STUDY

MONITORING OF HYDROLOGICAL, HYDRAULIC AND MORPHOLOGICAL CHARACTERISTICS OF THE DANUBE RIVER AND INVENTORY OF BIODIVERSITY COMPONENTS ON THE JOINT CROATIAN-SERBIAN SECTOR OF THE DANUBE





Client: Ministry of the Sea, Transport and

Infrastructure

Project number: I-2206/23

In Osijek, October 2024

Preparing FAIRway2 works in the Rhine Danube Corridor (2019-EU-TM-0262-S and 2019-HR-TMC-0263-S)

The contents of this publication are the sole responsibility of the author and do not necessarily reflect the opinion of the European Union.







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CLIENT:	Ministry of the Sea, Transport and Infrastructur	е

LOCATION: Danube river from rkm 1295,5 (llok) to rkm 1433,1

(border with Hungary)

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In Osijek, October 2024

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1. INTRODUCTION

The subject of this activity is the monitoring of the water regime and sediment by recording the velocity and flow fields and measuring the transport of suspended and bedload sediment on the section of the Danube from rkm 1295,5 to rkm 1433,1 as part of the project "Monitoring of hydrological, hydraulic and morphological characteristics of the Danube River and inventory of components biodiversity on the joint Croatian-Serbian sector of the Danube River". The general goal of the project is to ensure the foundation for a joint strategy and coordinated activities of Croatia and Serbia in order to maintain the Danube as an important international waterway in a way that will not endanger the remaining ecosystems and their biodiversity, and will continuously adapt to the current conditions in the rivercourse and its banks through appropriate adaptive planning. The recording of water velocity and flow fields and the measurement of the transport of suspended and bedload sediment was carried out at the following locations:

Table 1. Locations for monitoring water regime and sediment

Number	Location	from rkm	to rkm
1	Batina	1429,0	1425,0
2	The confluence od Drava	1383,4	1381,6
3	Vukovar	1332,0	1325,0
4	Ilok	1302,0	1300,0

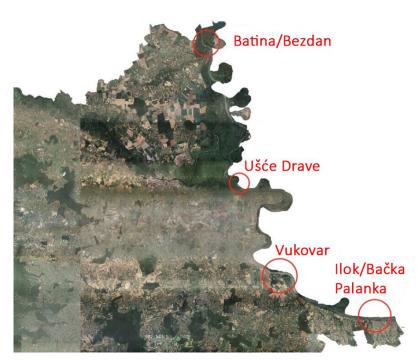


Figure 1. An overview of the situation with marked locations, monitoring the water regime and sediment along the Danube River



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In accordance with the Terms of Requirement (ToR), Hidroing Ltd. in cooperation with the Faculty of Civil Engineering from Zagreb and Mjernik Ltd. sfor geodetic services and design, carried out the following activities at the field:

- 1. Measurement of flow and velocity fields on two control (upstream, downstream) profiles along the locations: Batina, Vukovar and Ilok
- 2. Sampling and measurement of sediment on two control profiles (upstream, downstream) along the locations: Batina, the confluence of Drava and Ilok
 - a. Physical sampling of suspended sediment along the vertical of one location at a number of points depending on the depth of the vertical
 - b. Acoustic measurement of suspended sediment along control profiles
 - c. Physical sampling of bedload sediment at three locations along one control profile

Based on field measurements, this Study was prepared which contains the analysis of the collected data and presentation of the results. The document describes applied methodology and the results for each location separately, and at the end, the overall conclusion of the analysis is presented. When processing the results, each location contains:

- 1. the graphic representation with the position of the measuring profiles
- 2. data processing related to the measurement of flow and velocity fields
 - summary table of hydraulic parameters
 - field of flow velocity along the transverse profile
 - layout of the average velocity vector field along the water column
- 3. data processing related to sampling and measurement of suspended and bedload sediment
 - the concentration of suspended sediment by the depth of the measuring vertical obtained by physical sampling
 - distribution of sediment transport along the transverse profile obtained by acoustic measurement
 - the variation of bedload sediment along the transverse profile obtained by physical sampling
 - summary table of the transport of bedload and suspended sediment
 - granulometric curve for all control profiles

Data collection was carried out through three field measurements for each location to cover different hydrological events: low, medium and high water level. The schedule of measurements by day for each location is given in the table below



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Table 2. Summary table of conducted field measurements

Location	m01	m02	m03
Vukovar	24.05.2023.	14.06.2023.	26.09.2023.
Ilok	24.05.2023.	14.06.2023.	26.09.2023.
Batina	25.05.2023.	20.06.2023.	25.09.2023.
The confluence of Drava	25.05.2023.	20.06.2023.	25.09.2023.

Below is a graphic representation of recorded water levels at four water measuring stations (Batina, Aljmaš, Vukovar, Ilok) in the period 03/2023-11/2023. The dates of the measurements are indicated graphically. In addition, red lines mark the limits of unique values (intervals) for the high, medium and low water level of the entire subject area of the Danube River from rkm 1433,1 (Batina) to rkm 1295,5 (Ilok):

- low water level < 100 cm
- medium water level from 100 cm to 400 cm
- high water level > 400 cm

The aforementioned distribution was derived from the hydrological analysis given in the document "Analysis of the current state- rev02" (Hidroing d.o.o. Osijek, august 2023).

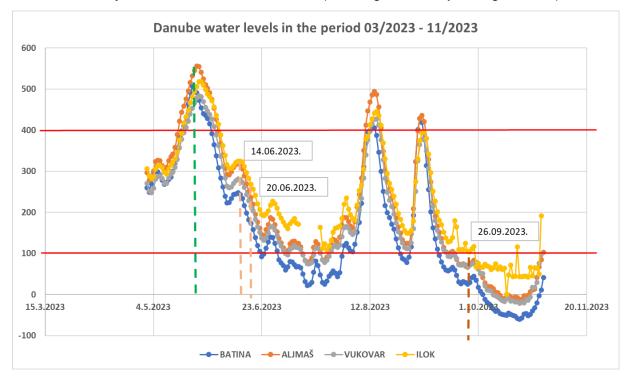


Figure 2. Recorded water levels on the Danube in the period 03/2023-11/2023 with indicated measurement dates



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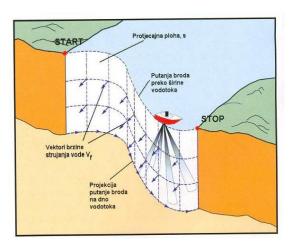
2. METHODOLOGY

As part of the activity, the following hydrographic measurements were carried out - hydraulic surveys of the detailed velocity field using an ADCP device and measurement of the transport of suspended and bedload sediment.

2.1 Measurement of flow and velocity field

An acoustic current meter (Acoustic Doppler Current Profiler) - ADCP, type RDI Workhorse Rio Grande was used for water flow and velocity field measurements. The ADCP was fixed on the side of the boat during the crossing along the river's transverse profile (Figure 3 - right). For positioning in space, an RTK-GPS device is used, which determines the exact location of the boat in real time, which in turn enables the layout placement of the velocity field in absolute X, Y, Z coordinates.

The ADCP device works on the principle of the Doppler effect, that is, it perceives a change in the frequency of the initial sound signal. By reflecting the sound signal from small particles in the water, a return sound image is obtained whose frequency is proportional to the velocity of the particles, because it is assumed that the particles travel at the same velocity as the water.



a) Schematic representation of current image recording



b) Current meter on the boat

Figure 3. Recording of current image with ADCP device

During velocity field recording, the device records instantaneous velocity data as a series of transverse profile units. The flow in the unit I is obtained by multiplying the area of one spatial unit and the associated mean velocity in the unit. By crossing the river, the flow is obtained on the measuring profile.

The values measured by the ADCP device can be directly monitored in real time and stored on the computer. The measured data about the velocity, the boat's route, the depth of the bed, etc. can be monitored on the computer during the measurement (Figure 4). In order to



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be able to interpret the collected raw data, it is necessary to process and display it graphically. Current velocity data is displayed as a velocity profile averaged over the water column.

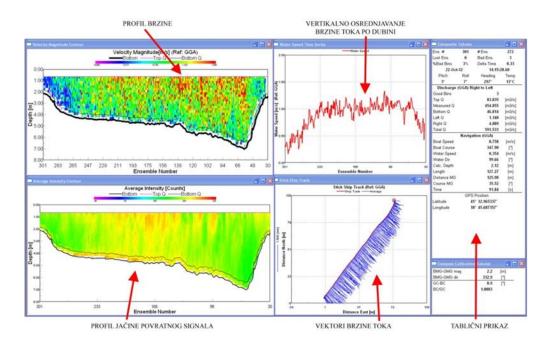


Figure 4. WinRiver user interface for a single profile

2.2 Measurement of suspended sediment

A non-invasive, acoustic sensor, LISST-ABS (http://www.sequoiasci.com/product/lisst-abs/), was used to measure sediment transport, an instrument that continuously records data on the concentration of suspended sediment in real time (Figure 5 left).



