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Field measurements on alluvial watercourses in light of numerical modeling: case studies on the Danube River

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Abstract Adequate monitoring and data acquisition of proper hydraulic, sediment, and constituent parameters in alluvial watercourses have become crucial aspects of human interaction with the environment. Conducting well-organized, comprehensive, and meaningful field measurements on natural watercourses are of great importance when assessing its hydraulic, morphological, and ecological state. However, this paper presents a methodology for field measurements on alluvial watercourses in light of numerical modeling. The proposed methodology focuses on collecting field data sets to calibrate numerical models for flow, sediment, and heavy metal transport. The proposed approach targets the simultaneous measurement of hydraulic, sediment transport, and heavy metal transport parameters that are key for calibrating constants and exchange mechanisms in contemporary numerical models. Using the principles laid out in this paper, two sets of measurements were carried out on the Danube River, one on a reach near Mohács in Hungary and the other on a reach near Belgrade in Serbia. The first case study discusses the measurement and results of comprehensive hydraulic and sediment parameters. The second case study considers hydraulic and sediment measurements complemented with trace metal measurements for zinc, lead, and mercury. These measurements were used for calibrating numerical models for flow, sediment, and heavy metal transport, as a proof of concept. It has been demonstrated that the gathered data sets contain key parameters that are strongly linked through physical laws and are needed for calibration purposes, as well as parameters that can allow the newly calibrated coefficients to be confirmed through other measured phenomena. Therefore, the proposed methodology provides minimal data sets with detailed measurements for calibrating numerical models for flow, sediment, and heavy metal transport. Guidelines for future measurements that can suffice the increasing need for numerical modeling and monitoring of natural watercourses are also offered.

Keywords Field measurements · Hydraulic parameters · Sediment · Heavy metals · Danube River

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Introduction

Proper monitoring and data gathering of hydraulic, sediment, and constituent parameters in alluvial watercourses is an increasingly important aspect of hydraulic and environmental engineering (Chen et al. 2012; Horvat and Horvat 2020a). This is supported by the fact that human activities on and around natural watercourses had left their impact on these aquatic habitats. In the past decades, hydraulic structures, river training works, and other factors changed the natural balance of hydraulic and sediment parameters in rivers (Jamieson et al. 2011), thus their morphological development has been frequently unfavorable. Furthermore, the inadequate processing of industrial waste or industrial accidents has introduced heavy (toxic) metals and other pollutants into watercourses (Akbulut and Tuncer 2011; Guay et al. 2010), further endangering biotic organisms in and around rivers. To combat these problems, numerical models for flow, sediment, and constituent transport have been utilized to better understand the human influence on natural watercourses. These tools could also provide information that can serve as a starting point for the remediation of natural watercourses in both environmental and hydro-morphological sense.

The development of 1-D (Horvat et al. 2017a, 2020b), 2-D (Horvat et al. 2015, 2020b, c) and 3-D hydraulic models (Wu et al. 2000), models for sediment transport and bed evolution (Horvat et al. 2015; Wu et al. 2000) and heavy metal transport (Horvat and Horvat 2016) increased the necessity of complete and detailed field measurements (e.g., three-dimensional measurements of suspended sediments in a reservoir conducted by Haun et al. (2013)). Although indisputably useful, numerical models can perform only with proper input parameters consisting of field measurements, which are frequently scarce at best (Jian et al. 2017). These complex models require certain data sets to be properly calibrated, after which they can be utilized to foresee certain scenarios and future hydro-morphological or environmental developments (Jing et al. 2013; Yao et al. 2018), contributing in this way to the sustainable management of water resources.

In general, hydraulic, sediment, and pollutant measurements in alluvial watercourses are abundantly present in contemporary hydraulic and environmental research (Akbulut and Tuncer 2011; Petrie et al. 2013a; Sakho et al. 2019). Measuring surface flow using drones was presented by Tauro et al. (2016), while other not conventional methods were, amongst others, explored by Melcher et al. (2002), Stockdale et al. (2008), and Li et al. (2019). Other researchers modeled suspended sediment distribution and deposition tendencies using numerical models, while the necessary measurements were carried out using LISST-SL that measures concentrations and grain size distribution instantly (Haun et al. 2015). Another approach to suspended sediment measurements is presented in Chung and Lin (2011), where the authors propose an innovative monitoring methodology based on time-domain reflectometry. Nord et al. (2014) investigated the influence of sediment transport on velocity measurements and discharge estimation by Acoustic Doppler devices. They found that sediment transport causes the underestimation of measured velocities. The underestimation was more significant for coarser sediment moving as bedload or by saltation and smaller in cases of significant suspended sediment transport. Cheviron et al. (2014) worked on alternative solutions in cases of infrequent or irregular sediment concentration measurements, proposing an improved rating curve and evaluated the number of required data to counterbalance the limitations of measurement accuracy and frequency. Furthermore, tracing the origin of suspended sediment in rivers and estimating the rate of sedimentation by measuring radionuclides' presence were investigated by several authors (Du and Walling 2012; Zebracki et al. 2015). Concerning hydraulic parameters, Lee et al. (2014) analyzed the uncertainty of the Acoustic Doppler Current Profiler and proposed an uncertainty analysis approach for other instruments as well. Stošić et al. (2012) suggested a method for optimizing river discharge measurements that can reduce the number of necessary velocity measurements. Legleiter et al. (2017) considered various methods of remote discharge sensing, such as thermal imaging of flow velocities, spectrally based depth retrieval from passive optical image data. Nihei and Kimizu (2008) and Hoitink et al. (2009) investigated the possibility of using a horizontal acoustic Doppler current profiler for measuring and monitoring river discharge. Other authors made great efforts in developing methodologies for improving the reliability of discharge measurements in rivers (Bekri et al. 2019). Gashi et al. (2011) published their experiences regarding the establishment of a monitoring system on major rivers with an accent on heavy (toxic) metals.

There is an abundance of research concerning measurements of various parameters in alluvial watercourses. However, these often precise and useful measurements give us information only on a single, or in a better case, on a couple of aspects of a complex interdependent system. Since numerical models developed for alluvial watercourses aim to solve many intertwined mechanisms that exist in these systems simultaneously, the necessary measurements to support these models have to be designed accordingly. Therefore, the formulation of a field measurement methodology that focuses not only on gathering accurate values for representative parameters but on gathering these in such a way to contain all necessary data for calibrating the mechanisms embedded in contemporary numerical models would be most beneficial. Hence, this paper presents a field measurement methodology for collecting data sets suitable for complex numerical models' calibration, as well as monitoring activities or assessments of natural watercourses. The presented methodology was implemented on two case studies on the Danube River, one near Mohács in Hungary and the other near Belgrade in Serbia, taking into account hydraulic, sediment, and heavy metal parameters. These measurements were used for calibrating numerical models for flow, sediment, and heavy metal transport, as a proof of concept.

Methodology

It should be noted that hydraulic, sediment, and heavy metal parameters are inseparably linked. Sediment transport processes are a direct consequence of water movement through shear stresses, turbulence, etc. Additionally, heavy metal can be found in two states in natural watercourses: as dissolved in water or adsorbed on sediment particles. To further complicate the matter, sediment particles can be found as suspended sediment or bed sediment. However, the same sediment particles (with or without adsorbed heavy metal on them) can find themselves in suspension or on the river bed, depending on the current hydraulic conditions. Although measurements of either hydraulic, sediment, or constituent parameters are available, it is often the case that these measurements are not synchronized with one another, leaving researchers to develop methods for calculating missing data (Cheviron et al. 2014; Durand et al. 2014; Bjerklie et al. 2020). The proposed methodology is based on the simultaneous gathering of all relevant hydraulic, sediment, and constituent parameters. These measurements should serve the purpose of providing the necessary data needed for the calibration of hydraulic, sediment transport, and heavy metal transport models for alluvial watercourses, which can be later used for detailed calculations, predictions, etc. If a data set is minimal but complete, one can adequately calibrate a numerical model. It should also be noted that the proposed measurement methodology relies on gathering parameters defined by deterministic principles embedded in numerical models. However, if the measurements campaign is intended for monitoring purposes only, multivariate analysis can also be used to select relevant parameters (Pastor et al. 2016).

Firstly, the measurement of river bed elevations at the studied reach is necessary for hydraulic computations. These measurements, usually conducted with an echo-sonar and a GPS, should be dense enough to build a river bed's digital terrain model. Data verticals on pre-selected cross-sections (i.e., data ranges) should be fixed so that velocity measurements, water, suspended sediment, and bed sediment sample gathering could be conducted at the same time on each of these locations—this way, all the mutually dependant parameters can be determined at once. The uncertainty of these measurements (using an echo-sonar and GPS) was 2%.

Discharge measurements presented in this paper were carried out by an ADCP on a moving vessel (Petrie et al. 2013a), while the water surface elevation was determined for every cross-section. Velocity measurements were conducted on a data vertical using an ADCP on a fixed vessel (Petrie et al. 2013b). The velocity record time was selected to be 10 min, ensuring the averaging of "instantaneous" velocity profiles. An example of this phenomenon is depicted on Fig. 1 (left), where the deviations from final values are negligible after only 4 min of recording. The selected measurement time was monitored by real-time averaging of velocity profiles (Fig. 1, right). The uncertainty of these measurements (using an ADCP) was 10%.

Fluvial grain size determination is nowadays possible using airborne remote sensing, which can be very useful for remote and long river reaches (Carbonneau et al. 2005). Furthermore, several researchers developed methodologies to estimate suspended sediment concentration in natural rivers using the now

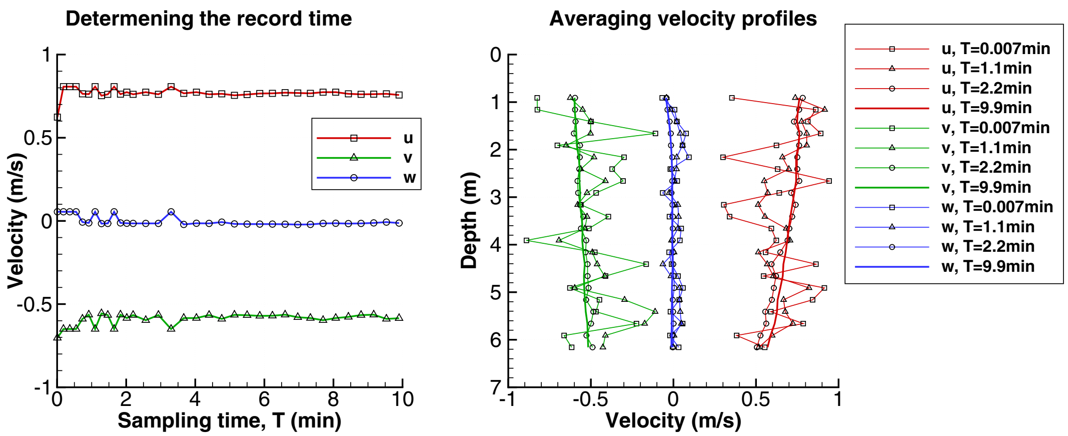


Fig. 1 Velocity measurement with an ADCP

widely available acoustic methods (Elçi et al. 2009). However, the proposed methodology relies on more conventional techniques to minimize the additional measuring uncertainty that indirect methods have.

In the presented case studies, each vertical for sediment and heavy metal measurements had five points where suspended sediment and water samples were collected along with bed sediment samples on the river bed. From these samples, suspended sediment concentrations could be measured along with their size-class distribution at different depths (Rai and Kumar 2019), while every vertical gave a bed material size-class distribution as well. Smaller grain sizes were determined using a sedimentation method, and coarser particles were analyzed using a series of sieves. Although several methods are available for bedload transport measurements (Lemma et al. 2019), the bedload transport itself was not measured. The reasoning for this lies in the fact that in natural alluvial watercourses, the majority of sediment transport is accredited to suspended sediment. For the proper calibration of a sediment transport model, it is by far the most important to correctly approximate the exchange mechanisms between suspended and bed sediment. Accordingly, the proposed measurement methodology focuses on gathering data concerning suspended and bed sediment along with their size-class distributions. As to the used equipment for sediment measurements, the samples for suspended sediment were obtained using a pump. The pump's inlet was lowered to a pre-defined depth (five in each vertical), and a 10-L sample was obtained. A disturbed bed material sample was secured using a Van Veen grab. Combining these acquisition methods with the samples' post-processing (e.g., sedimentation method, using an analytical scale) gave an uncertainty for suspended sediment measurements of around 15%. At the same time, for bed material, this value was approximately 20%. For reasons stated earlier, bedload sampling was not conducted.

Finally, collected water samples allowed determining the dissolved heavy metal concentrations. The presence of adsorbed heavy metals was ascertained on both the suspended and bed sediment. In this way, the proposed measurement methodology enables gathering a data set that can be used for calibrating a heavy metal transport model (and all the relevant exchange mechanisms within it). The heavy metal concentrations in dissolved and adsorbed form were determined relying on EPA standards (USEPA 2004, 1974). It should be noted that the samples from which the heavy metal parameters were determined were the same samples as for the suspended sediment and the bed material. Combining these acquisition methods with the samples' post-processing based on the used EPA standards gave an uncertainty for dissolved heavy metals of around 13%. In contrast, for adsorbed heavy metals, this value was approximately 22%.

Field measurements

Field measurements were conducted on two locations: one near Mohács in Hungary and one near Belgrade in Serbia. Considering the circumstances, these measurements were carried out to be as similar as possible to attain two comparable data sets that can be used to calibrate hydraulic, sediment transport, and heavy metal transport numerical models. Furthermore, the measurements gave an insight into hydraulic and sediment parameters and the distribution of certain toxic metals.

Figure 2 depicts the precise locations of the conducted case studies. Although measurements that can be accredited to have environmental considerations were conducted on this section of the Danube River (Grahek et al. 2016), as the time of writing this paper, there have been no simultaneous and comprehensive scientific measurements of relevant hydraulic, sediment, and/or heavy metal parameters on the considered domain of the river. The two locations for the presented case studies were selected so that the first reach is positioned before the confluence of the Danube River with its major tributaries (Drava, Tisa, and Sava rivers), while the second reach is on a location after these confluences. In this way, the measurements would be conducted for significantly different discharges.

Case study 1: the Danube reach near Mohács (Hungary)

The data collection for the firs case study was conducted from the 23rd until the 27th of May in 2011, on the Danube near Mohács in Hungary.

