10.3133/ts3C5

Lanef SN, Parsons DR, Best JL, Orefe O, Kostaschuk RA, Hardy RJ (2008) Causes of rapid mixing at a junction of two large rivers: Rio Paraná and Rio Paraguay, Argentina. J Geophys Res 113:16. https://doi.org/10.1029/2006JF000745

Latosinski FG, Szupiany RN, García CM, Guerrero M, Amsler ML (2014) Estimation of concentration and load of suspended bed sediment in a large river by means of acoustic doppler technology. J Hydraul Eng 140(7):15p. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000859

Mackay JR (1970) Lateral mixing of the Liard and Mackenzie rivers downstream from their confluence. Can J Earth Sci 7:111–124. https://doi.org/10.1139/e70-008

Matsui E, Salati F, Friedman I, Brinkman WLF (1976) Isotopic characteristics of suspended sediments of different and mixed mineralogical composition. Cont Shelf Res 7:3–15. https://doi.org/10.1016/0278-4343(76)90078-1

Mead AA, Demas CR, Ebersole BA, Kleiss BA, Little CD, Meselhe EA, Powell NJ, Pratt TC, Vosburg BM (2012) A water and sediment budget for the lower Mississippi-Atchafalaya River in flood years 2008–2010: implications for sediment discharge to the oceans and coastal restoration in Louisiana. J Hydrol 432:84–97. https://doi.org/10.1016/j.jhydrol.2012.02.020

Moaed BD, Thorne PD (2012) Interpreting acoustic backscatter from suspended sediments of different and mixed mineralogical composition. Cont Shelf Res 46:67–82. https://doi.org/10.1016/j.csr.2011.10.007

Moore SA, Le Coz J, Hurther D, Paquier A (2012) On the application of horizontal ADCPs to suspended sediment transport surveys in rivers. Cont Shelf Res 46:50–63. https://doi.org/10.1016/j.csr.2011.10.013

Moore SA, Le Coz J, Hurther D, Paquier A (2013) Using multi-frequency acoustic attenuation to monitor grain size and concentration of suspended sediment in rivers. J Acoust Soc Am 133(4):1959–1970. https://doi.org/10.1121/1.4792645

Mossa J (1996) Sediment dynamics in the lowermost Mississippi River. Eng Geol 45(1–4):457–479. https://doi.org/10.1016/S0013-7952(96)00026-9

Nones M (2019) Dealing with sediment transport in flood risk management. Acta Geophys 67:677–685. https://doi.org/10.1007/s11600-019-00273-7

Park J, Batalla RJ, Birgand F, Esteves M, Gentile F, Harrington JR, Navratil O, López-Tarazona JA, Vericat D (2019) Influences of catchment and river channel characteristics on the magnitude and dynamics of storage and re-suspension of fine sediments in river beds. Water 11(5):878. https://doi.org/10.3390/w11050878

Pomázi F, Baranya S (2020a) Comparative assessment of fluvial suspended sediment concentration analysis methods. Water 12(3):873. https://doi.org/10.3390/w12030873

Pomázi F, Baranya S (2020b) New investigation methods of suspended sediment transport in large rivers 2–Comparative investigation of direct and indirect analysis methods In Hungarian. J Hung Hydr Soc 100(3):64–73

Rai AK, Kumar A (2015) Continuous measurement of suspended sediment concentration: technological advancement and future outlook. Measurement 76:209–227. https://doi.org/10.1016/j.measurement.2015.08.013

Rasmussen PP, Gray JR, Glysson GD, Ziegler AC (2009) Guidelines and procedures for computing time-series suspended-sediment concentrations and loads from in-stream turbidity-sensor and streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. C4, 52 p

Sassi MG, Hoitink AJF, Vermeulen B (2012) Impact of sound attenuation by suspended sediment on ADCP backscatter calibrations. Water Resour Res 48:1–14. https://doi.org/10.1029/2012WR012008

Sequoia Scientific (2018) LISST-PortableXR Manual Version 1.3. http://www.sequoiasci.com/wp-content/uploads/2015/06/LISST-PortableXR-Manual-Version-1_3.pdf. Accessed on 14 Oct 2021

Sequoia Scientific (2016) How the LISST-ABS Works. Online article: https://www.sequoiasci.com/article/how-the-lisst-abs-works/ Accessed 1 Apr 2020

Stallard RF (1987) Cross-channel mixing and its effect on sedimentation in the Orinoco River. Water Resour Res 23:1977–1986. https://doi.org/10.1029/WR023i010p01977

Teledyne (2013) Workhorse H-ADCP Technical Specifications. Available online: http://www.teledynemarine.com/Lists/Downloads/hadcpcdatasheet_lr.pdf. Accessed 1 Apr 2022

Thorne PD, Meral R (2008) Formulations for the scattering properties of suspended sandy sediments for use in the application of acoustics to sediment transport processes. Cont Shelf Res 28:309–317. https://doi.org/10.1016/j.csr.2007.08.002

Thorne PD, Hanes DM (2002) A review of acoustic measurement of small-scale sediment processes. Cont Shelf Res 22(4):603–632. https://doi.org/10.1016/S0278-4343(01)00101-7

Thorne PD, Hurther D (2014) An overview on the use of backscattered sound for measuring suspended particle size and concentration profiles in non-cohesive inorganic sediment transport studies. Cont Shelf Res 73:97–118. https://doi.org/10.1016/j.csr.2013.10.017

Thorne PD, Vincent CE, Hardcastle PJ, Rehman S, Pearson N (1991) Measuring suspended sediment concentrations using acoustic backscatter devices. Mar Geol 98:7–16. https://doi.org/10.1016/0025-3227(91)90031-X

Topping DJ, Wright SA (2016) Long-term continuous acoustical suspended-sediment measurements in rivers—Theory, application, bias, and error: U.S. Geological Survey Professional Paper 1823, 98 p. http://dx.doi.org/https://doi.org/10.3133/pp1823.

Urick RJ (1983) Principles of underwater sound, 3rd edn. McGraw-Hill, New York

van Rijn LC (1984) Sediment transport, part I: bed load transport. J Hydraul Eng 110(10):1431–1456. https://doi.org/10.1061/(ASCE)0733-9429(1984)110:10(1431)

Venditti JG, Church M, Attard ME, Haught D (2015) Use of ADCPs for suspended sediment transport monitoring: an empirical approach. Water Resour Res 52:2715–2736. https://doi.org/10.1002/2015WR017348

Wall GR, Nystrom EA, Liten, S (2006) Use of an ADCP to compute suspended-sediment discharge in the tidal Hudson River, New York: U.S. Geological Survey Scientific Investigations Report 2006–5055, 16 p

Weibezahn FH (1983) Downstream natural mixing of water from the Orinoco, Atabapo and Guaviare rivers. Eos Trans AGU 64(45):699

Wright S, Topping DT, Williams CA (2010) Discriminating silt-and-clay from suspended-sand in rivers using side-looking acoustic profilers. In Proceedings of the 2nd Joint Federal Interagency Sedimentation Conference