Figure 5. Acoustic sensor LISST-ABS (left) and isokinetic physical sediment catcher DH-59 (right)

LISST-ABS is fixed to the boat using a manual winch located on the bow. In addition to the LISST-ABS device, there is also an isokinetic sediment catcher on the hand winch (Figure 5 right), which is hydraulically shaped so that its head is always directed towards the flow, which ensures that the head of the LISST-ABS device is also always directed towards the flow. During the recording by crossing over the profile, the head of the LISST-ABS device is immersed in the water so that during the crossing, the sediment concentration is recorded over the entire width of the river (Figure 6).



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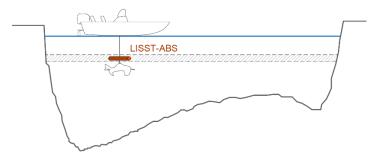


Figure 6. Schematic representation of the position of the LISST device and the belt along which data on the concentration of suspended sediment are collected when crossing over the control transverse profile

In order for the displays of raw data on suspended sediment concentrations to be accurate and reliable, the device must be calibrated with known reference values. For calibration purposes, physical samples taken at the field are used to establish a connection between the measured acoustic signals and the actual concentrations of particles in the water. For the purposes of calibration, physical sampling was performed at the same position and at the same time as the measurement with the sensor. For sampling, the so-called multi-point method of vertical measurement of the water column of the river profile is used. For this purpose, the measuring vertical is divided into approximately equal segments (Figure 7).

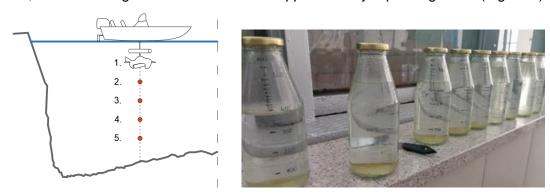


Figure 7. Representation of the position of the measuring points along the vertical of one location for which the suspended sediment was sampled with a physical catcher DH-59 (left) and a portable glass bottle placed in the physical catcher during sampling (right)

An isokinetic sediment trap type DH-59 was used for physical sampling of suspended sediment (Figure 5 right). The catcher is attached to a hand winch fixed to the vessel, below the LISST-ABS device. The inlet nozzle of the catcher is designed in such a way that the velocity in the nozzle is equal to the velocity of the flow in conditions when the catcher would not represent an obstacle to the flow. The sample is captured in glass vials that are portable in order to transport the samples in them to the laboratory where further analysis is carried out.



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Figure 8. Position of LISST-ABS device and isokinetic sediment catcher DH-59

The measurement of the concentration of suspended sediment in the profile takes place continuously during the crossing over the transverse profile. In order to measure the spatial distribution of suspended sediment along the entire transverse profile, data on the backscattering of the acoustic signal recorded by the ADCP device during the measurement of the flow velocity field along the transverse profiles were used. By applying the sediment concentration estimation procedure proposed by Baranya and Józsa (2003), the measured values of the backscatter of the acoustic signal recorded by the ADCP device can be converted into local values of the suspended sediment concentration.

For the purpose of calibrating the ADCP device, the average values of the relative dispersion of the acoustic signal from the stationary ADCP measurements from the same points where the sampling of the suspended sediment was carried out were used. In the described way, it is possible to calculate the spatial distribution of the concentration of suspended sediment along the entire profile. The calculation of the unit transport of suspended sediment is obtained by multiplying the flow rate and the concentration of suspended sediment. And to obtain the total sediment load per profile, it is necessary to integrate the unit sediment transport over the entire width and depth of the river profile (kg/s) or (t/year). Interpolation of such discrete data means summing the areas of triangular, rectangular and trapezoidal surfaces to approximate sediment concentration.

2.3 Measurement of bedload sediment

The assessment of the transport of bedload sediment is carried out in the same control profiles where the velocity field and bathymetry are recorded. A physical sediment catcher of the Helley-Smith type (8055) designed for sandy riverbeds was used to sample the bedload sediment (Figure 9 left). The physical characteristics of the bedload sediment catcher are as follows: length 960 mm, height 200 mm, end width 400 mm, opening size 152 x 152 mm and dry weight 17 kg. A portable, waterproof bag with 0,2 x 0,2 mm openings is attached to the catcher. During the measurement, the catcher is lowered to the bottom of the riverbed where it remains for 5-10 minutes, during which it is filled with bedload sediment. After that, the catcher is lifted, and the sample caught in a portable bag is stored in it and transported to the laboratory for further analysis.



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Figure 9. Helley-Smith sediment catcher (left) and Star Oddi (right)

For the sampling of bedload sediment, the control measurement profile is divided into 3 segments. The control profiles at each subject location with the location of the measurement points where the bedload sediment was sampled are shown in the figure below.

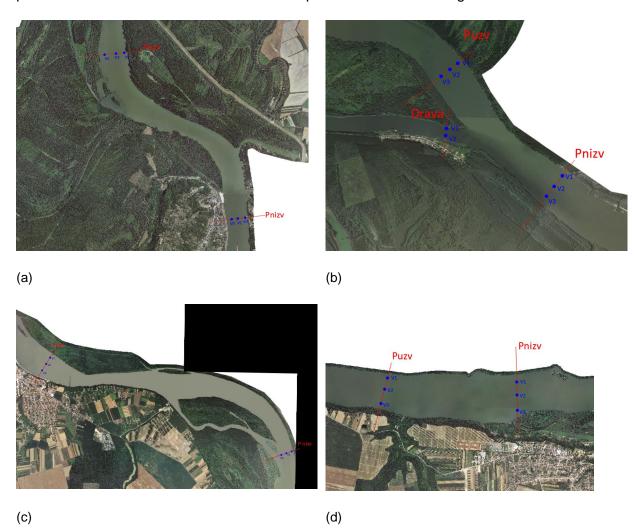


Figure 10. The position of the control transverse profiles on which the bedload sediment was sampled (red) and the position of the verticals on them (blue): Batina (a), the confluence of Drava (b), Vukovar (c), Ilok (d)



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The samples of bedload sediment were dried and weighed in the laboratory. Granulometric curves of sediment composition were also determined for the samples. Transport of bedload sediment was calculated on the basis of samples collected on transverse profiles. First, the unit sediment transport was calculated for each measurement point, using the following equation:

$$q_b = \frac{G}{b \cdot T \cdot \rho_S}$$

where: \underline{G} is the weight of the dry sample, \underline{b} is the width of the sediment catcher opening, \underline{T} is the sampling time and \underline{os} is the density of the sediment. The total transport of sediment for each profile is calculated by integrating the unit transport of sediment across the width of the bed, which determines the mass transport of sediment over time, i.e. kg/s.

Measuring the transport of bedload sediment is extremely demanding, given that it is carried out by sampling at discrete points on the bottom along the width of the observed riverbed. Therefore, when analyzing physically collected data, it is important to take into account the possible degree of unreliability of the results. A typical problem that occurs when using a manual sediment catcher is the unknown orientation of the physical catcher at the bottom of the river. Although the catcher is hydraulically shaped so that it is directed with its head (opening) towards the direction of the flow, when it is lowered to the bottom of the riverbed, it may deviate from that direction. If the opening of the sediment catcher is not oriented perpendicular to the river flow, the amount of captured sediment can significantly deviate from the average profile transport of sediment. In addition to the deviation from the flow direction, it should also be taken into account that dunes are formed on the subject section. The location of the catcher on the upstream or downstream side of the dune also represents a deviation from the ideal position for measurement.

In order to ensure the maximum reliability of the collected data, when measuring the transfer of bedload sediment, a tilt sensor is used that measures the deflection of the catcher from the ideal position (Figure 9 right). The tilt sensor is attached to the Helley-Smith physical catcher and collects data on the deflection of the catcher from the flow direction, as well as its transverse and longitudinal inclination. In addition to the mentioned slopes, the sensor also measures temperature, depth, light, sound and acceleration. By reviewing the collected data, the position, depth and orientation of the sediment catcher is defined. If it is determined that the catcher does not fit properly on the bottom, such data is corrected or discarded. Reliable data can only be obtained by proper operation of the bedload sediment catcher.

Therefore, it is important to determine the appropriate flow conditions under which sampling will be carried out - the intensity of sediment transport varies depending on the rising or falling branch of the hydrograph of the water wave, depending on the granulometric composition of the bed, but also the degree of complexity and spatial development of the dunes (Camenen et al., 2012; Vericat et al., 2006; Gaweesh and Van Rijn, 1994; Gaudet et al., 1994).

Selection of appropriate flow conditions, location and duration of sampling requires considerable technical and logistical equipment. In situations where physical sediment



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sampling cannot be recommended as a reliable method, then it is necessary to complement it with indirect methods, such as monitoring movement of dunes (Gilja et al., 2017) or the velocity field of the moving bottom.



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3. RESULTS

Hydrological conditions that were present at the days when the recording were carried out can be estimated from the levels of nearby water-meter stations. Given that it was necessary (per ToR) to collect data during different hydrological events (at a time of low, medium and high water levels), the figure below showed recorded levels for all locations and dates when measurements were carried out.