River bed elevations were measured in cross-sections, approximately 100 m apart, using an echo sonar and a GPS. The results of these measurements are presented on the upper right part of Fig. 3. This raw data enabled the building of a digital river bed model as presented on the central part of Fig. 3, where the flow direction is from the north (data range 1) towards the south (data range 7). The bed elevation was roughly between 69 and 80 m, while the thalweg shifts from the right to the left bank, as expected. On this reach, seven cross-sections (data ranges) were selected (Fig. 3), each with seven data verticals where detailed hydraulic and sediment measurements were conducted. Furthermore, on each data vertical, five points were fixed on different depths for suspended sediment sampling. A more detailed depiction of range 1 is presented on the lower left part of Fig. 3, while ranges 2 through 7 are (with

Fig. 2 Case study locations on the Danube River

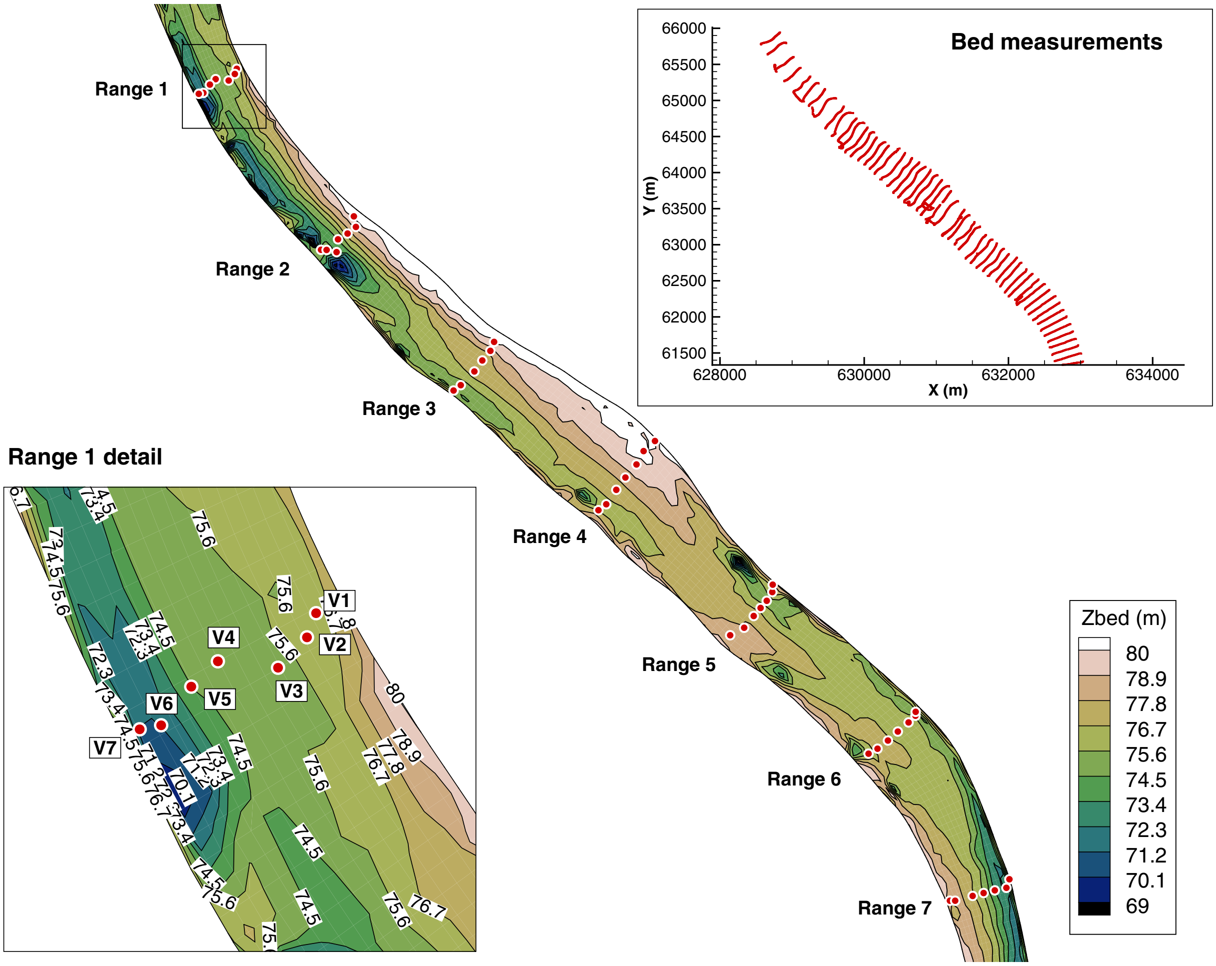


Fig. 3 River bed elevation measurements at Mohács on the Danube

their verticals marked V1 to V7 from the left to the right bank) shown on Fig. 18 (Appendix 1). During the data collection campaign, discharge measurements were carried out utilizing an ADCP on a moving vessel with four consequential passes for each range. The average discharge during the field measurements was 1602.11 m^3/s. Velocity measurements were carried out for every vertical on every range, using an ADCP on a fixed vessel. The measurements gave three components of the velocity vector (marked u the velocity component in the x-direction, v the component in the y-direction, and w the vertical velocity component) through depth. Results of these measurements for range 1 are depicted on Fig. 4, while results for ranges 3, 5 and 7 are presented in Appendix 1 (Figs. 19, 20 and 21). It should be noted that the measurements did not detect any locations with a significant w component of the velocity vector. Consequently, although the measurements can facilitate a 3-D hydraulic model, a 2-D (plain-view) model should suffice.

To properly describe the sediment mixture, sediment size-classes were selected (Table 1 in Appendix 1). This size-class distribution was implemented on both bed and suspended sediment samples. The importance of treating the suspended sediment as a sum of a certain number of size-classes cannot be overstated from the numerical modeling aspect. Various authors confirmed (Budinski and Spasojevic 2014; Horvat et al. 2015, 2016) that modeling the sediment (especially the suspended sediment) as a number of size-classes gives far better results for the total suspended sediment concentration in contrast to the

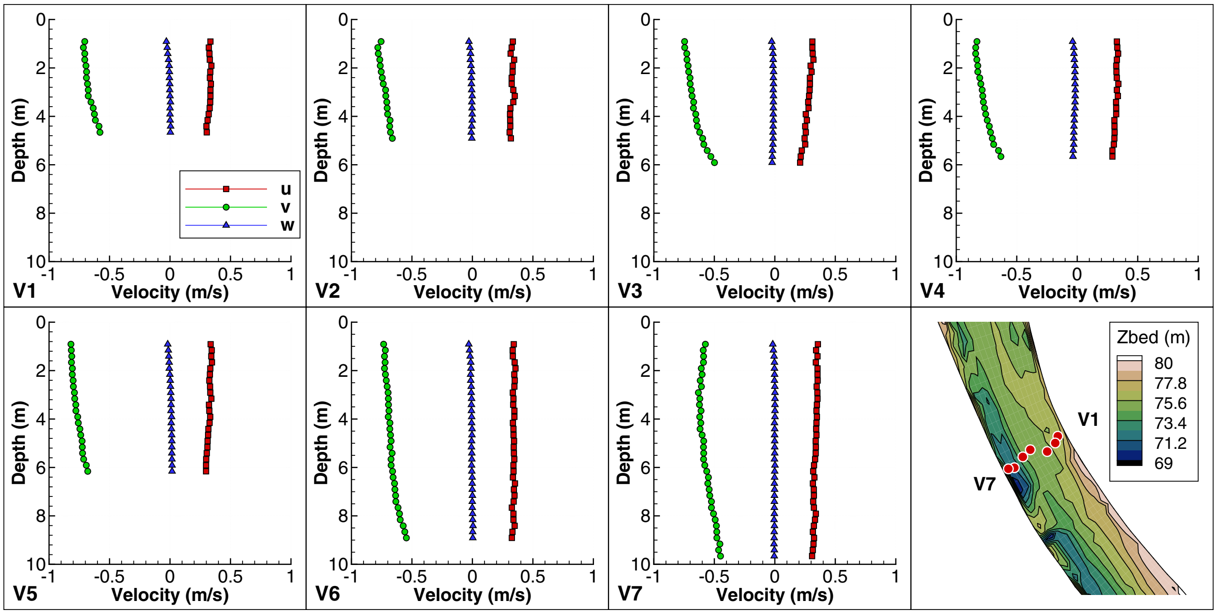


Fig. 4 Velocity measurements at data range 1

suspended sediment represented by one characteristic particle diameter.

Sediment measurements were conducted at all seven ranges on verticals 2 through 6, resulting in five verticals at each range. The sediment measurements consisted of determining the suspended sediment concentration, as well as the concentration of its size-classes in five different depths, and the size-class distribution of the bed sediment on the bottom of every considered vertical. Figure 5 depicts the results of sediment measurements for data range 1, while the results for data ranges 3, 5 and 7 can be found in Appendix 1 (Figs. 22, 23 and 24). The suspended sediment concentration is measured in parts per million (ppm), while the bed sediment mixture is defined as a percentage of a certain size-class.

After processing all the measured sediment parameters for the whole considered reach, box plots with outliers were constructed to give a better insight into the sedimentation processes (Fig. 6).

Case study 2: the Danube reach near Belgrade (Serbia)

The second case study's reach was on the Danube River near Belgrade in Serbia, where the data collection was carried out from July 11th until July 17th of 2013.

On the considered reach, between *rkm* 1168.0, and *rkm* 1159.54, river bed elevations were determined using a GPS and an echo sonar. This was conducted on successive cross-sections approximately 100 m apart, depicted on the upper right portion of Fig. 7. Consequently, a digital river bed model was constructed shown on the lower part of Fig. 7, where the bed elevation varies between 54, and 69 m. Similarly to the first case study, seven data ranges were selected (Fig. 7), on each of them with seven verticals for detailed hydraulic, sediment, and heavy metal measurements. Every vertical had five points on different depths for suspended sediment and heavy metal sampling. A detailed presentation of range 2 is shown on the upper left part of Fig. 7, while range 1 and ranges 3 through 7 (with verticals marked V1 to V7) are shown on Fig. 25 (Appendix 1).

The discharge measurements were conducted using an ADCP on a moving vessel with four consequential passes at each range. The average discharge during the field measurements was 4915.63 m^3/s. The velocities were measured at every vertical in every range, using an ADCP on a fixed vessel. These measurements yielded three components of the velocity vector (marked u the component in the x-direction, v the y-component, and w the vertical velocity component) through depth. Measurements for range 1 are presented on Fig. 8, while results for the remaining

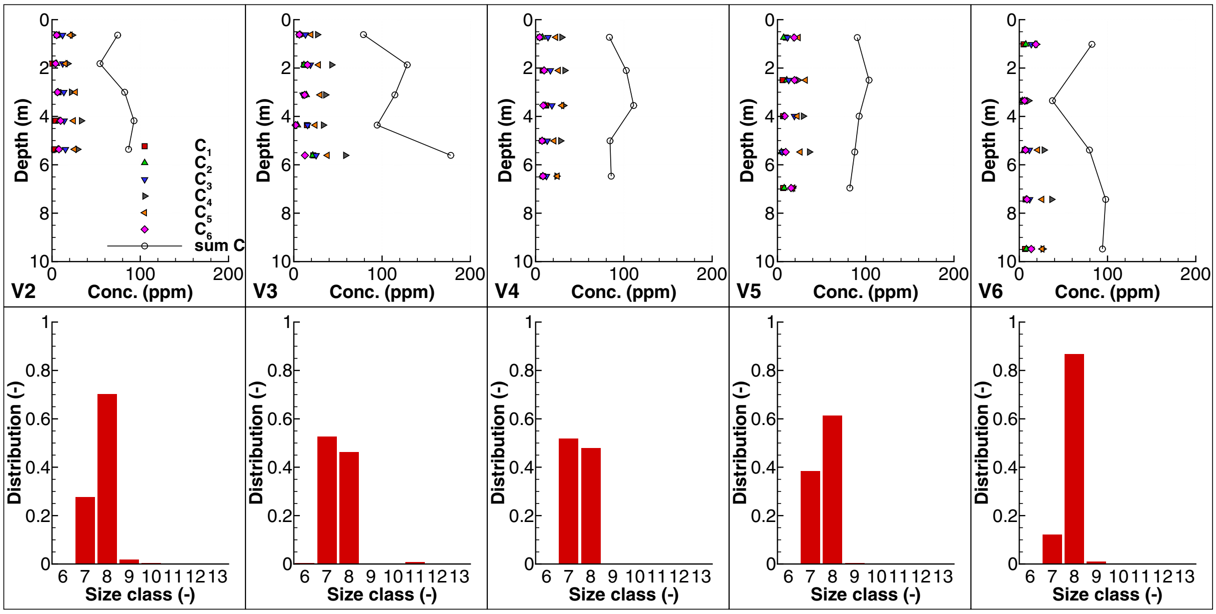
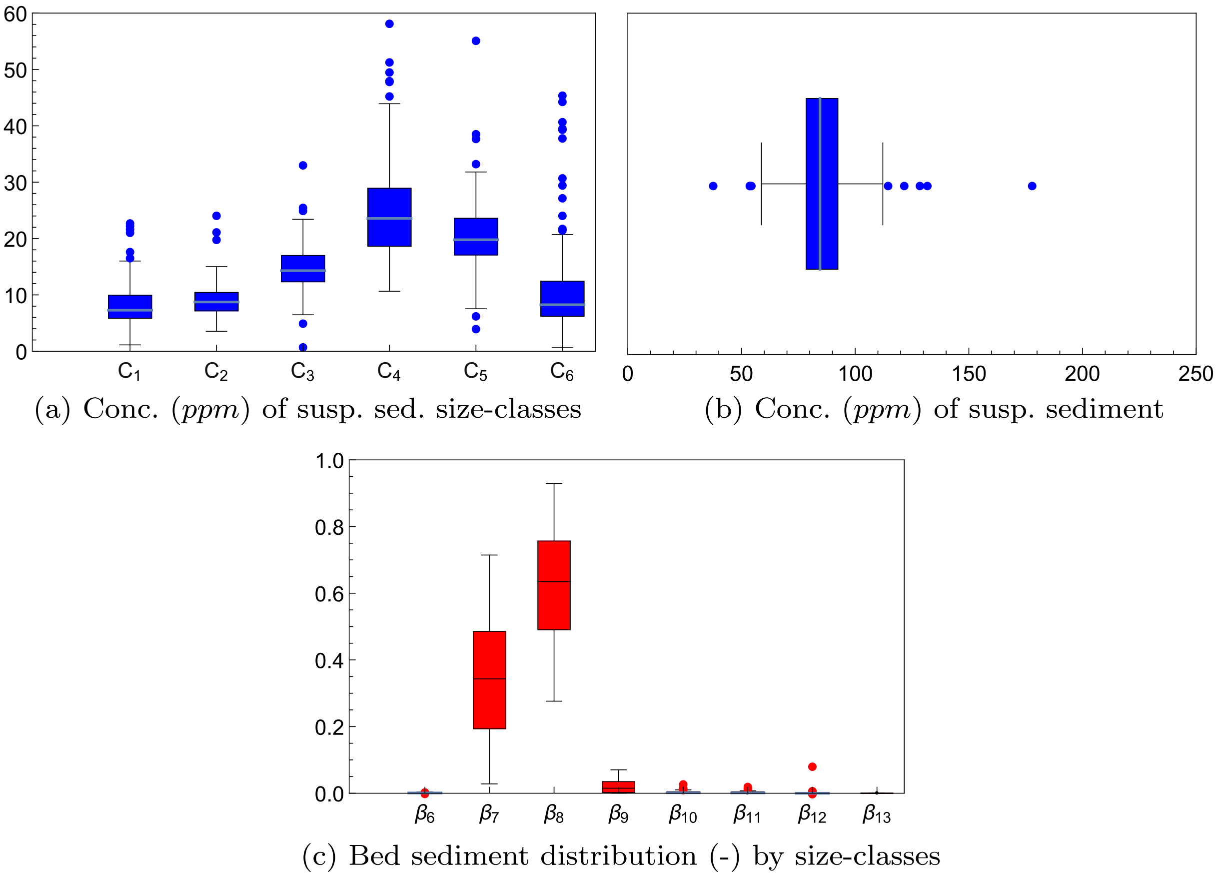