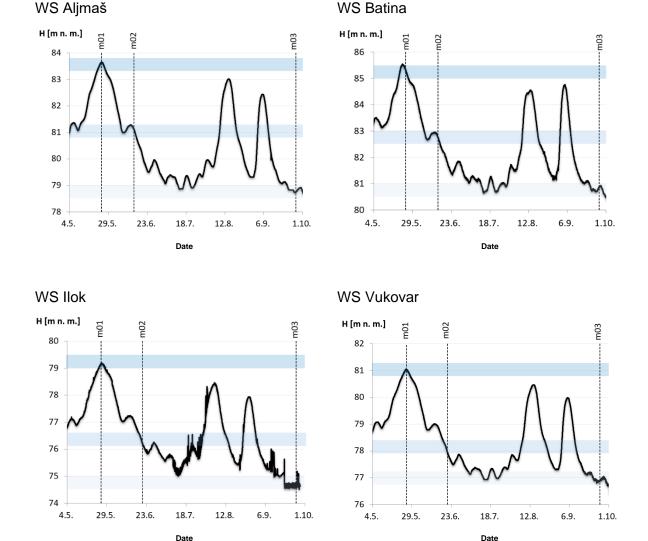


Figure 11. Levels from the water-meter stations at the time when field work was carried out



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3.1 Batina / Bezdan

The upstream profile (P_{uzv} – rkm 1429+000) is located at the beginning of a gentle left bend of the Danube in which the groyne were performed along the right shore. Downstream profile (P_{niz} – rkm 1425+000) is located on the exit from the right bend (Figure 12).



Figure 12. Measuring profiles and sampling points for a Batina location

* $P_{uzv} = P_{upstr}$; $P_{nizv} = P_{downstr}$

3.1.1 Velocity and flow recording

Collective display of measured flows (Q), maximum depths (h_{MAX}), flow surfaces (A), cross section surface area (O), profile width at the level of water surface (B), averaged profile longitudinal velocities (U) and hydraulic radius (h_{SR}) by control transverse profiles is given for each measurement in the table below.

Table 3. Sumary table of all measurements of hydraulic parameters by control transverse profile of Batina location

Measurement	Profile	Q [m ³ /s]	U [m/s]	h _{MAX}	A [m ²]	O [m]	B [m]	h _{SR} [m]
	P _{upstr}	3862	0.91	10.9	4249	518	509	8.34
m01	P _{downstr}	3916	1.02	13.0	3843	400	387	9.93
00	Pupstr	1833	0.72	8.0	2553	512	500	5.10
m02	P _{downstr}	1839	0.72	9.9	2566	379	367	6.99
	P _{upstr}	1367	0.66	6.4	2061	506	499	4.13
m03	P _{downstr}	1393	0.67	8.7	2071	357	351	5.90



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The first m01 measurement corresponds to the highest flow, so the graphics below for this measurement shows detailed velocity fields in the control transverse profiles. If the distribution of current water velocity on the upstream profile is observed (Figure 13), it is evident that the distribution of water velocity is relatively uniform throughout the profile width, with a velocity of 1,4 m/s in the mainstream. The asymmetry of the profile indicates that the left bend of the control profile begins to form.

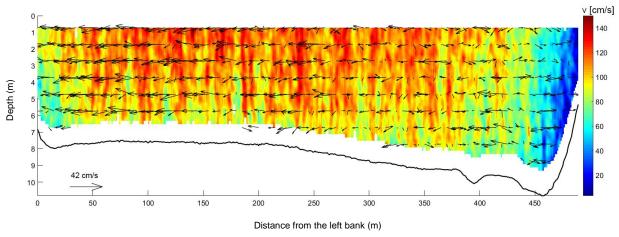


Figure 13. Field of the current water velocity of the transverse profile P_{upstr} of the Batina location at the time of recording m01

If the distribution of the current velocity of water on the downstream profile (Figure 14) is observed, it is evident that the concentration of higher velocity is concentrated along the left bank, with a velocity of 1,5 m/s in the mainstream. The asymmetry of the profile indicates that the location of the control profile is at the exit of the right bend.

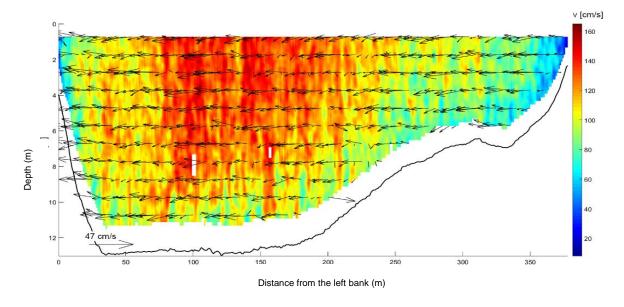


Figure 14. Field of the current water velocity of the transverse profile $P_{downstr}$ of the Batina location at the time of recording m01



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The vectors of the current water velocity are averaged by the depth of the water column are projected on the control profiles and displayed on the orthophoto background. The graphics below show the layouts of velocity vector fields of all measurements for the upstream control profile (Figure 15) and for the downstream control profile (Figure 16).

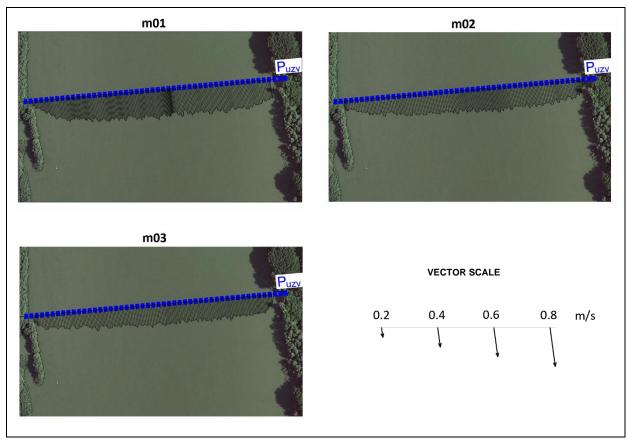
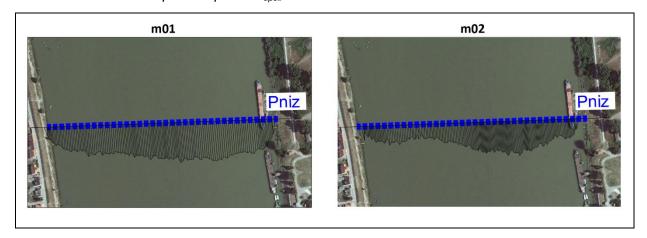


Figure 15. Layout of the water velocity vector fields averaged over the depth of the water column for all measurements on the upstream profile P_{upstr} for the Batina location





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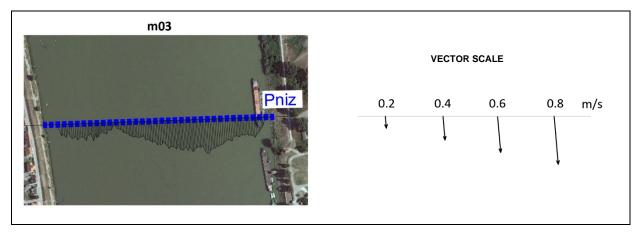


Figure 16. Layout of the water velocity vector fields averaged over the depth of the water column for all measurements on the downstream profile $P_{downstr}$ for the Batina location

3.1.2 Measurement of the transport of suspended and bedload sediment

Recorded fields of velocity and bathymetry along the control profiles were complemented with the results of sediment transport measurements. First, the concentration of suspended sediment vertically in the water column obtained by physical sampling is presented. Physical sampling at the Batina location was carried out on the upstream profile P_{upstr}, for the first measurement m01 in the middle of the transverse profile, and for the second and third along the right bank. During the third recording of m03, one sample was additionally collected from the middle of the downstream transverse profile P_{downstr}. The display of concentrations is given depending on the relative depth of the water. The graphic below shows the suspended sediment sampling results for all measurements. Sample concentrations increase regularly with depth – up to 75 mg/L for measuring m02 and m03. While for the first measurement m01, the concentration profile is higher and ranges from 50 mg/L to 176 mg/L, which is expected given that the flow was the highest that day.



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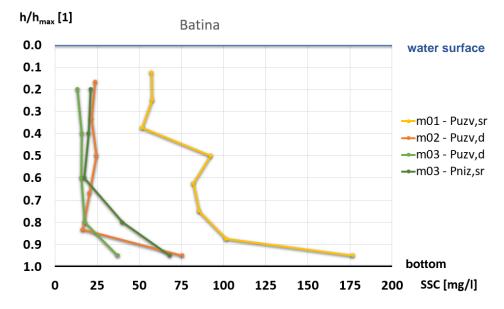


Figure 17. Distribution of a suspended silt concentration at the depth of measuring vertical- measured by physical sampling for all measurements at Batina location

The following graphs show the distribution of suspended sediment transport along control transverse profiles for recording m01 when flow and velocity were highest. A regular distribution of sediment transport can be observed on all profiles: along the banks it is less than in the middle of the profile, while in the case of vertical distribution, the sediment transport is most pronounced in the bottom layer of the flow profile.