Fig. 5 Sediment measurements at data range 1



(a) Conc. (ppm) of susp. sed. size-classes

(b) Conc. (ppm) of susp. sediment

(c) Bed sediment distribution (-) by size-classes

Fig. 6 Box plots for sediment measurements

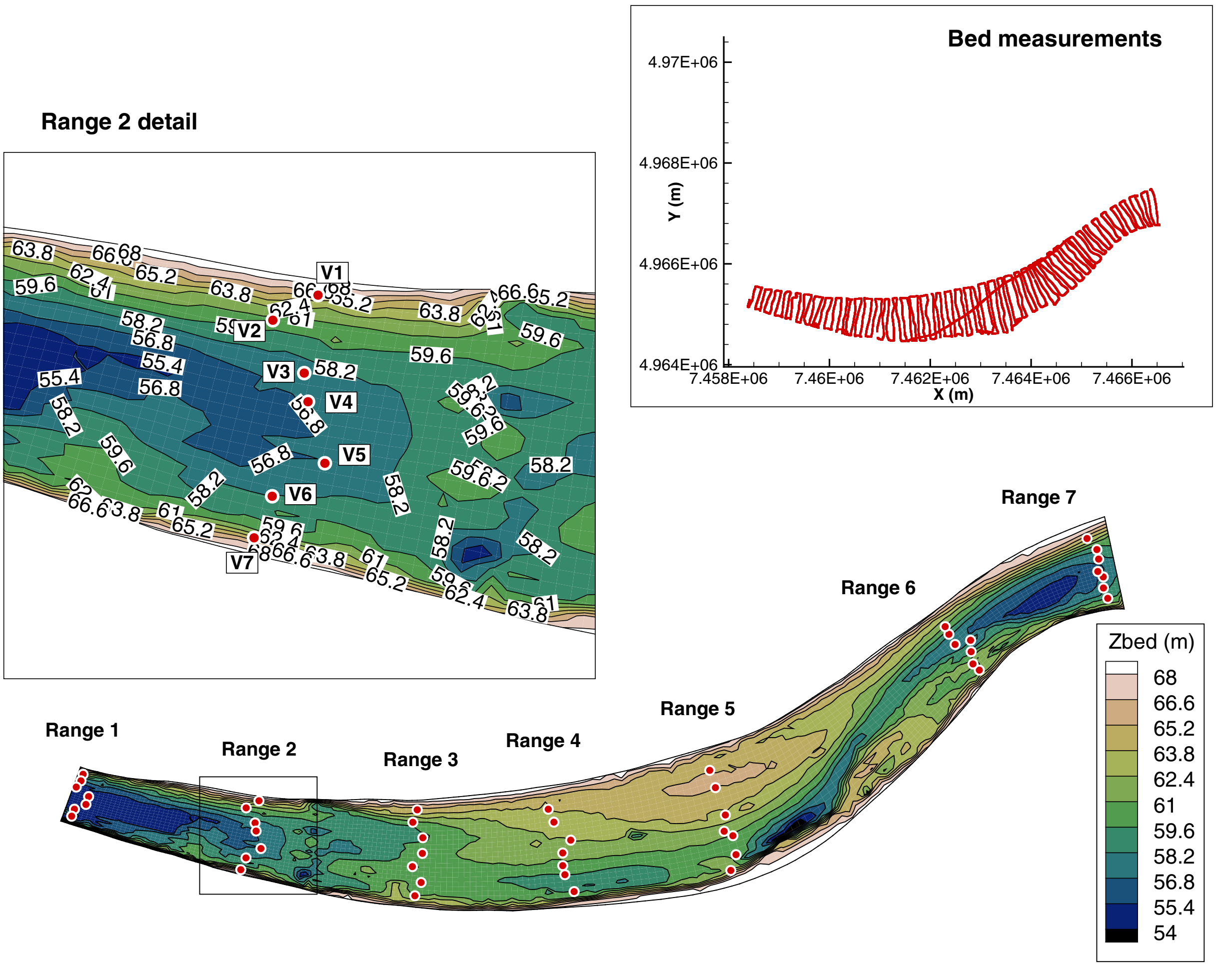


Fig. 7 River bed elevation measurements at Belgrade on the Danube

data ranges 3, 5 and 7 can be found in Appendix 2 (Figs. 26, 27 and 28). Similarly, as in the first case study, the performed measurements did not find sites with a significant w component of the velocity vector, indicating a predominantly 2-D (plain view) case.

As in the first case study, to accurately characterize the sediment mixture, size-classes were selected (Table 2 in Appendix 2). Due to the nature of interlocking sediment processes, the adopted size-class distribution was used on both bed and suspended sediment.

On the whole reach, sediment measurements were carried out on 35 locations, in every seven ranges on verticals 2 through 6. To attain the best possible assessment of sedimentation processes, the total suspended sediment concentrations, and its size-classes' concentration was measured in five different depths of every sediment vertical. Apart from this, in these locations, the size-class distributions of bed material are also available. Figure 9 communicates the sediment measurements for range 1, while the results for data ranges 3, 5 and 7 can be found in Appendix 2 (Figs. 29, 30 and 31). As before, the suspended sediment concentration is measured in parts per million (ppm), while the bed sediment mixture is defined as a percentage of a certain size-class.

On Fig. 10 box plots with marked outliers are presented for the conducted sediment measurements, taking into account the entire analyzed reach.

Apart from hydraulic and sediment measurements, this case study also studied the presence of heavy metals in water and sediment while analyzing the Danube River's investigated reach. Three elements were considered, zinc (Zn), lead (Pb), and mercury (Hg). Water

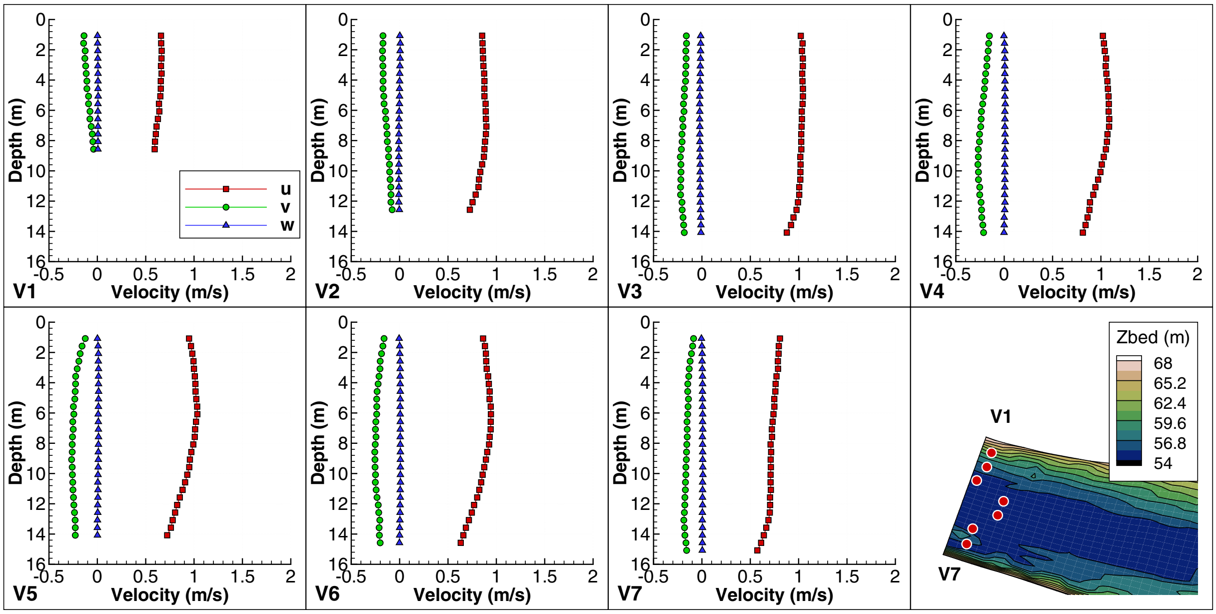


Fig. 8 Velocity measurements at data range 1

samples for the determination of dissolved forms of these trace metals were taken as composite samples for verticals 2, 4, and 6 in every data range. The same is true for bed material samples, while the presence of heavy metals adsorbed on suspended sediment was determined for every vertical in every data range.

The measurement results for zinc dissolved in water, adsorbed on suspended sediment, and adsorbed

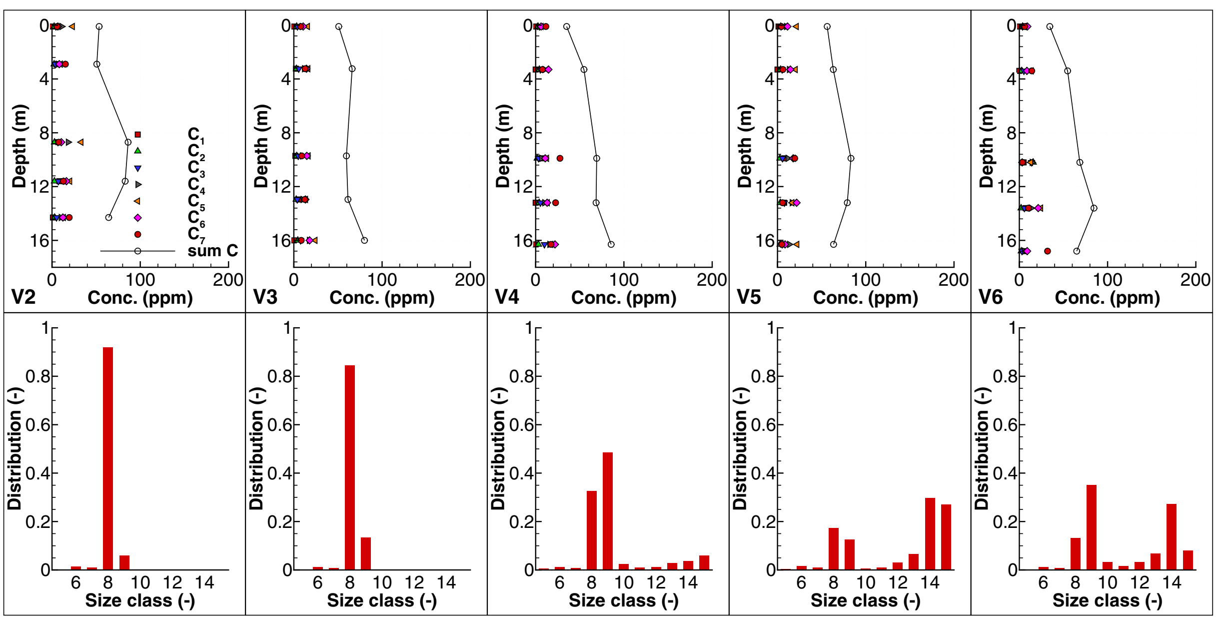
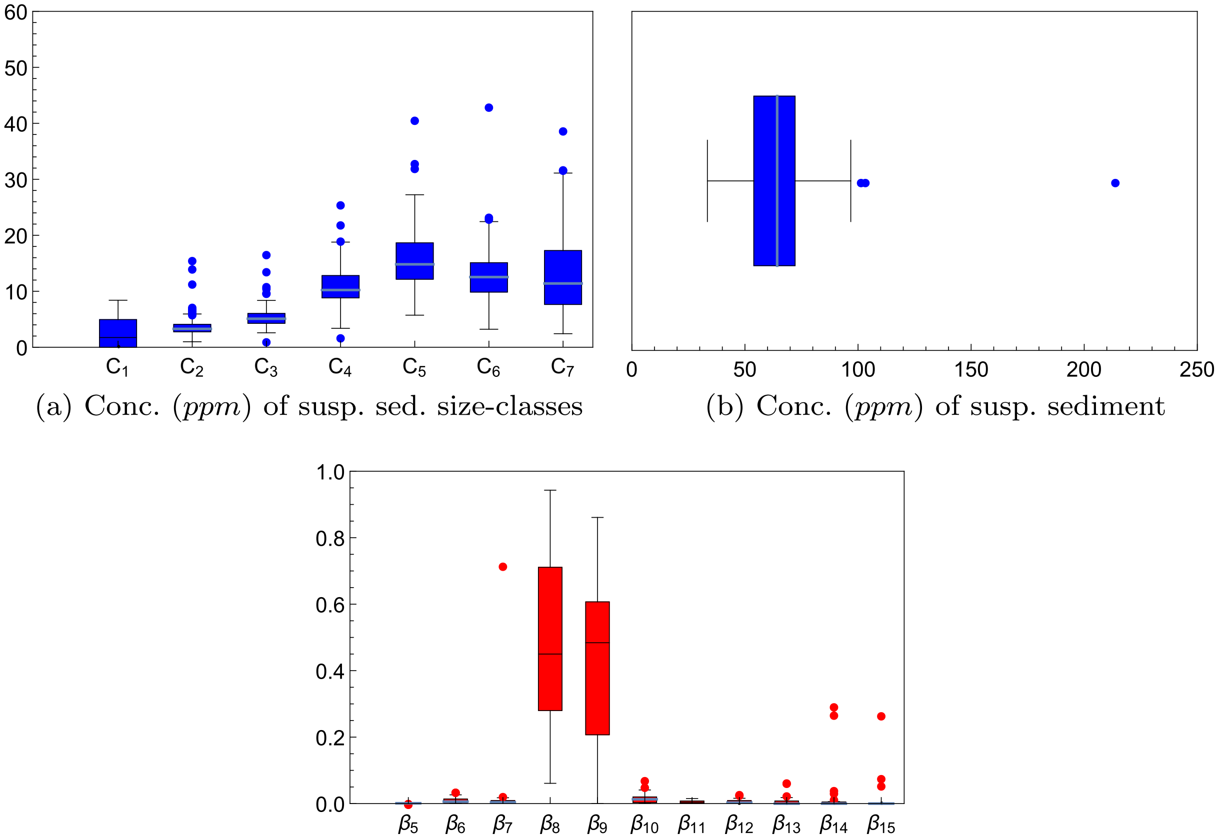


Fig. 9 Sediment measurements at data range 1



(a) Conc. (*ppm*) of susp. sed. size-classes

(b) Conc. (*ppm*) of susp. sediment

(c) Bed sediment distribution (-) by size-classes

Fig. 10 Box plots for sediment measurements

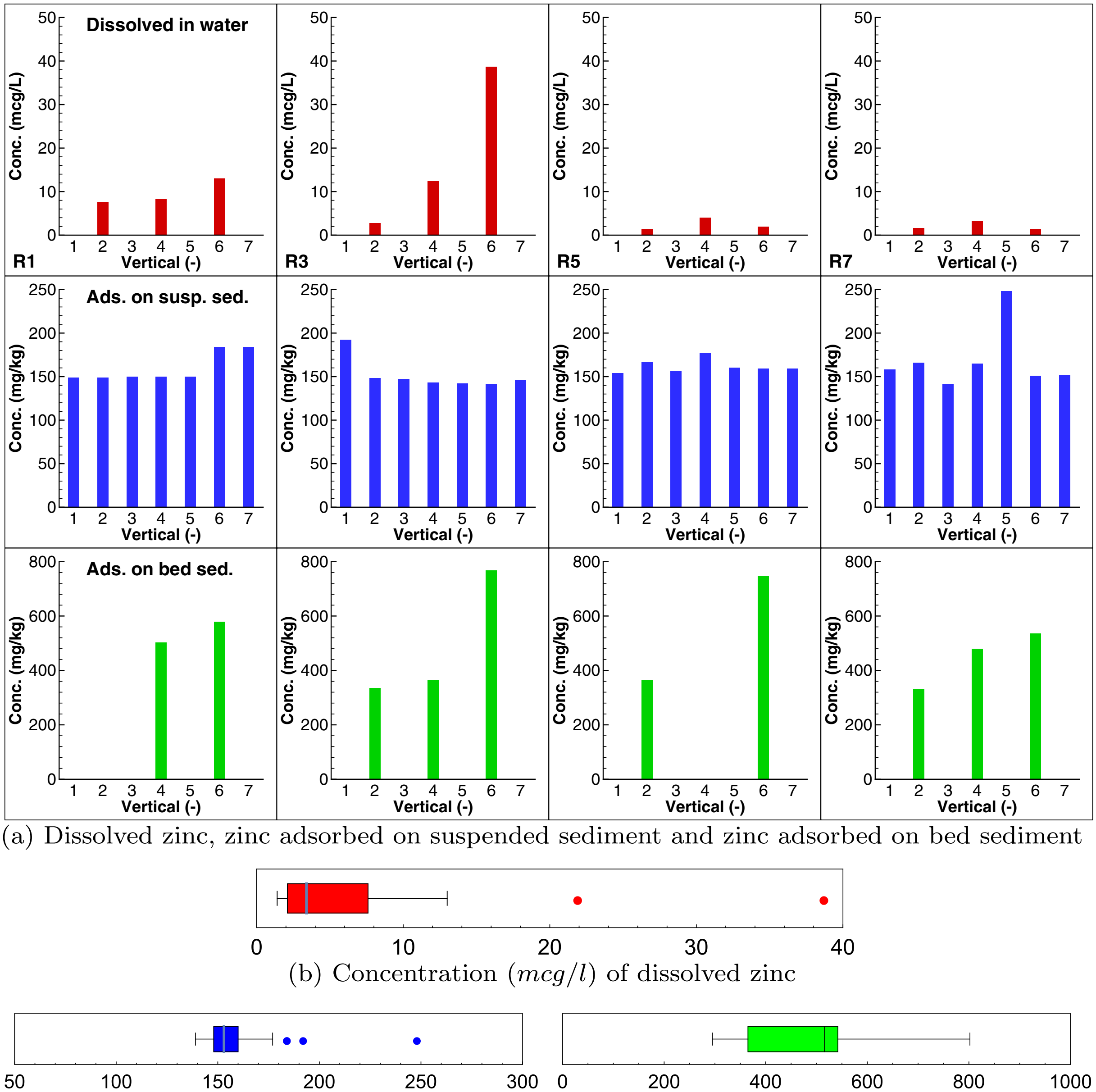
on bed sediment were determined following the EPA 6020A standards (United States Environmental Protection Agency 2004), and are presented on Fig. 11.

For the second trace metal, lead, the results for all samples for dissolved form gave the result of < 0.5 mcg/l; hence, they are omitted from graphical presentation. Figure 12 depicts the presence of lead in adsorbed form on suspended and bed sediment. All measurements were carried out according to the EPA 6020A standard (United States Environmental Protection Agency 2004).

The third considered trace metal was mercury, whose presence was quantified according to the EPA 245.5 standard (United States Environmental Protection Agency 1974). As in the previous case, the results for all samples for dissolved form gave the result of < 0.1 mcg/l. Therefore this form of mercury was left out from the graphical presentation, given on Fig. 13.

The use of the attained data sets in calibration of numerical models

Since the proposed measurement methodology serves to attain data sets that are detailed enough to properly calibrate hydraulic, sediment transport, and heavy metal transport models, this aspect of the conducted measurements will be further analyzed. For good measure, it should be noted that the data sets compiled during the two case studies represent the state of that particular Danube River reaches at that moment in time. Although, until the writing of this paper, there have been no significant interventions on the Danube River's middle section. Therefore, one can assume that the recorded situations depict a reasonably good image of that reach under similar hydraulic conditions when they occur nowadays.



(a) Dissolved zinc, zinc adsorbed on suspended sediment and zinc adsorbed on bed sediment

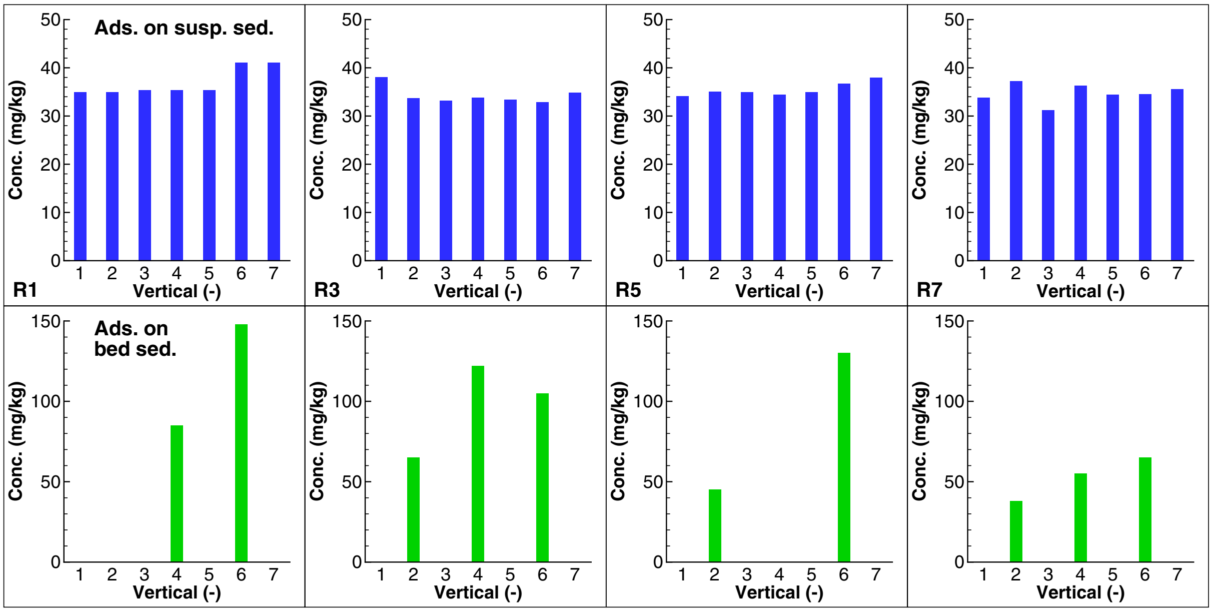
(b) Concentration (mcg/l) of dissolved zinc

(c) Conc. of zinc on susp. sed. (mg/kg)

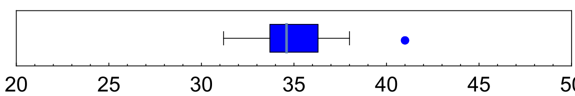
(d) Conc. of zinc on bed sed. (mg/kg)

Fig. 11 Zinc measurements at Belgrade on the Danube

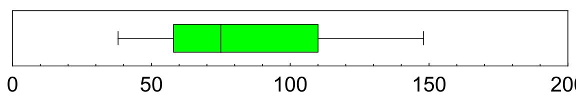
The first step when establishing complex numerical models for alluvial watercourses is the hydraulic computation. To demonstrate the benefits when implementing the proposed field measurement methodology, a 2-D flow model developed by the authors will be used, whose mathematical and numerical aspects are described in a previously published paper (Horvat et al. 2015). The main physical parameter to be calibrated in a hydraulic model is the Manning's roughness coefficient. By defining this coefficient for the modeled domain in such a way to reproduce the measured water surface elevations, the measured velocities can then be used to check the ability of the model to reproduce the flow field as well. For the first case study (the Danube reach near Mohács in Hungary), after the conducted calibration process,



(a) Lead adsorbed on suspended sediment and lead adsorbed on bed sediment



(b) Conc. of lead on susp. sed. (mg/kg)



(c) Conc. of lead on bed sed. (mg/kg)

Fig. 12 Lead measurements at Belgrade on the Danube

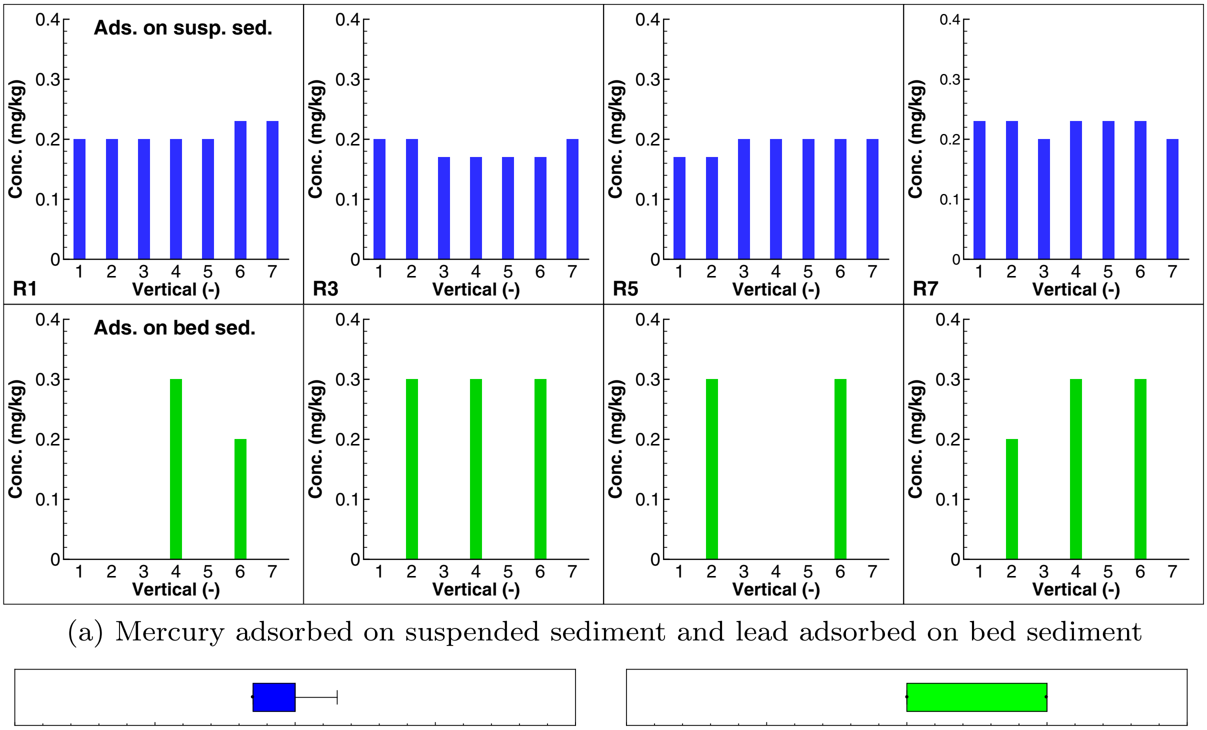
the differences between measured and computed water surface elevations were between $+0.7$ and -1.7 cm. This was achieved by a Manning's roughness factor of $0.02\,\mathrm{m}^{-1/3}\mathrm{s}$. The proposed measurement methodology now allows for a double checkup of the calibrated model. First is by comparing measured and computed velocities. An example is given on Fig. 14 for data range 5 of the first case study.