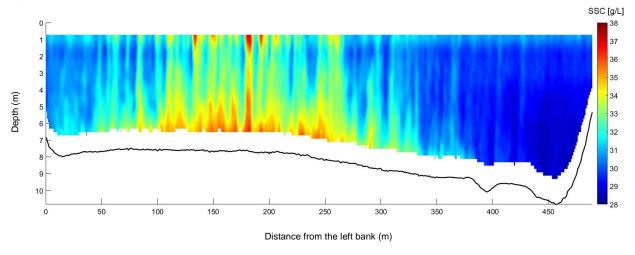


Figure 18. Distribution of suspended sediment transport along the transverse profile P_{upstr} of the Batina location at the time of recording m01



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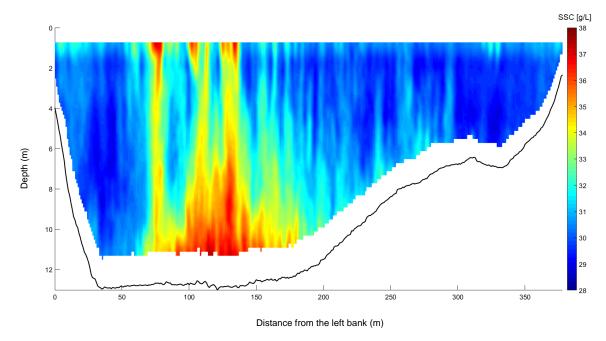
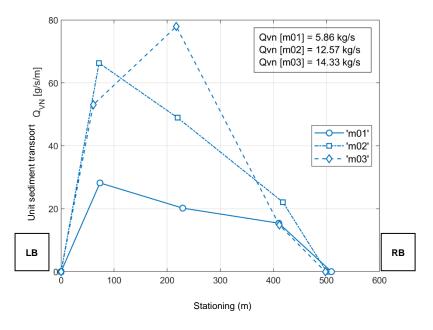


Figure 19. Distribution of suspended sediment transport along the transverse profile $P_{downstr}$ of the Batina location at the time of recording m01

The result of the measurement of the bedload sediment transport is shown graphically as a unit transport of sediment at each sampling point along the control transverse profile for all measurements. From the distribution of the unit transport of bedload sediment along the upstream control profile P_{upstr}, a more pronounced transport of sediment can be observed along the left, convex coast for all measurements (Figure 20). The displayed graphic shows the trend of increasing the total transport of bedload sediment with a decrease in flow, because the total transport of bedload sediment is the highest for the third and the smallest for the first measurement.





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Figure 20. Variation of the unit transport of bedload sediment across the width of the control profile P_{upstr} for all measurements at the Batina location

Distribution of the unit transport of bedload sediment along the downstream control profile $P_{downstr}$ shows a more pronounced transport of sediment along the left bank (Figure 21). The trend of changes in the total transport of bedload sediment depending on the flow on this profile Pniz is reversed compared to the previous profile, because the total transport is the highest at the time of the highest flow.

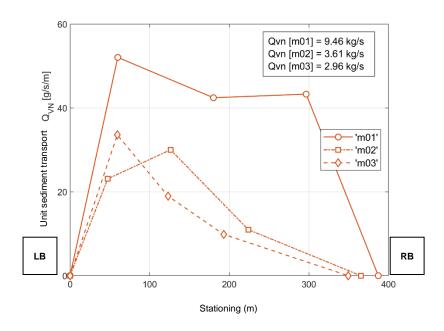


Figure 21. Variation of the unit transport of bedload sediment across the width of the control profile $P_{downstr}$ for all measurements at the Batina location

The intensity of the movement of bedload sediment for both profiles is higher along the left bank, although the upstream profile is on the convex side, and the downstream profile is the concave side. The total calculated values of the transport of bedload, suspended and total sediment is presented in a table for all measurements on both control profiles (Table 4). The average share of bedload sediment in the total movement of sediment on the upstream profile is <16%, and on the downstream profile <6%.

Table 4. Total transport of bedload and suspended sediment and measured flow for all measurements on both control profiles of the Batina location



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Measurement	Profile	Q	Q_{VN}	$\mathbf{Q}_{\mathbf{SN}}$
		$[m^3/s]$	[kg/s]	[kg/s]
m01	P _{upstr}	3862	5.9	128.3
	P _{downstr}	3916	9.5	129.5
m02	P _{upstr}	1833	12.6	57.6
	P _{downstr}	1839	3.6	58.4
m03	P _{upstr}	1367	14.3	42.6
	P _{downstr}	1393	3.0	43.7

On the basis of laboratory analysis, a granulometric curve was obtained for all samples of bedload sediment. Below are the characteristic granulometric curves for both control profiles. The composition of the bedload sediment is homogeneous and sandy, ranging from fine to coarse sand.

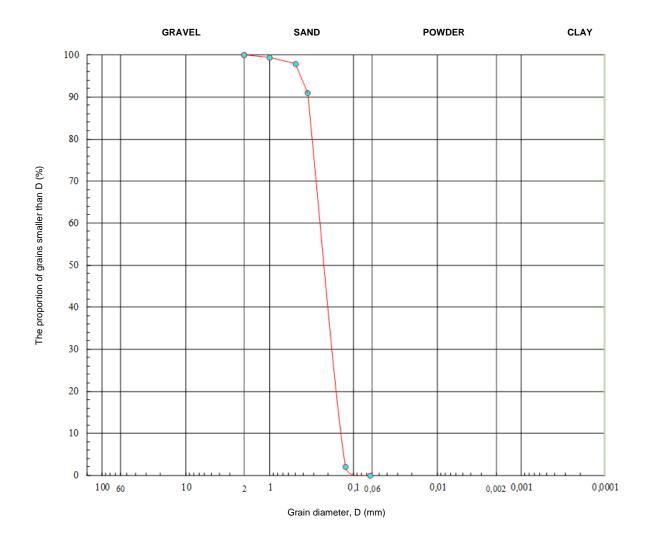


Figure 22. Granulometric curve of bed composition - sample taken along the left bank of the upstream control profile of the Batina location



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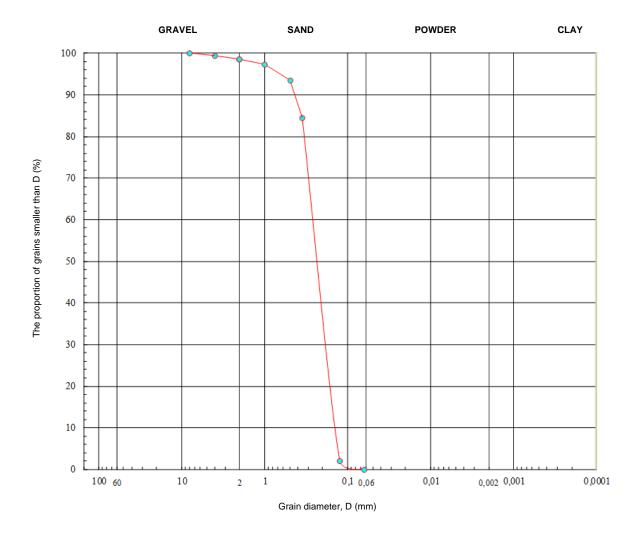


Figure 23. Granulometric curve of bed composition - sample taken in the middle of the downstream control profile of the Batina location



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3.2 The confluence of Drava

The upstream profile (rkm 1383+000) is located at the exit from the right bend of the Danube, immediately upstream from the confluence of the Drava River. The downstream profile (rkm 1381+600) is located on a flat section of the Danube immediately upstream of the groyne built along the left bank. The profile on the Drava River is located at the very confluence (Figure 24).

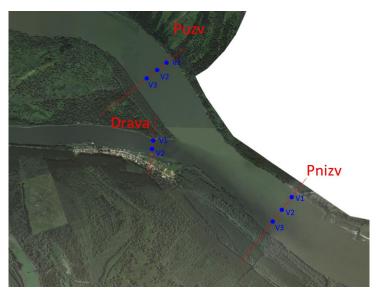


Figure 24. Measurement profiles and sediment sampling points for the confluence of Drava location

3.2.1 Measurement of the transport of suspended and bedload sediment

Recorded fields of velocity and bathymetry along the control profiles were complemented with the results of sediment transport measurements. First, the concentration of suspended sediment vertically in the water column obtained by physical sampling is presented. Physical sampling at the confluence of Drava location was carried out on the upstream profile Pupstr of the Danube, in the middle of the control profile for all measurements. During the second recording m02, one sample was additionally collected from the middle of the control profile on the Drava River (rkm 0+500). The presentation of concentrations is given depending on the relative depth of the flow. The graphic below shows the results of sampling suspended sediment for all measurements. Concentrations of samples increase regularly with depth and with increasing flow. Concentrations of suspended sediment in the depth of the water column during low and medium water levels on both rivers range from 12 to 123 mg/L. However, during high water levels, this value is higher, which can be seen from the samples collected on the Danube during the first measurement m01 and they vary from 51 to 172 mg/L for the Drava.



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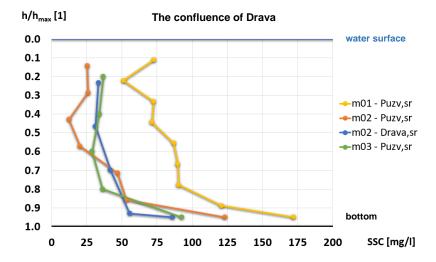


Figure 25. Distribution of the concentration of suspended sediment by the depth of the measuring vertical- measured by physical sampling for all measurements at the confluence of Drava location

The following graphs show the distribution of suspended sediment transport along control transverse profile for recording m01 when flow and velocity were highest. On all profiles, a regular distribution of sediment transport can be observed, which is most pronounced in the middle of the profile, while it is half as much along the banks. As expected, the vertical distribution of sediment transport indicates a pronounced sediment transport in the bottom layer of the flow profile.