The second is to compute the Manning's roughness coefficient by using one of the available empirical formulas (Julien 2002) and compare it with the calibrated one. After processing the measured bed material size-class distributions for the first case study, the value of the Manning's roughness coefficient was calculated to be $0.017\,\mathrm{m}^{-1/3}\mathrm{s}$. This roughly corresponds to the calibrated value. Therefore, one can see that the proposed measurements methodology provides a data set that can be used to calibrate a hydraulic model and to perform a double checkup on the model using independent hydraulic parameters.

The sediment transport model can be calibrated only after the establishment of a fully functioning hydraulic model. For this purpose, a 2-D model developed by the authors will be used, whose mathematical and numerical aspects are described in a previously published paper (Horvat et al. 2015). The most important mechanism in such a model is the exchange dynamic between suspended and bed sediment. It should be recognized that state of the art sediment transport models define the interaction between the bed and suspended sediment differently for each size-class (different fall velocities, availability on the bed, availability in suspension, etc.) as demonstrated by the equation

$$S_k = -\epsilon_s \left. \frac{\partial\,(\rho\, C_k)}{\partial z} \right|_a - w_k\, \rho\, (C_b)_k\,, \tag{1}$$

where S_k is the suspended sediment source term for the kth size-class, ϵ_s marks the diffusion coefficient, ρ is the water-sediment mixture density, C_k is the



(a) Mercury adsorbed on suspended sediment and lead adsorbed on bed sediment

(b) Conc. of mercury on susp. sed. (mg/kg) (c) Conc. of mercury on bed sed. (mg/kg)

Fig. 13 Mercury measurements at Belgrade on the Danube

concentration of the kth size-class of suspended sediment, z is the vertical coordinate, subscript a marks that the flux is evaluated on a distance a above the river bed surface, w_k is the fall velocity of the kth size-class sediment, and finally, $(C_b)_k$ is a representative near-bed concentration of the kth size-class suspended sediment (Horvat et al. 2015). Equation (1), after discretization, has the following form Horvat et al. (2015)

$$S_k = -\epsilon_s \frac{(\rho\, C_k)_{a+\Delta a} - (\rho\, C_k)_a}{\Delta a} - (w_k\, \rho\, C_k)_{a+\Delta a}\,, \tag{2}$$

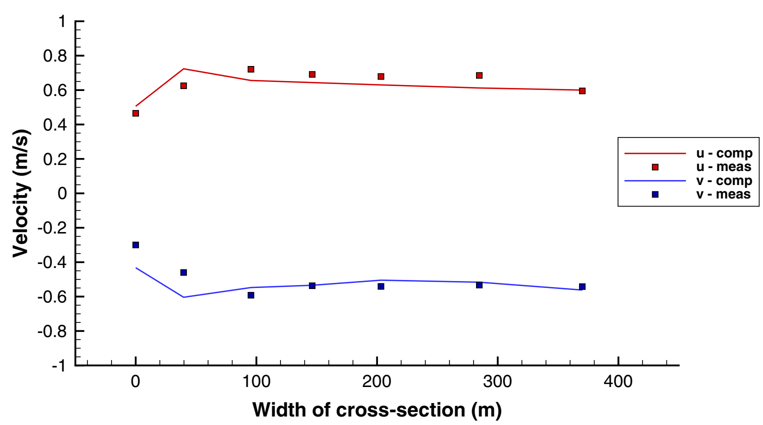


Fig. 14 Computed and measured velocities (data range 5, first case study)

where a and Δa refer to distances from the bed needed for calibration of the suspended sediment source term. Size-classes are also needed when defining the thickness of the active layer (a layer of bed sediment under the influence of flow) on the bed, on account of some methods that use the smallest non-movable grain size for this purpose as shown in Eq. (3)

$$E_a = \frac{D_A}{1-p} - C\left(z_b^{n+1} - z_b^n\right), \quad (3)$$

where E_a marks the active layer depth, D_A is the diameter of the smallest non-mobile sediment size-class, p is the porosity of the sediment mixture, C marks a calibration parameter, and z_b^{n+1} and z_b^n respectively mark the river bed elevation at two sequential computational time steps (Horvat et al. 2015). For the first case study (the Danube reach near Mohács in Hungary), after the conducted calibration process, the distance $a + \Delta a$ in Eq. (2) was set to be 4% of the local depth, while a was set to be 0.003% of local depth. Calibration parameter C in Eq. (3) was set to be 20. After properly calibrating the exchange terms, using the data set compiled by implementing the proposed measurements approach, one can compare computed and measured bed material size-class distributions, computed and measured suspended sediment concentration for each size-class, and computed and measured total suspended sediment concentration, for which an example is given on Fig. 15, for data range 5 of the first case study.

The final model, whose calibration requirements are considered in this paper, is the heavy metal transport model. For the intent of demonstrating the principle, a 2-D model developed by the authors will be used, whose mathematical and numerical aspects are described in a previously published paper (Horvat and Horvat 2016). It should be noted that the presence of heavy metals in both dissolved and adsorbed form on suspended and bed sediment is of the utmost importance when assessing a natural watercourse or when building a numerical model. The proposed methodology for field measurements goes hand in hand with comprehensive hydraulic and sediment measurements, imposed by the interaction between the flow, sediment, and constituent movement. This principle can be demonstrated here with the dissolved pollutant source term that accounts for the adsorption/desorption process in the active-layer sediment (Horvat and Horvat 2016), which is modeled as

$$S_k^{\dagger} = \mu_2 \, \rho_s \, (1-p) \; E_a \, \beta_k \, \beta_k^{\ddagger} \, \iota_c - \mu_1^{bs} \, p \, E_a \, \rho \, C^{\dagger}, \quad (4)$$

where $S_k^{\dagger}$ marks the considered source term for the kth sediment size-class, μ_2 is the kinetic coefficient governing the transfer from adsorbed to dissolved phase, ρ_s is the sediment particle density, β_k marks the kth size-class fraction in active-layer, $\beta_k^{\ddagger}$ is the dimensionless concentration of heavy metal adsorbed on the kth size-class of the active-layer sediment, ι_c marks a surface reduction coefficient, μ_1^{bs} is the kinetic coefficient for adsorption on bed sediment, while $C^{\dagger}$ denotes the dimensionless concentration of dissolved heavy metal in the water. On the other hand, the kinetic coefficient $(\mu_1)_k$ that governs the transfer from dissolved to adsorbed phase can be modeled as

$$(\mu_1)_k = \chi_k^{ss} \, \omega_k^{ss}, \quad (5)$$

where χ_k^{ss} denotes the speed of pollutant adsorption on the kth size-class of suspended sediment, while ω_k^{ss} marks the surface area of available kth suspended sediment size-class per water volume containing the available sediment (Horvat and Horvat 2016). Using the

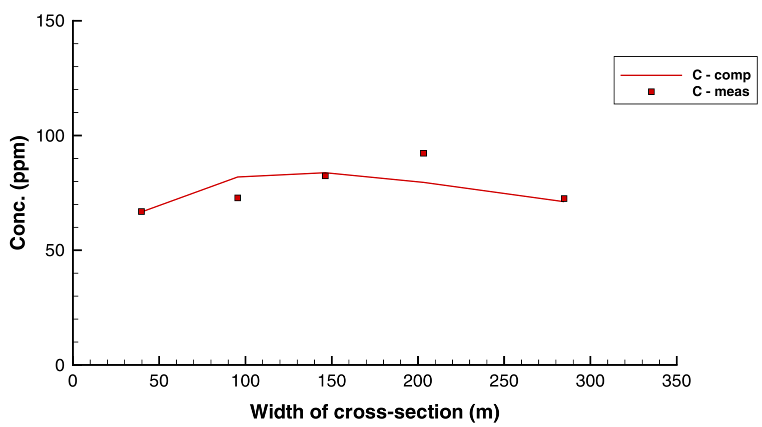


Fig. 15 Computed and measured total suspended sediment concentrations (data range 5, first case study)

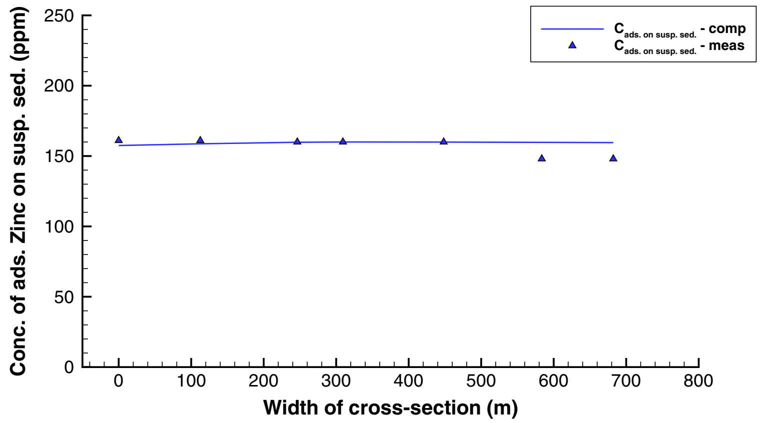


Fig. 16 Computed and measured adsorbed zinc on suspended sediment (data range 2, second case study)

data set collected in the second case study (the Danube reach near Belgrade in Serbia), after conducting the calibration of the heavy metal transport model for zinc, the μ_2 kinetic coefficient was set to be $1.16 \cdot 10^{-5}$, the χ_k^{ss} coefficient ranged between $2 \cdot 10^{-7}$ and $9.5 \cdot 10^{-6}$ for various size-classes, while the surface reduction coefficient ι_c was 0.1. Hence, by calibrating the model's various parameters (kinetic coefficients, surface reduction coefficients, etc.), one can compare computed and measured values for dissolved and adsorbed heavy metal concentrations. An example of the latter is given on Figs. 16 and 17, where adsorbed zinc on suspended and bed sediment in data range 2 of the second case study can be seen.

Discussion

In Section 2, a comprehensive description of a preformed measurement campaign (near Mohács on the Danube River) utilizing the proposed methodology was given. The hydraulic measurements (Fig. 4, and Figs. 19, 20 and 21 in Appendix 1) yielded the information that measured velocities were between 1.09 and 0.25 m/s. Velocity distribution in ranges 1 and 5 is quite uniform, whereas range 3 displays considerably higher velocities on the right bank. Range 7 shows a decrease in velocities on both banks. As to the sediment measurements (Fig. 5 and Figs. 22, 23 and 24 in Appendix 1), the only sediment size-class that could be found in both suspended sediment and bed sediment was the 6th size-class. As far as the bed sediment size-class distribution is concerned, the 7th size-class is more present on the left, while the 8th size-class is dominant on the right bank of the studied reach. It seems as if hydraulic armoring might be occurring in the second vertical of the fifth range (Appendix 1, Fig. 23) since the presence of larger size-classes (compared to other locations) was detected on the river bed. Following the statistical analysis and the construction of box plots (Fig. 6), it was deduced that the 4th and 5th size-classes are imperious in the suspended sediment mixture, while the bed sediment is dominated by the 7th and 8th size-classes. The 6th size-classz was the

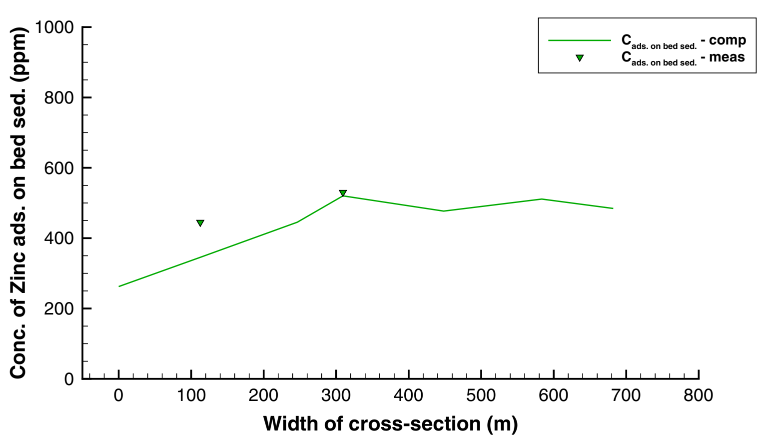


Fig. 17 Computed and measured adsorbed zinc on bed sediment (data range 2, second case study)

only one found both in suspended and bed sediment. The box plot for the total suspended sediment concentration is presented on Fig. 6b. Although various size-classes of suspended sediment sometimes show a significant variation in concentration with a considerable number of outliers, the total suspended sediment concentration has a reasonably low variation.

Section 2 contains the description of a second measurement campaign (near Belgrade on the Danube River) utilizing the proposed methodology. The hydraulic measurements (Fig. 8 and Figs. 26, 27 and 28 in Appendix 2) gave velocity values were between 1.11 and 0.38 m/s. Velocity distribution in ranges 3 and 5 is predominantly uniform, while in ranges 1 and 7, there is a notable drop on both banks. Since the considered reach is at its narrowest (and deepest) at range 1, the velocities here are considerably higher than in the rest of the reach. The result for sediment measurements (Fig. 9 and Figs. 29, 30 and 31 in Appendix 2) supported the conclusion that two size-classes, namely the 6th and 7th, can be detected in suspension and on the river bed as well. Hydraulic armoring can be detected in the first range (Fig. 9) since far larger size-classes of the sediment mixture can be found here compared to the rest of the reach. This is in accordance with the hydraulic measurements that suggested higher values of velocities in this range. Following the statistical analysis and the construction of box plots (Fig. 10), it could be deduced that the 5th and 6th size-classes are most present in the suspended sediment, while in the case of bed sediment, the predominant size-classes are the 8th and the 9th. The two size-classes of sediment in the mixture that can be found in both suspension and on the river bed are the 6th and 7th size-class. The results for the total suspended sediment concentration are depicted on Fig. 10b. Although the concentrations of suspended sediment size-classes show some variation in their “joint” effect through the total suspended sediment concentration, these variations diminish.

The second case study also focused on the presence of heavy metals in the water and on the sediment. The measurement results for zinc dissolved in water, adsorbed on suspended sediment, and adsorbed on bed sediment are presented on Fig. 11a. It can be noted that the presence of this element is far greater on the bed sediment compared with suspended sediment. Also, while zinc can be found on the bed and suspended sediment fairly uniformly on the entire reach, dissolved zinc shows considerable variation both in data ranges and in the whole considered reach altogether. Box plots with marked outliers of zinc found in dissolved form and adsorbed form on both suspended and bed sediment are depicted on Fig. 11b, c and d. The fate of zinc (at the time of the conducted field measurements) is its migration from adsorbed form on bed sediment directly into dissolved form and its transition from being adsorbed on suspended sediment into dissolved form once the bed sediment is entrained into suspension. This conclusion is supported by the fact that the concentration of adsorbed zinc is far more significant on the river bed than on suspended sediment. As a result, once the bed sediment finds itself in suspension, it releases some of the adsorbed zinc into the water.

The measurement results for zinc dissolved in water, adsorbed on suspended sediment, and adsorbed on bed sediment are presented on Fig. 12a. While the suspended sediment carries a relatively uniform quantity of this heavy metal, the bed sediment shows some variations in the measured concentrations. Box plots with marked outliers of lead found in adsorbed form on both suspended and bed sediment are depicted on Fig. 12b and c. The lead concentration is considerably more significant on the bed than on suspended sediment, suggesting that lead is being released from bed sediment directly into dissolved form or is possibly released from bed sediment particles entrained into suspension.

The results for adsorbed mercury on suspended and bed sediment show a reasonably uniform distribution both in data ranges and the whole analyzed reach of the Danube River, as depicted on Fig. 13a. Box plots with marked outliers of mercury found in adsorbed form on both suspended and bed sediment are depicted on Fig. 13b and c. The fate of mercury was similar to the previous two trace metals since its concentration on bed sediment was greater than it was on suspended sediment.

Finally, the use of the described data sets during the calibration process of hydraulic, sediment transport, and heavy metal transport models were presented in Section 2. The measured water levels and velocities could be used to determine the main physical parameter to be calibrated in a hydraulic model. Namely, the Manning’s roughness coefficient can be later double-checked using the bed sediment grain distribution. An excellent example of this process is given on

Fig. 14 for data range 5 of the first case study. The principles of calibrating the sediment transport model were explained through the exchange dynamic between suspended and bed sediment. Using the data sets acquired by implementing the proposed measurement methodology, the results of the sediment transport model's calibration are presented on Fig. 15, for data range 5 of the first case study. Finally, the calibration of the heavy metal transport model using the second case study's data set was achieved through the adsorption/desorption process in the active-layer sediment and the kinetic coefficient that governs the transfer from dissolved to adsorbed phase. The results concerning the calibration of the heavy metal transport model are given on Figs. 16 and 17 for zinc adsorbed on suspended and bed sediment.

As demonstrated by the given examples, the proposed methodology for conducting field measurements to calibrate hydraulic, sediment transport, and heavy metal transport models provides a wide range of possibilities to perform this task satisfactorily. The two case studies provided data sets that contain simultaneous measurements of all the necessary parameters needed to estimate the fundamental mechanisms that describe the flow field and the migration of sediment and heavy metals in all of their forms. Naturally, one can always opt for an even more comprehensive data set. However, the intent of the proposed measurement methodology is to provide the minimal but crucial number of relevant parameters needed for the calibration of numerical models.

Conclusion

Due to human activities, which often occur on and around natural alluvial watercourses, the relevance of proper and meaningful field measurements has surged. Although many authors study water pollution, sediment, and morphological development of watercourses or flow conditions, these aspects of the same issue are rarely coupled consistently. The filed measurement methodology presented in this paper serves to gather data sets that could be used to build and calibrate numerical models that could provide an insight into the flow conditions, sediment, and constituent faith, and thus the state of aquatic habitats. The proposed approach targets the simultaneous measurement of hydraulic, sediment transport, and heavy metal transport parameters that are key for calibrating constants and exchange mechanisms in numerical models that can't be determined without field measurements. This methodology aims not to encompass all existing parameters but rather to give researchers the framework to compile meaningful data sets with minimal measurements that are usable for calibrating numerical models[1].

Using the proposed approach, two case studies were conducted on the Danube River, one near Mohács in Hungary and the other near Belgrade in Serbia. Hydraulic and sediment measurements gave indications concerning the morphological tendencies of the studied reaches and the processes between the bed and suspended sediment. The presence of trace metals was also researched in dissolved and adsorbed forms in the second case study. It was determined that the bed sediment is far more polluted by these elements than the suspended sediment. Taking into account the sediment transport processes, the primary source of this pollution was discovered. Box plots have been employed on both sediment and trace metal measurements to attain a more comprehensive judgment on the studied reaches.

To demonstrate the principle, numerical models' calibration procedures were presented using the data sets compiled in the two case studies. It has been shown that these data sets are quite useful for this purpose and that they give a wide range of opportunities for calibrating and double-checking the calibrated numerical model. The data sets contain both parameters which are strongly linked through physical laws and are simultaneously needed for calibration purposes and parameters that allow confirmation of the calibrated values through other measured phenomena.

Although the proposed field measurements methodology seems to be sound and useful, gathering similar (comparable) data sets for the Danube River in extreme drought and extreme flood would be most beneficial. In these circumstances, different hydraulic, sedimentation, and transport mechanisms become more dominant. Hence, these data sets could expand our knowledge of calibration coefficients regarding their usefulness and/or numeric values. Furthermore, case studies on other large alluvial watercourses should be an undertaking worth considering.

Funding This work was funded by the Ministry of Education, Science and Technical development of the Republic of Serbia.

[1] All data sets mentioned in this paper are available upon request to the corresponding author.

Appendix 1. Case study 1 (Danube reach near Mohács in Hungary)