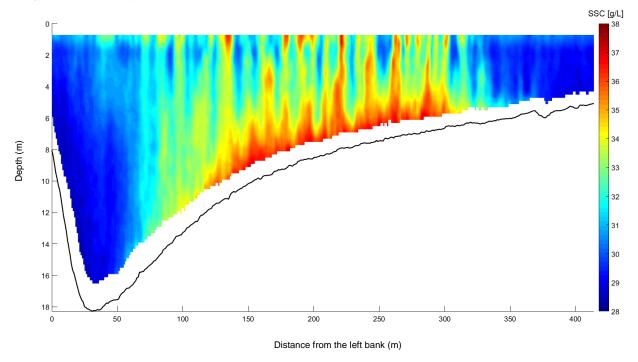


Figure 26. Distribution of suspended sediment transport along the upstream transverse profile of the Danube P_{upstr} at the confluence of Drava location at the time of recording m01



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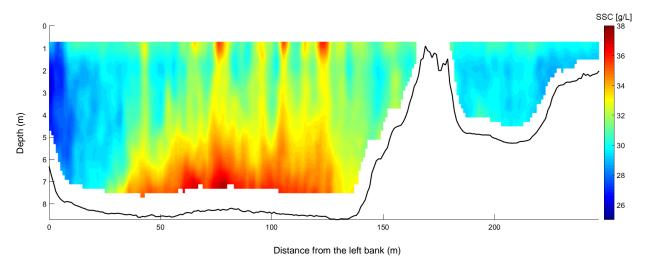


Figure 27. Distribution of suspended sediment transport along the downstream transverse profile of the Danube $P_{downstr}$ at the confluence of Drava location at the time of recording m01

The result of the measurement of the bedload sediment transport is shown graphically as a unit transport of the bedload sediment at each sampling point along the control transverse profile for all measurements. From the distribution of the unit transport of the bedload sediment for all three control profiles, an uneven distribution of the bedload sediment transport along the transverse profile can be observed, depending on the change in flow. For example, for the upstream section of the Danube, the transport of bedload sediment during high water levels (m01) is most pronounced along the right bank, at medium water levels (m02) it is most pronounced in the middle of the profile and at low water levels (m03) it is most pronounced along the left bank (Figure 28). A similar trend occurs on the profile of the Drava River (rkm 0+500). The most pronounced sediment transport moves from the right to the left bank as the flow increases (Figure 30). Although the transport of bedload sediment on the downstream control profile of the Danube P_{downstr} is always located along the left bank, here an unusual connection between the bedload sediment transport and the flow occurs. Namely, the highest values of transport of bedload sediment were recorded at the time of low water levels (m03), while with the increase towards high water levels (m02 and m01) this value drops twice.



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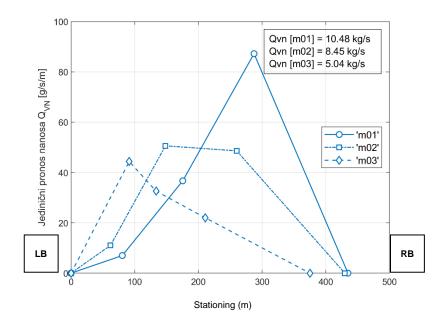


Figure 28. Variation of the unit transport of bedload sediment across the width of the upstream control profile of the Danube P_{upstr} for all measurements at the confluence of Drava location

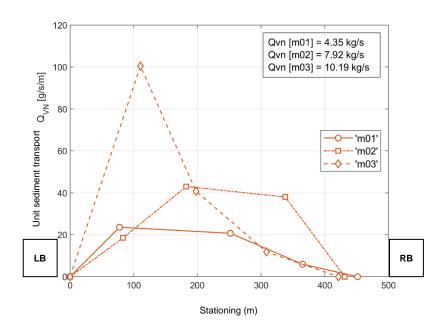


Figure 29. Variation of the unit transport of bedload sediment across the width of the downstream control profile of the Danube P_{downstr} for all measurements at the confluence of Drava location



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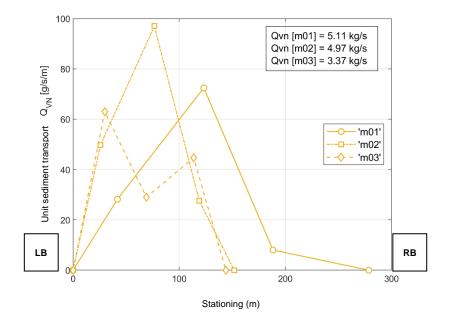


Figure 30. Variation of the unit transport of bedload sediment across the width of the downstream control profile of Drava P_{DRAVA} for all measurements at the confluence of Drava location

From the collected samples, it was observed that the intensity of the movement of the bedload sediment does not follow the dynamics of the flow change. At the time of high water levels (m01), intensive transport of bedload sediment comes from the banks on the upstream section of the Danube and in the middle of the Drava river. However, after the confluence, the flow intensity is greatly reduced and is uniform across the width of the river. Furthermore, during medium water levels (m02), the transport of bedload sediment on the Danube is about 10% lower compared to high water levels, in contrast to the Drava, where the transport of bedload sediment is 45% higher at medium compared to high water levels. The spatial distribution of the most pronounced transport of bedload sediment at the time of medium water levels moves along the middle of the upstream section of the Danube and more strongly along the left bank of the Drava River, and after passing the confluence, bedload sediment continues to move with less intensity along the right bank of the downstream section of the Danube. Finally, the dynamics of bedload sediment transport during low water levels is as follows: greater intensity of transport comes from the Drava River along the left bank, and in a slightly smaller amount from the upstream section of the Danube along the deeper, left bank. Passing through the confluence, the transport of bedload sediment continues along the left bank of the downstream section of the Danube, in a larger amount than upstream of the confluence.

From the described dynamics of the movement of bedload sediment, it can be concluded that the bedload sediment is not carried downstream in sufficient quantity, but is retained at the confluence itself. In advance, it can be concluded from the average amounts of the movement of the bedload sediment according to all measurements that it is 7 kg/s in the Drava, 8 kg/s in the upstream section of the Danube, and 4 kg/s in the downstream section



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of the Danube. The total calculated values of the transport of bedload, suspended and total sediment is presented in a table for all measurements on all three control profiles (Table 5). The average share of the movement of bedload sediment in relation to the total transport of sediment for the upstream profile of the Danube is 10%, for the downstream 4%, while for the Drava River it is 28%.

Table 5. Total transport of bedload and suspended sediment and measured flow for all measurements on all three control profiles of the confluence of Drava location

Measurement	Profile		Q	Q_{VN}	Q_{SN}
ivieasurement	Prome		$[m^3/s]$	[kg/s]	[kg/s]
	P _{upstr}		4009	10.5	134.8
m01	P _{Drava}		1336	4.4	47.1
	P _{downstr}		5373	5.1	188.6
	Pupstr		1963	8.5	61.1
m02	P_{Drava}		531	7.9	18.0
	P _{downstr}		2797	5.0	90.4
	P_{upstr}	Γ	1348	5.0	42.3
m03	P_{Drava}		363	10.2	12.9
	P _{downstr}		1863	3.4	62.7



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On the basis of laboratory analysis, a granulometric curve was obtained for all samples of bedload sediment. Below are the characteristic granulometric curves for both control profiles. The composition of the bedload deposit is homogeneous and sandy, ranging from fine to coarse sand.

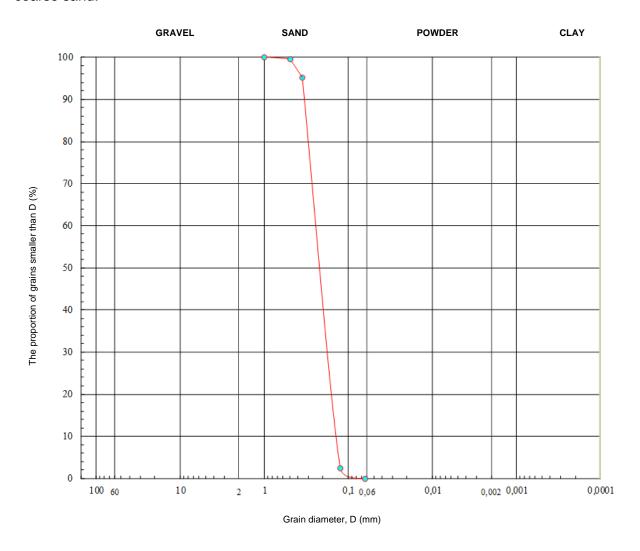


Figure 31. Granulometric curve of bed composition- sample taken along the right bank of the upstream control profile of the confluence of Drava location



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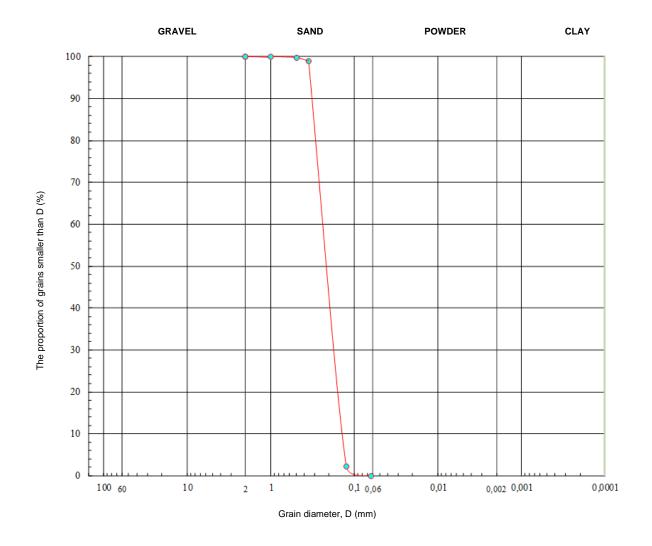


Figure 32. Granulometric curve of bed composition- sample taken along the left bank of the downstream control profile of the confluence of Drava location



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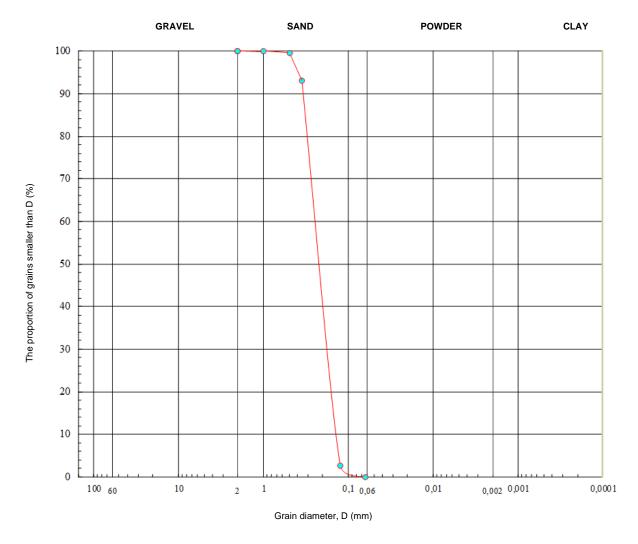


Figure 33. Granulometric curve of bed composition- sample taken along the right bank of the control profile on the Drava river for the confluence of Drava location



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3.3 Vukovar

The upstream profile (rkm 1332+000) is located at the exit from the right bend of the Danube, immediately upstream from the confluence of the Drava River. The downstream profile (rkm 1325+000) is located on a flat section of the Danube immediately upstream of the groyne built along the left bank (Figure 34).



Figure 34. Measuring profiles and points for the Vukovar location

3.3.1 Velocity and flow recording

Collective display of measured flows (Q), maximum depths (h_{MAX}), flow surfaces (A), cross section surface area (O), profile width at the level of water surface (B) and averaged profile longitudinal velocities (U) and hydraulic radius (h_{SR}) by control transverse profiles is given for each measurement in the table below.

Table 6. Summary table of all measurements of hydraulic parameters by control transverse profiles of the Vukovar section

Measurement	Profile	Q [m ³ /s]	U [m/s]	h _{MAX} [m]	A [m ²]	O [m]	B [m]	h _{SR} [m]
01	P _{upstr}	5439	0.99	11.1	5479	737	720	7.61
m01	P _{downstr}	5082	1.18	13.8	4290	436	418	10.26
m02	P _{upstr}	3484	0.88	8.4	3978	758	738	5.39
	P _{downstr}	3112	0.91	11.5	3423	435	419	8.16
m03	Pupstr	1739	0.73	6.2	2377	599	595	3.99
	P _{downstr}	1691	0.67	9.3	2524	403	396	6.38

The first measurement m01 corresponds to the highest flow, therefore the graphs below for that measurement show in detail the velocity fields in the control transverse profiles. If one observes the current flow velocity distribution on the upstream profile (Figure 35), it can be



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seen that the core is located along the left bank, with a velocity that locally exceeds 2,0 m/s. The geometry of the profile is atypical for its position in a left bend.

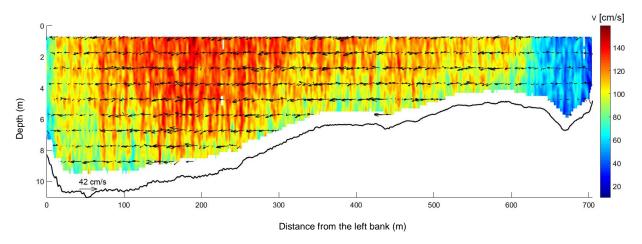


Figure 35. Field of the current flow velocity along the transverse profile P_{upstr} of the Vukovar location at the time of recording m01

If the distribution of current water velocity on the downstream profile (Figure 36) is observed, it is evident that the concentration of higher water velocity is along the left, concave bank, where it exceeds 2,0 m/s in the mainstream. Profile asymmetry indicates that the location of the control profile is in the right bend.

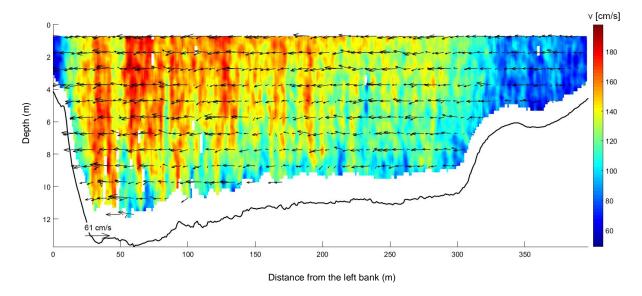


Figure 36. Field of the current flow velocity along the transverse profile $P_{downstr}$ of the Vukovar location at the time of recording m01

Current flow velocity vectors averaged over the depth of the water column were projected onto the control profiles and displayed on the orthophoto base. The graphs below show the top view of the velocity vectors of all measurements for the upstream control profile (Figure 37) and for the downstream control profile (Figure 38).



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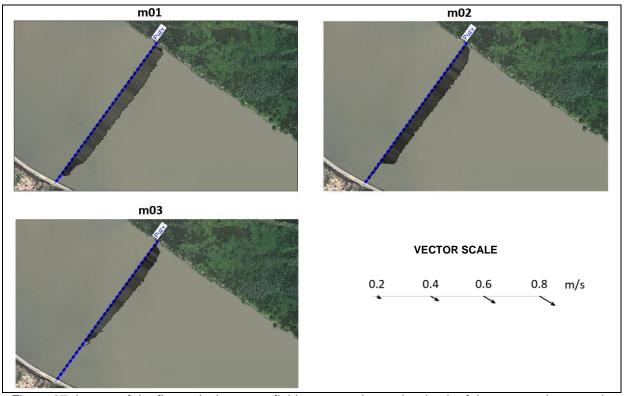


Figure 37. Layout of the flow velocity vector fields averaged over the depth of the water column on the upstream profile P_{upstr} for the location Vukovar

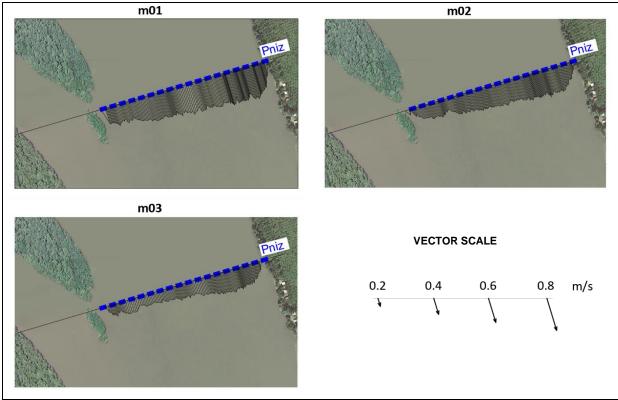


Figure 38. Layout of the flow velocity vector fields averaged over the depth of the water column on the downstream profile $P_{downstr}$ for the location Vukovar



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3.4 Ilok

Both the upstream profile (rkm 1302+000) and the downstream profile (rkm 1300+000) are located on a flat section of the Danube surrounded by regulation structures on both banks (Figure 39).



Figure 39. Measurement profiles and sediment sampling points for the llok location

3.4.1 Velocity and flow recording

Collective display of measured flows (Q), maximum depths (h_{MAX}), flow surfaces (A), cross section surface area (O), profile width at the level of water surface (B) and averaged profile longitudinal velocities (U) and hydraulic radius (h_{SR}) by control transverse profiles is given for each measurement in the table below.

Table 7. Summary table of all measurements of hydraulic parameters by control transverse profiles of the llok section

Measurement	Profile	Q [m ³ /s]	U [m/s]	h _{MAX} [m]	A [m ²]	O [m]	B [m]	h _{SR} [m]
m01	P _{upstr}	5389	1.17	10.0	4596	548	524	8.76
m01	P _{downstr}	5301	1.05	12.1	5045	636	624	8.08
m02	P _{upstr}	3559	1.01	8.0	3522	541	534	6.59
	P _{downstr}	3232	0.85	9.7	3798	593	573	6.63
m03	P _{upstr}	1956	0.82	5.9	2390	532	521	4.59
	P _{downstr}	1876	0.88	7.0	2131	407	393	5.42

The first measurement m01 corresponds to the highest flow, therefore the graphs below for that measurement show in detail the velocity fields in the control transverse profiles. If the distribution of the instantaneous water velocity along the upstream profile is observed (Figure 40), it is evident that the distribution of the water velocity is relatively uniform over the entire width of the profile, with a relatively high velocity over the entire width of the profile (1,5 m/s).