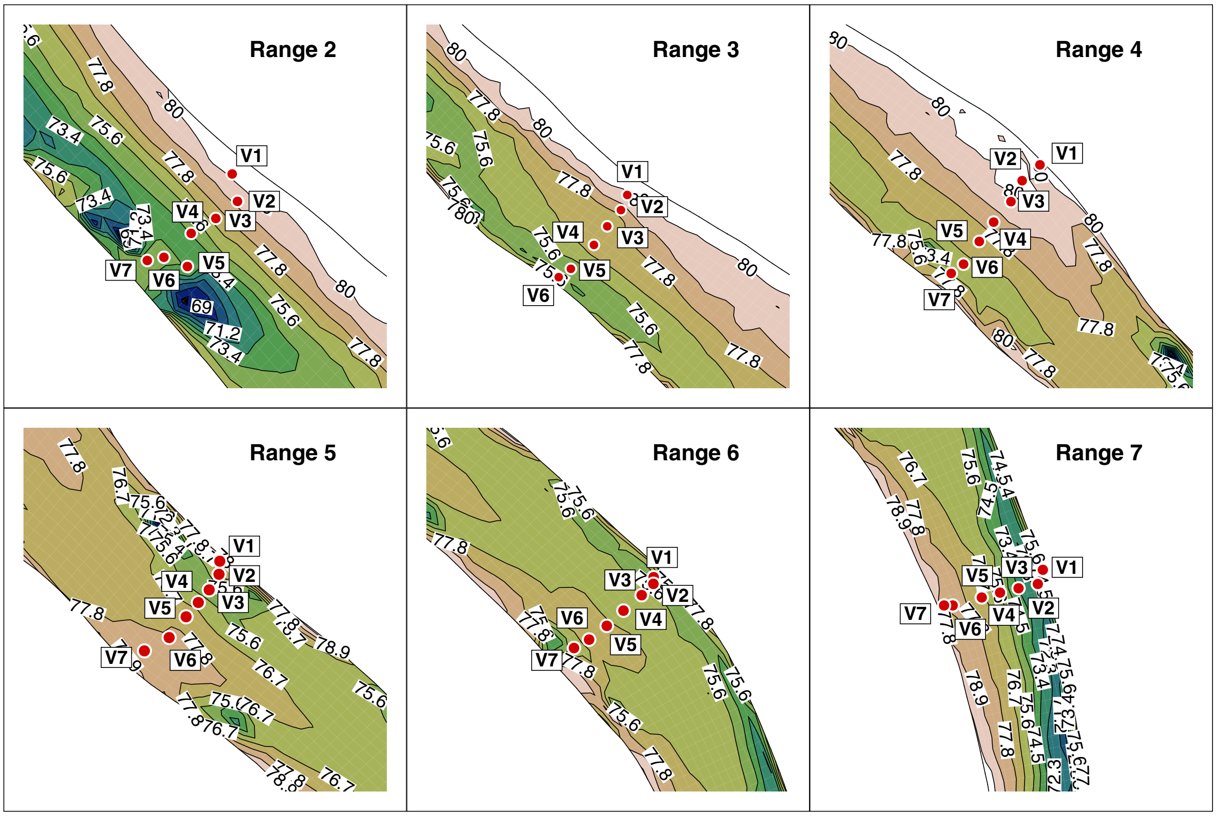


Fig. 18 Overview of data ranges at Mohács on the Danube

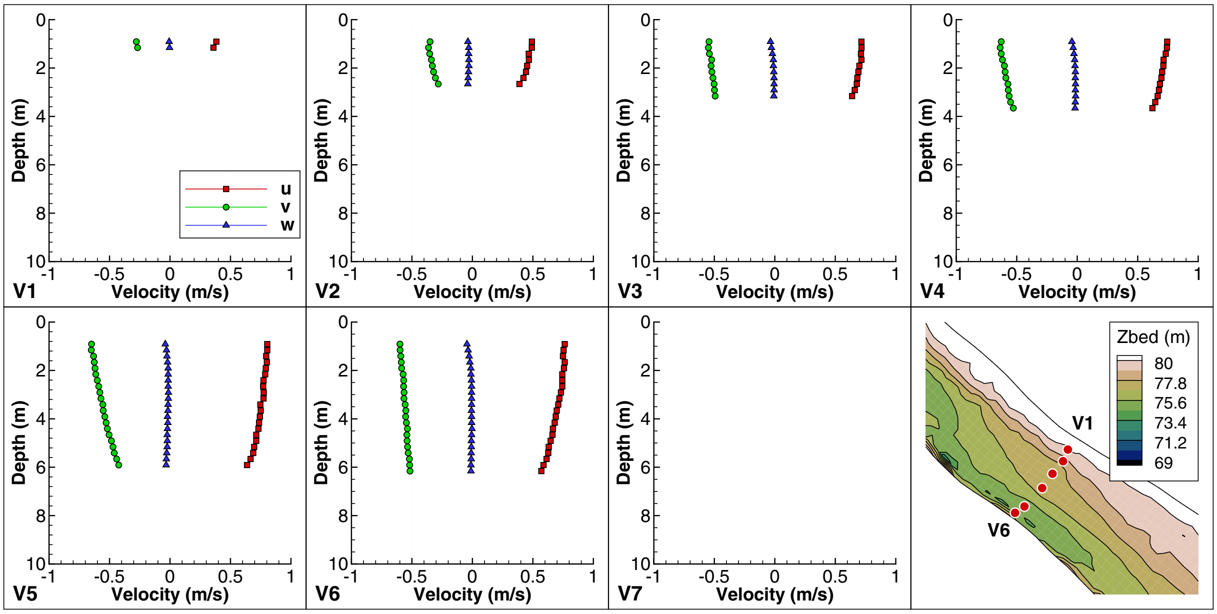


Fig. 19 Velocity measurements at data range 3

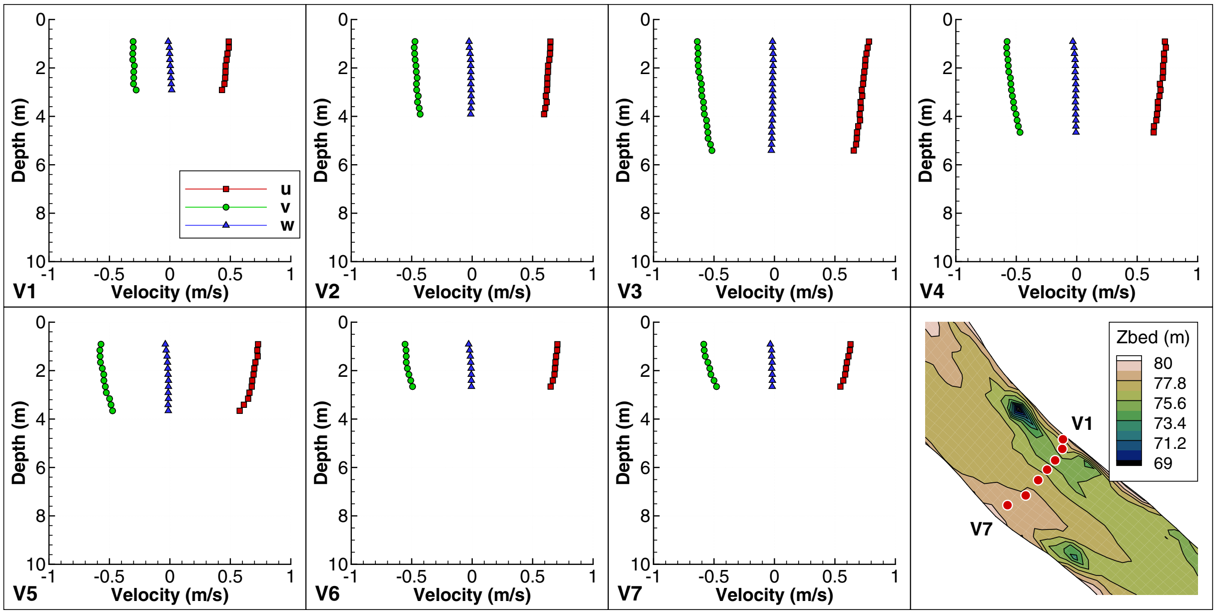


Fig. 20 Velocity measurements at data range 5

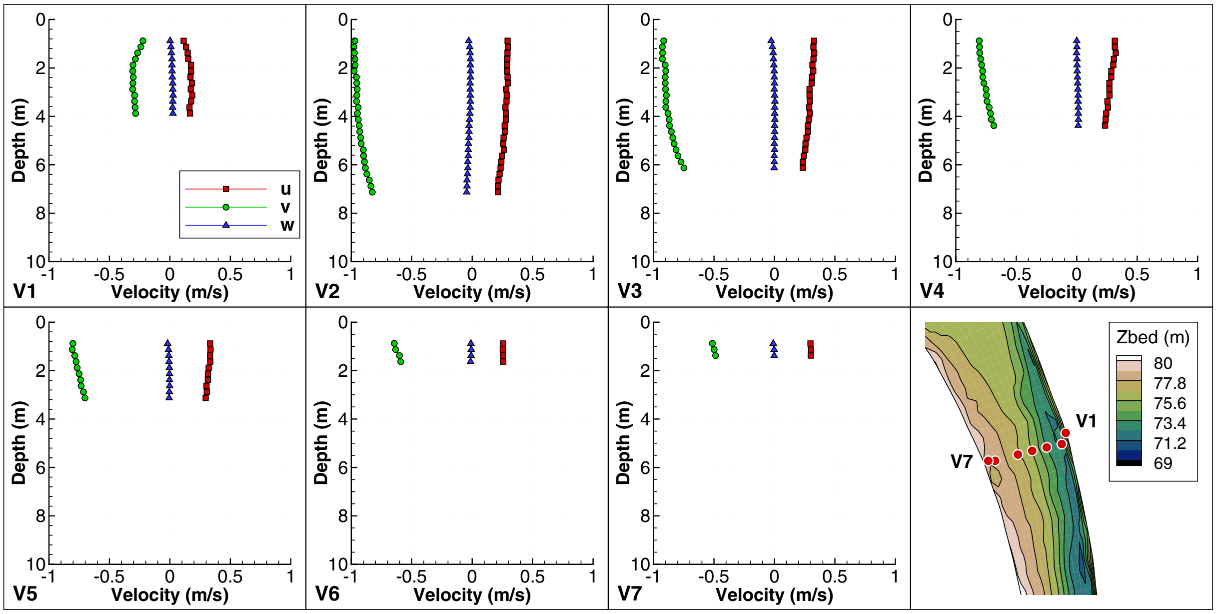


Fig. 21 Velocity measurements at data range 7

Table 1 Size-classes for sediment measurements at Mohács on the Danube

Size-class	Passed through sieve (mm)	Did not pass through sieve (mm)	Size-class diameter (mm)
1	0.005	0.001	0.0022
2	0.01	0.005	0.0071
3	0.02	0.01	0.014
4	0.05	0.02	0.032
5	0.1	0.05	0.071
6	0.125	0.1	0.11
7	0.25	0.125	0.18
8	0.5	0.25	0.35
9	1.0	0.5	0.71
10	2.0	1.0	1.41
11	4.0	2.0	2.83
12	8.0	4.0	5.66
13	16.0	8.0	11.31

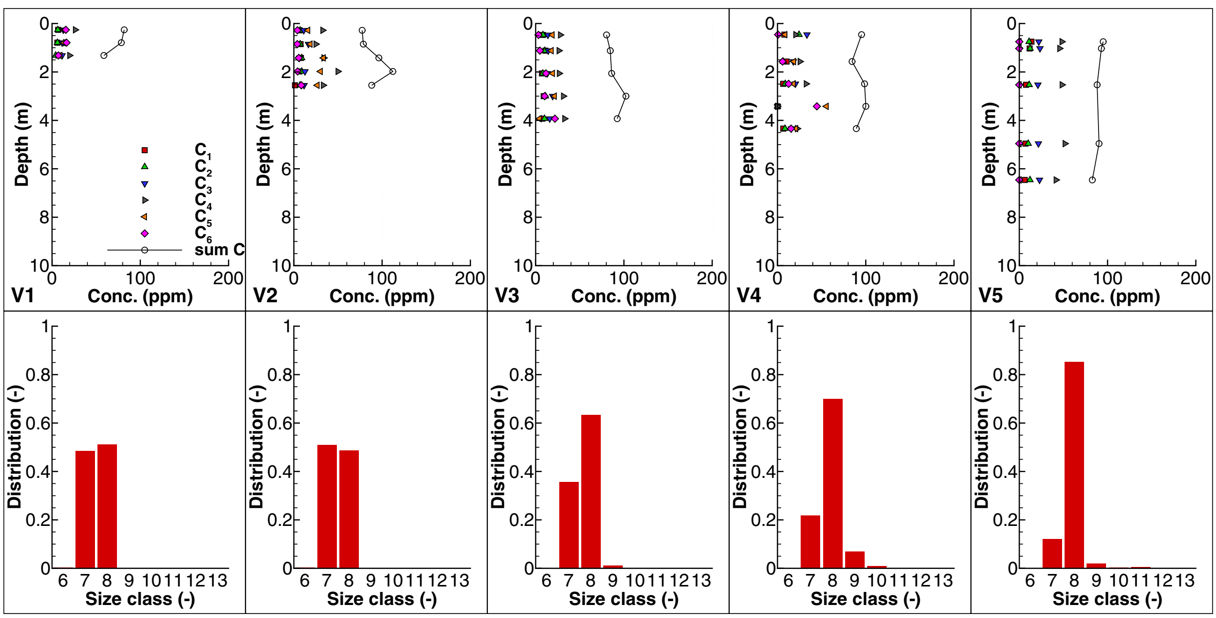


Fig. 22 Sediment measurements at data range 3

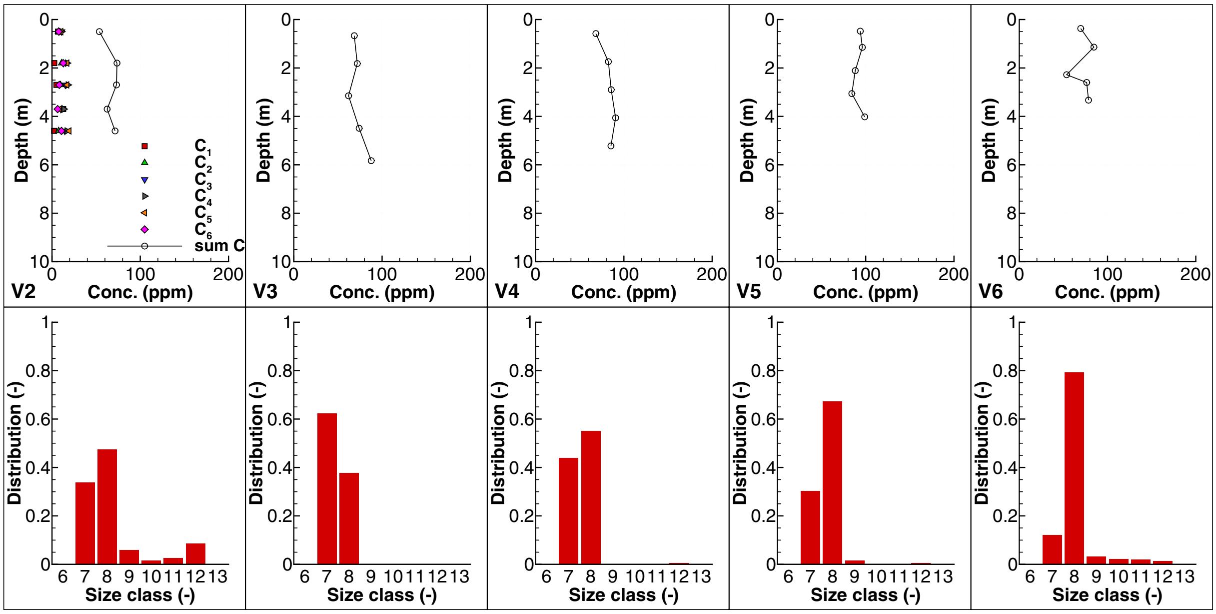


Fig. 23 Sediment measurements at data range 5

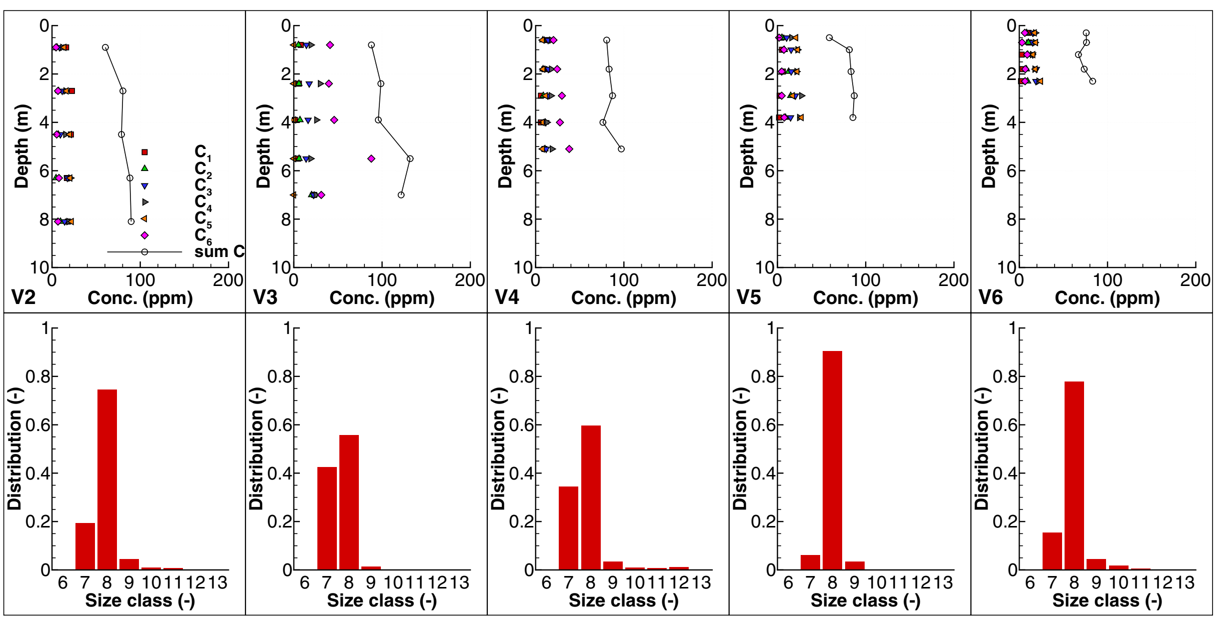


Fig. 24 Sediment measurements at data range 7

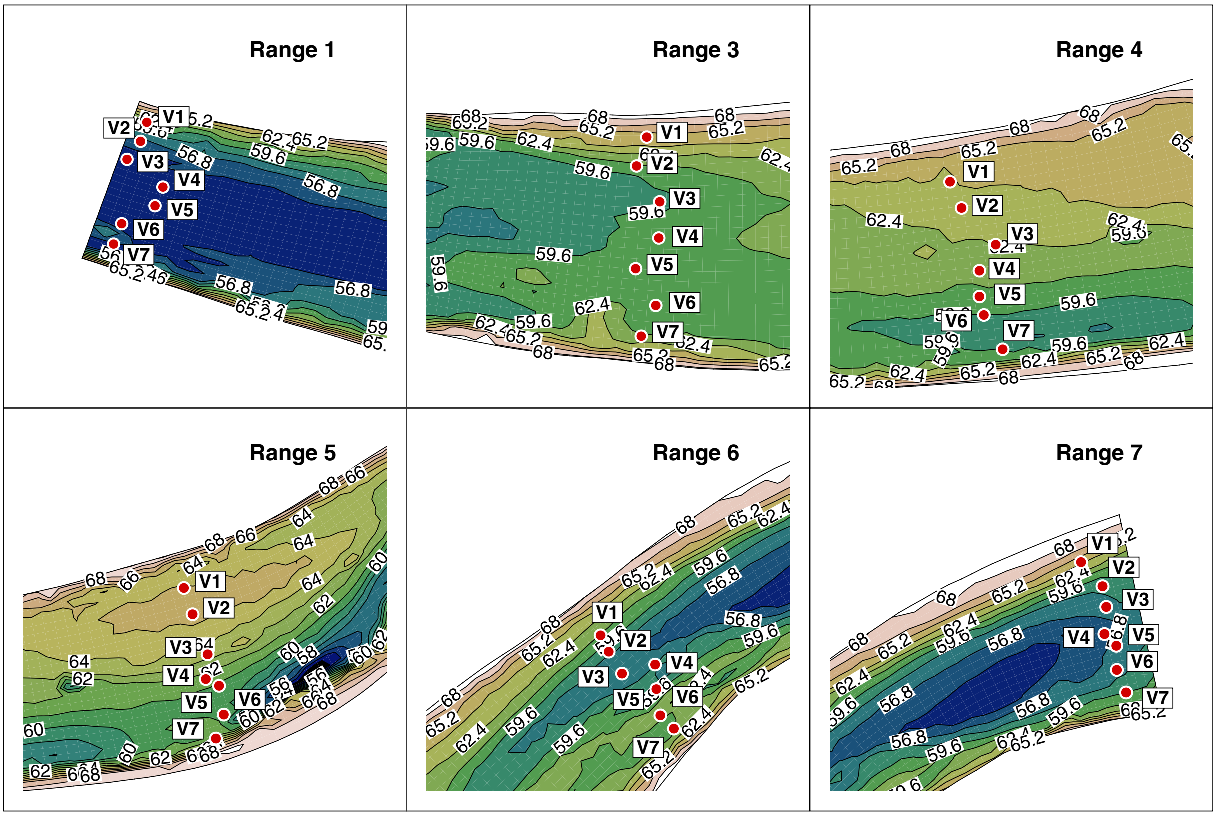


Fig. 25 Overview of data ranges at Belgrade on the Danube

Appendix 2. Case study 2 (Danube reach near Belgrade in Serbia)