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The symmetry and saddle shape of the profile indicates that it is located in the transition between two bends.

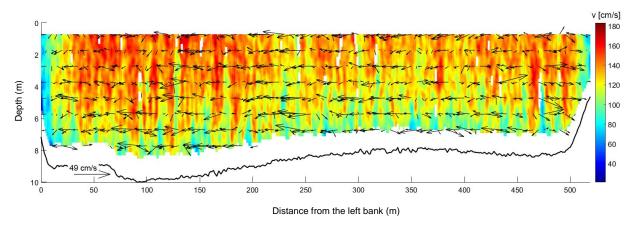


Figure 40. The field of current flow velocity along the transverse profile P_{upstr} of the llok location at the time of recording m01

If the distribution of current flow velocity is observed on the downstream profile (Figure 41), it is evident that the concentration of higher flow velocity is next to the building on the left bank, where the flow in the mainstream exceeds the velocity of 1,5 m/s. The symmetry of the profile indicates that the location of the control profile is on a relatively flat section.

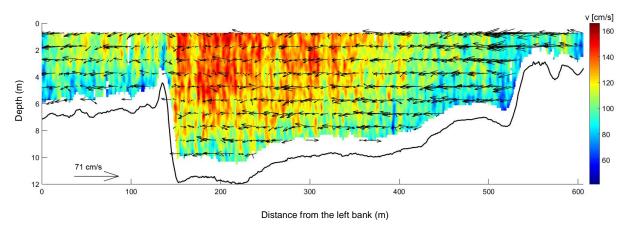


Figure 41. The field of current flow velocity along the transverse profile $P_{downstr}$ of the llok location at the time of recording m01

Current water velocity vectors averaged over the depth of the water column were projected onto the control profiles and displayed on the orthophoto base. The graphs below show the top view of the velocity vectors of all measurements for the upstream control profile (Figure 42) and for the downstream control profile (Figure 43).



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MONITORING OF HYDROLOGICAL, HYDRAULIC AND MORPHOLOGICAL CHARACTERISTICS OF THE DANUBE RIVER AND INVENTORY OF BIODIVERSITY COMPONENTS ON THE JOINT CROATIAN-SERBIAN SECTOR OF THE DANUBE RIVER

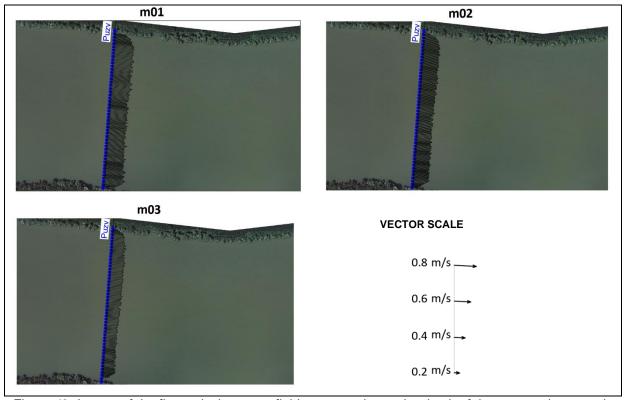


Figure 42. Layout of the flow velocity vector fields averaged over the depth of the water column on the upstream profile P_{upstr} for the llok location

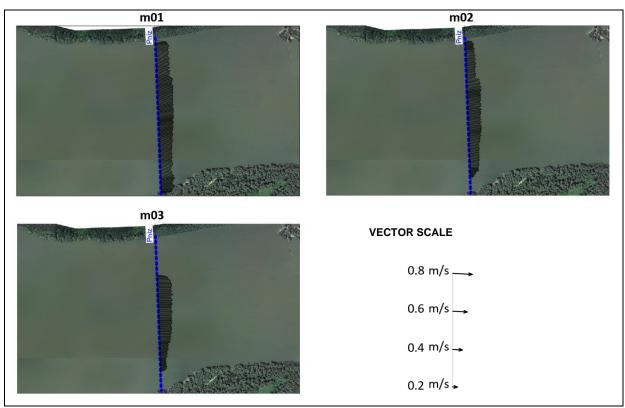


Figure 43. Layout of the water velocity vector field averaged over the depth of the water column on the downstream profile $P_{downstr}$ for the llok location



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3.4.2 Measurement of the transport of suspended and bedload sediment

Recorded fields of velocity and bathymetry along the control profiles were complemented with the results of sediment transport measurements. First, the concentration of suspended sediment vertically in the water column obtained by physical sampling is presented. Physical sampling at the llok location for the first measurement m01 was carried out in the middle of the downstream control profile P_{downstr}, while for the second and third measurements sampling was carried out along the left bank of the upstream control profile P_{upstr}. The display of concentrations is given depending on the relative depth of the water. The graphic below shows the results of sampling suspended sediment for all measurements. Sample concentrations increase regularly with depth and with flow increase, and their average values per profile range from 50 mg/L for sampling during low water levels, 83 mg/L during medium water levels and 97 mg/L for sampling during high water levels.

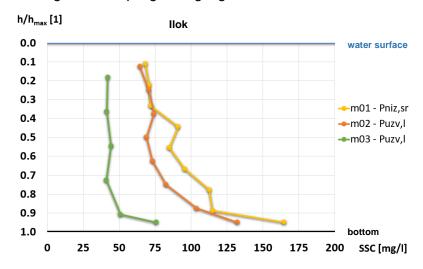


Figure 44. Distribution of the concentration of suspended sediment by the depth of the measuring vertical- measured by physical sampling for all measurements at the llok location

The following graphs show the distribution of suspended sediment transport along control transverse profiles for recording m01 when flows and velocities were highest. On the upstream control profile Pupstr, a uniform distribution of sediment transport across the width of the transverse profile can be observed (Figure 45). This distribution of sediment transport follows the trend of velocity distribution along the transverse profile. On the downstream control profile, the Pdownstr of sediment transport is more pronounced along the left bank, which is accompanied by greater depths (Figure 46). It can also be observed that the sediment transport is higher in the zone of the bed that is protected by a true parallel structure, which deviates from the velocity field, which indicates that the flow is relatively calm in that part of the bed.



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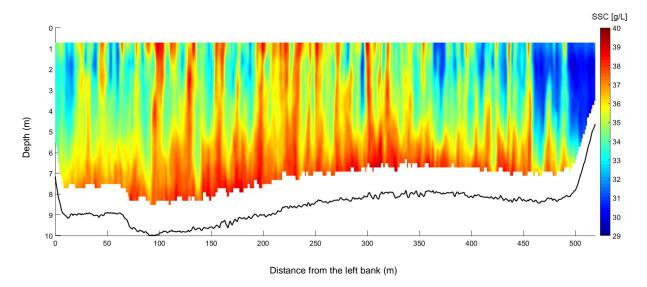


Figure 45. Distribution of suspended sediment transport along the transverse profile P_{upstr} of the llok location at the time of recording m01

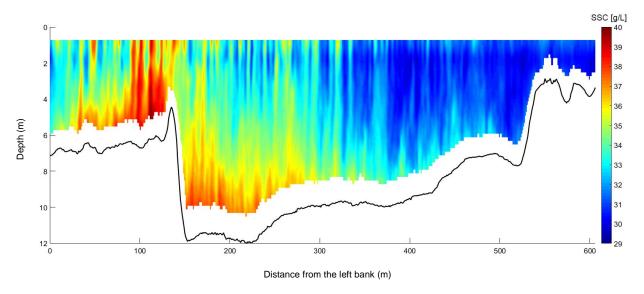


Figure 46. Distribution of suspended sediment transport along the transverse profile $P_{downstr}$ of the llok location at the time of recording m01

The result of the measurement of the bedload sediment transport is shown graphically as a unit transport of the bedload sediment at each sampling point along the control transverse profile for all measurements. From the distribution of the unit transport of bedload sediment along the upstream control profile P_{upstr} , a more pronounced transport of sediment along the right bank can be observed for all measurements (Figure 47). The graphic shows the trend of the increase of the total transport of bedload sediment with the increase in flow, with the fact that the distribution of the unit transport of bedload sediment across the width of the river is more uniform in times of low water. The distribution of the unit transport of bedload sediment on the downstream control profile $P_{downstr}$ shows that the transport is more intense along the



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left bank for all measurements with a proportional relationship of the increase in total transport with the increase in flow (Figure 48).