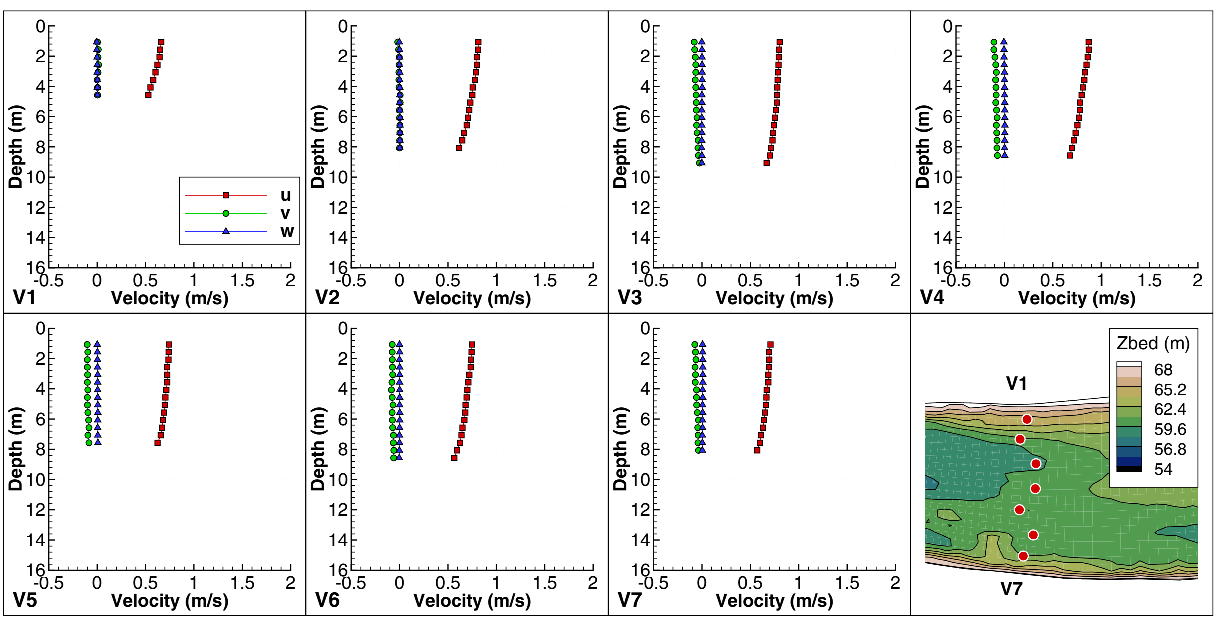


Fig. 26 Velocity measurements at data range 3

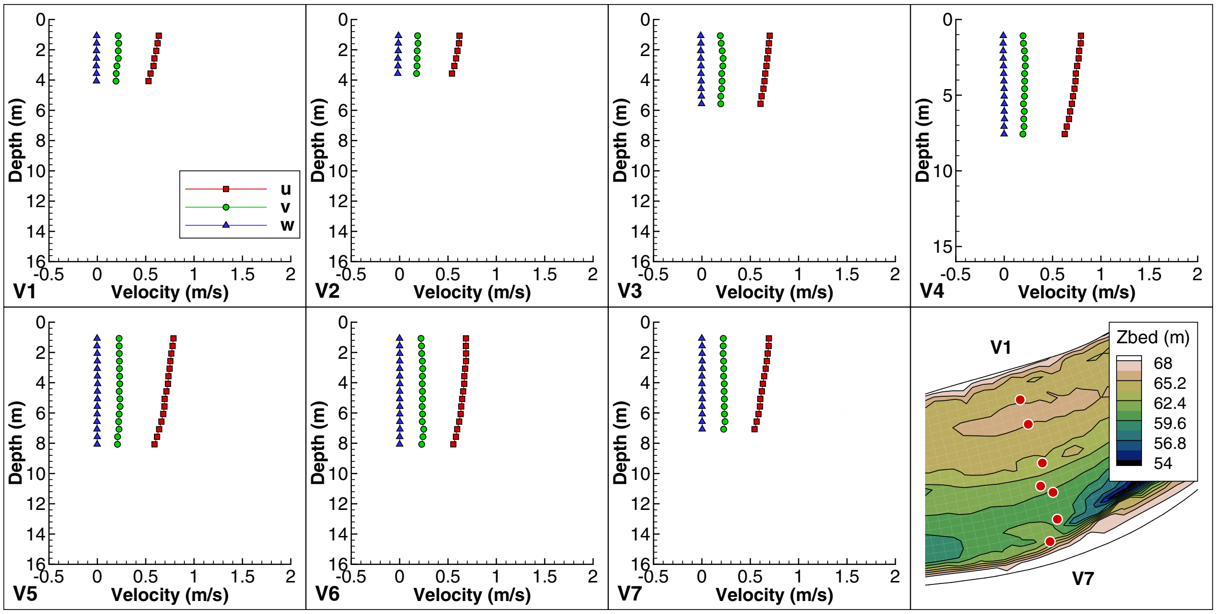


Fig. 27 Velocity measurements at data range 5

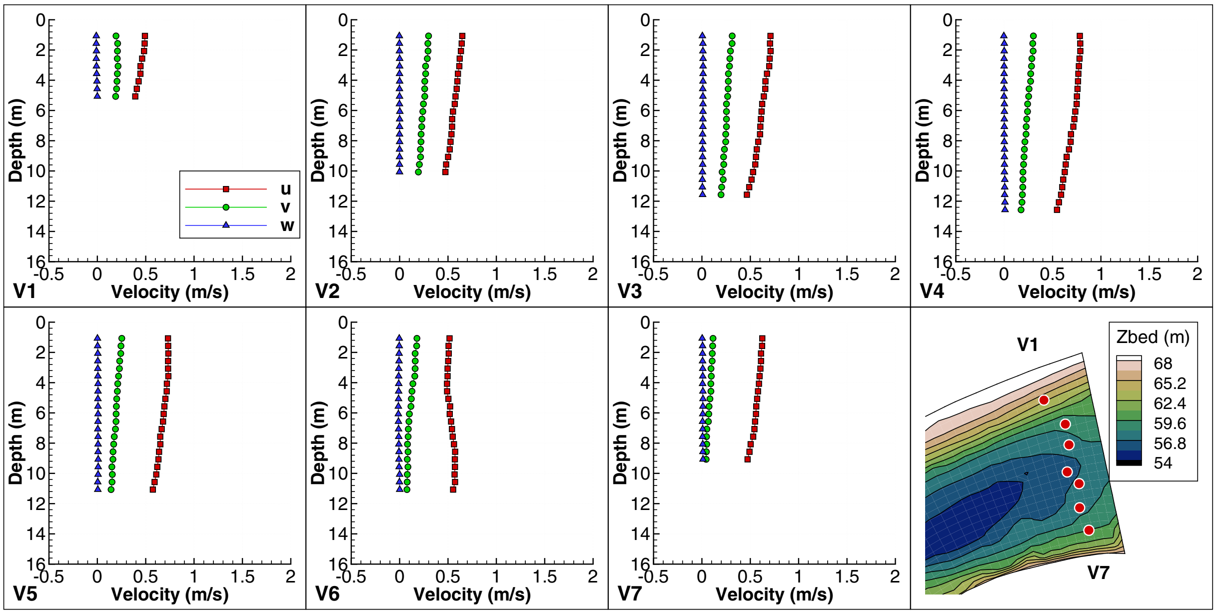


Fig. 28 Velocity measurements at data range 7

Table 2 Size-classes for sediment measurements at Belgrade on the Danube

Size-class	Passed through sieve (mm)	Did not pass through sieve (mm)	Size-class diameter (mm)
1	0.001	0.0005	0.00071
2	0.005	0.001	0.0022
3	0.01	0.005	0.0071
4	0.02	0.01	0.014
5	0.05	0.02	0.032
6	0.1	0.05	0.071
7	0.125	0.1	0.11
8	0.25	0.125	0.18
9	0.5	0.25	0.35
10	1.0	0.5	0.71
11	2.0	1.0	1.41
12	4.0	2.0	2.83
13	8.0	4.0	5.66
14	16.0	8.0	11.31
15	32.0	16.0	22.63

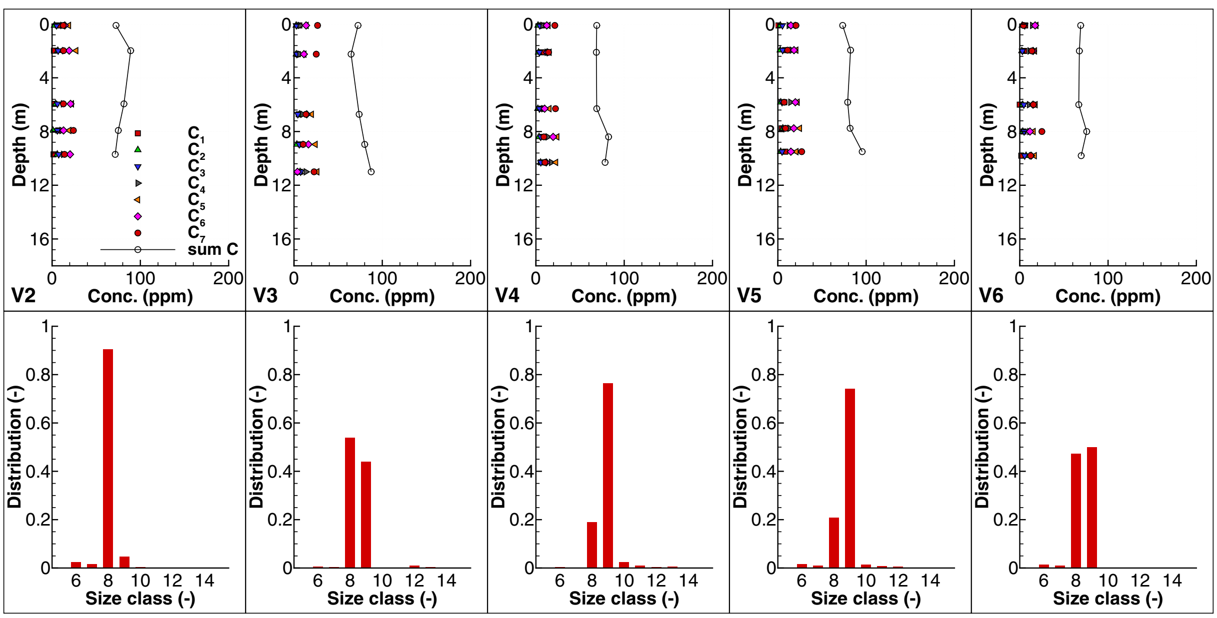


Fig. 29 Sediment measurements at data range 3

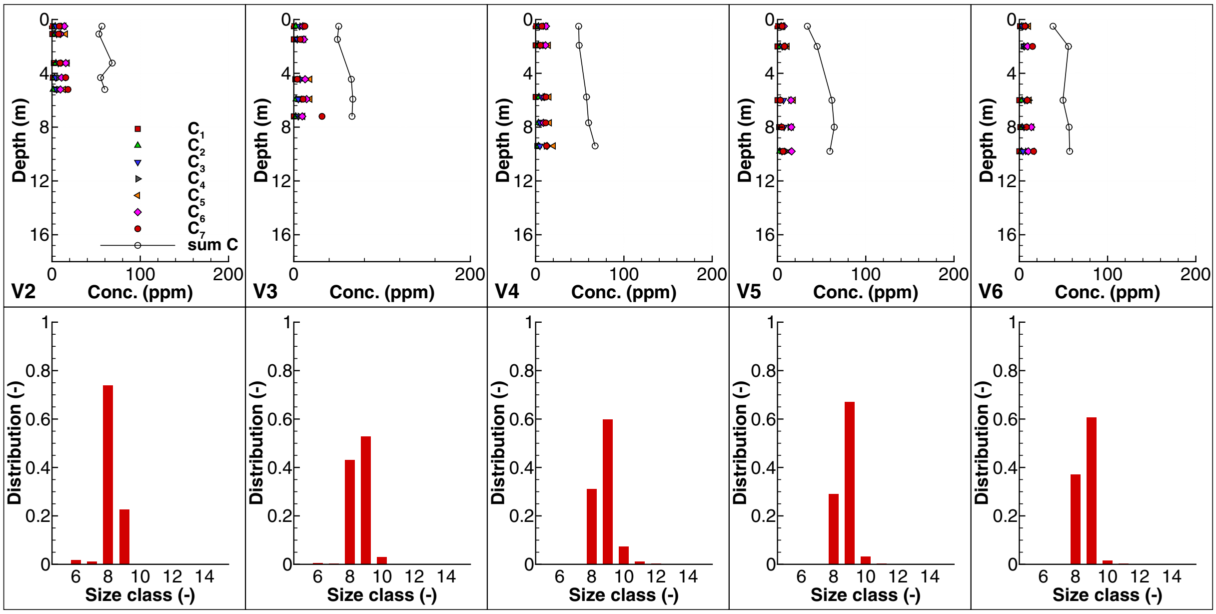


Fig. 30 Sediment measurements at data range 5

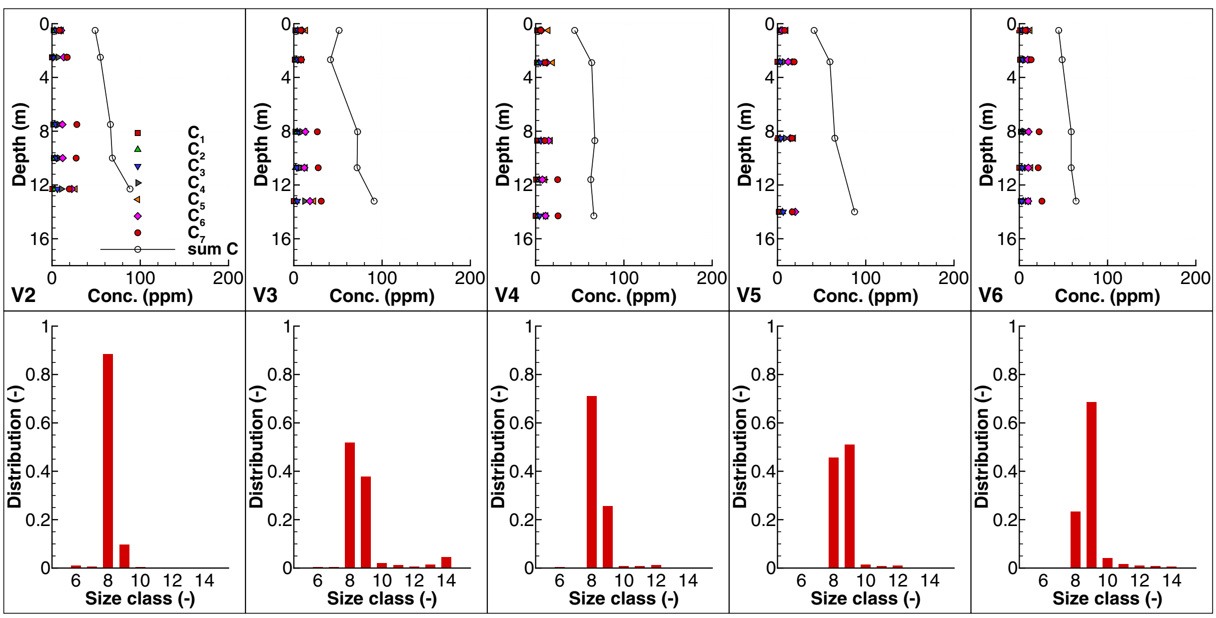


Fig. 31 Sediment measurements at data range 7

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