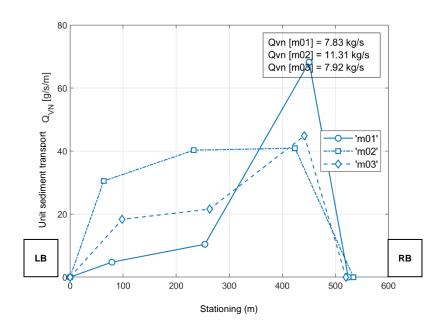


Figure 47. Variation of the unit transport of bedload sediment across the width of the control profile P_{upstr} for all measurements at the llok location

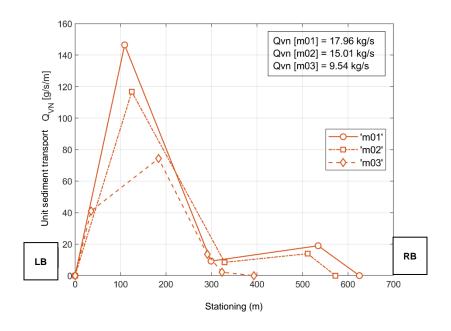


Figure 48. Variation of the unit transport of bedload sediment across the width of the control profile $P_{downstr}$ for all measurements at the llok location

Although the location is located on a flat section of the Danube, the dynamics of the movement of the bedload sediment is irregular. The direction of movement of the bedload



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sediment from upstream to downstream abruptly changes direction from a more pronounced drift along the right bank to a more pronounced drift along the left bank. On the upstream section, the average transport of bedload sediment along the profile for all measurements is 9 kg/s, while for the downstream section this amount is 14 kg/s. The average share of bedload sediment in the total sediment movement at this location is <10%. The total calculated values of bedload, suspended and total sediment transport are tabulated below for all measurements on both control profiles separately.

Table 8. Total bedload and suspended transport and measured flow for all measurements on both control profiles of the llok location

Measurement	Profile	Q [m ³ /s]	Q _{VN} [kg/s]	Q _{SN} [kg/s]
m01	P _{upstr}	5389	7.8	198.3
11101	P _{downstr}	5301	18.0	184.3
m02	P _{upstr}	3559	11.3	117.8
11102	P _{downstr}	3232	15.0	109.1
··· 03	Pupstr	1956	7.9	62.5
m03	P _{downstr}	1876	9.5	62.7

On the basis of laboratory analysis, a granulometric curve was obtained for all samples of bedload sediment. Below are the characteristic granulometric curves for both control profiles. The composition of the bedload deposit is homogeneous and sandy, ranging from fine to coarse sand.



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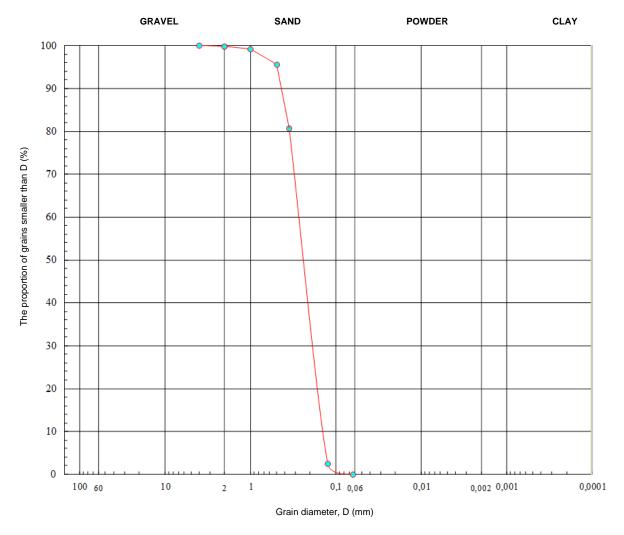


Figure 49. Granulometric curve of bed composition- sample taken along the right bank of the upstream control profile of the llok location



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MONITORING OF HYDROLOGICAL, HYDRAULIC AND MORPHOLOGICAL CHARACTERISTICS OF THE DANUBE RIVER AND INVENTORY OF BIODIVERSITY COMPONENTS ON THE JOINT CROATIAN-SERBIAN SECTOR OF THE DANUBE RIVER

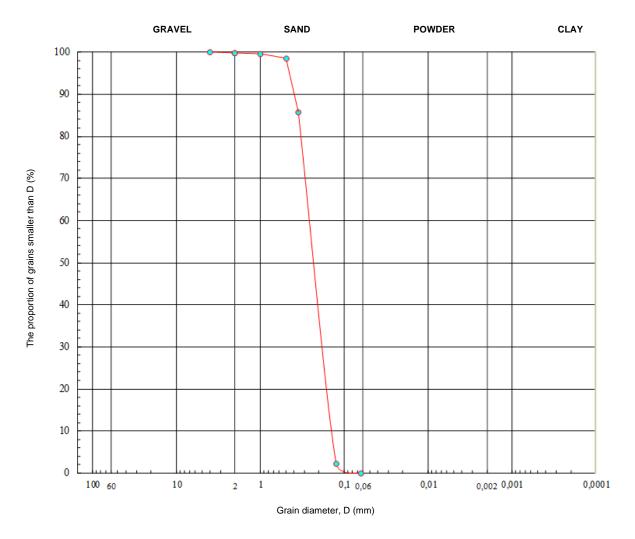


Figure 50. Granulometric curve of bed composition- sample taken along the right bank of the downstream control profile of the llok location



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4. CONCLUSION

This report presents the results of monitoring the water regime and sedimentation of the Danube River at 4 locations of the joint Croatian-Serbian section. Below are the most important results:

Element / Location	Measuring unit	Batina/Bezdan	The confluence of Drava	Vukovar	llok
The position of the upstream profile	rkm	rkm 1429+000	1383+000	1332+000	1302+000
The position of the downstream profile	rkm	rkm 142+5000	1381+600	1325+000	1300+000
		Medi	um depth		
m01 (high water level)	т	8,3-9,9		7,6-10,3	8,8-8,1
m02 (medium water level)	т	5,1-7,0		5,4-8,2	6,6
m03 (low water level)	m	4,1-5,9		4,0-6,4	4,6-5,4
		Maxir	num depth		_
m01 (high water level)	m	10,9-13,0		11,1-13,8	10,0-12,1
m02 (medium water level)	m	8,0-9,9		8,4-11,5	8,0-9,7
m03 (low water level)	m	6,4-8,7		6,2-9,3	5,9-7,0
		Measur	ed velocities		
m01 (high water level)	m/s	0,91-1,02		0,99-1,18	1,17-1,05
m02 (medium water level)	m/s	0,72-0,72		0,88-0,91	1,01-0,85
m03 (low water level)	m/s	0,66-0,67		0,76-0,67	0,82-0,88
Maximum velocity (mainstream)	m/s	~ 1,5		~ 2,0	~ 1,5
		Meas	ured flows		T
m01 (high water level)	m³/s	3.862-3.916	4.009-5.373	5.439-5.082	5389-5301
m02 (medium water level)	m³/s	1.833-1.839	1.963-2.797	3.484-3.112	3559-3232
m03 (low water level)	m³∕s	1.367-1.393	1.348-1.863	1.736-1.691	1956-1876
Transport of bedload sediment					
m01 (high water level)	kg/s	5,9-9,5	10,5-5,1		7,8-18,0
m02 (medium water level)	kg/s	12,6-3,6	8,5-5,0		11,3-15,0
m03 (low water level)	kg/s	14,3-3,0	5,0-3,4		7,9-9,5



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Element / Location	Measuring unit	Batina/Bezdan	The confluence of Drava	Vukovar	llok
Transport of suspended sediment					
m01 (high water level)	kg/s	128-130	135-189		198-184
m02 (medium water level)	kg/s	55	61-90		118-109
m03 (low water level)	kg/s	43,-44	42-63		62-63
Granulometric curve		D50 ~ 0,3 mm	D50 ~ 0,25 mm		D50 ~ 0,2 mm

Although the measurements cover the entire range of flow and water level (low, medium and high water level), it is evident that discrete measurements do not reflect the complex dynamics of the interaction of turbulent flow and sediment movement. This is most pronounced in measurements of bedload sediment, where there are considerable variations of sediment transport within a signle profile during the same event. The aforementioned deviation is a consequence of discrete physical sampling that cannot cover the entire spatial variability of sediment transport in riverbeds. Therefore, traditional sediment monitoring methods are complemented by indirect methods such as monitoring the velocity of the moving bottom, which is an indicator of the intensity of the movement of the bedload sediment (Gilja et al. 2017). Also, in order to reduce the error caused by the limiting factors of the method, it is necessary to collect a large amount of data that can only be obtained by systematic and regular measurement of sediment transport.

An alternative to the traditional methods of sediment transport measurement are indirect sediment measurement methods, which enable faster implementation of measurements with higher spatial resolution. Therefore, in sediment transport studies, it is advisable to combine traditional and indirect methods of sediment monitoring, which enable the measurement of a larger spatial and temporal scope of the sediment regime and thus a comprehensive overview of the process. Their application enables the collection and simultaneous overlay of data on the velocity field, the concentration of suspended sediment and the intensity of the movement of bedload sediment, as well as an overview of the complete river morphodynamics. Indirect methods need to be calibrated with traditional methods at each measurement location so that their results can be accurately interpreted.

From the display of water waves from the relevant water measuring stations, it is evident that the measurement was carried out on different hydrograhic conditions (low, medium, high water-levels). It is known that the sediment transport hysteresis is not synchronized with the flow hysteresis, which means that there is no direct dependence between water and sediment regimes. Therefore, monitoring should be continuous and include several measurements during the same hydrological event in order to determine the simultaneous water and sediment regime of the entire hydrological event.



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