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Advances in Monitoring and Understanding the Dynamics of Suspended-Sediment Transport in the River Drava, Slovenia: An Analysis More than a Decade-Long

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Abstract: Managing sediment transport in streams is crucial to the surface water resource development strategy and has several implications for flood risk and water management, hydropower use, and balancing river morphology. This paper summarises the movement and behaviour of suspended sediment within the Slovenian portion of the River Drava, covering a span of thirteen years from 2005 to 2018. An analysis of relevant data collected during this period is also presented. Suspended-sediment dynamics strongly depend on flow velocity, seasonal variations in sediment sources, and human interventions in the riverbed. The transportation of material in the River Drava results in the accumulation of sediments in reservoirs and riverbeds, consequently impeding the natural hydrological cycle by reducing the outflow into aquifers. The 2018 high-water event is analysed in terms of the dependence of concentration of suspended sediments on discharge, where counterclockwise hysteresis was observed, providing an essential clue to the origin of sediment. Sediments from the River Drava in Slovenia are managed with some conventional processes and are mainly deposited or reintegrated into rivers and aquatic ecosystems. Some additional sediment management strategies with long-term solutions for efficient and comprehensive water management, hydropower, and ecological problems are proposed.

Keywords: suspended-sediment dynamics; River Drava; sediment management

Citation: Kramer Stajnko, J.; Jecl, R.; Nekrep Perc, M. Advances in Monitoring and Understanding the Dynamics of Suspended-Sediment Transport in the River Drava, Slovenia: An Analysis More than a Decade-Long. *Appl. Sci.* **2023**, *13*, 9036. https://doi.org/10.3390/app13159036

Academic Editor: Kelin Hu

Received: 21 June 2023
Revised: 27 July 2023
Accepted: 3 August 2023
Published: 7 August 2023

1. Introduction

Sediment transport in surface waters is a complex dynamic process and has multiple implications, particularly in the areas of environmental protection, hydropower exploitation of rivers, flood risk management, and water resources management. Recently, suspended-sediment dynamics have been investigated intensively, as suspended sediment represents the majority of material that is in motion within a stream. The deposition of sediment in water bodies has significant impacts on the accumulation of silt in river channels, flood-prone areas, and surface waters such as lakes and coastal areas, as well as environmental impacts due to sediment-bound pollutants. Sediments found in rivers are a result of the weathering processes occurring on the upper layers of the Earth's crust, which interact with the forces of erosion that cause the movement of material and its transportation along river channels. Suspended-sediment concentration depends on the current flowrate, climate changes, glacial melting, and intense erosional processes. Human intervention in riverbeds, such as the construction of hydropower plants and other hydraulic structures, can have a significant impact on the transport dynamics and quantity of sediment in a watercourse. As a consequence of material transport, reservoirs and the riverbed become filled, which ultimately affects the natural hydrological cycle by reducing the discharge into aquifers [1–6].

Previous studies investigating suspended sediment in Slovenian rivers [7–13] have indicated that the majority of the overall material is transported during periods of high water flow. However, not every high-water event increases the amount of suspended sediment, as the dynamics of sediment depend on the sum of hydrologic events in the river, the previous hydrologic condition, the intensity of precipitation in the hinterland, and many other factors. The source of suspended sediment can be predicted from the relationship between water discharge and the concentration of suspended sediments, which usually takes the form of a hysteresis loop during a high-water event. Depending on various factors during the event, e.g., runoff, erosion processes, and human activities, different forms of hysteresis loops are possible, e.g., a single-value (straight or curved) relationship, clockwise loop (positive), counterclockwise loop (negative), single-value plus a loop, and figure of eight [14–18].

The dynamics of suspended-sediment transport in streams has been intensively studied recently, as they are closely related to runoff formation and flooding. Erosion processes are particularly intense in agricultural catchments, where suspended-sediment transport dominates during flood events [19]. A comprehensive study of suspended-sediment transport using a log-time dataset to obtain more information about the factors that determine suspended-sediment transport in headwater watersheds was presented in [20]. In [21], the effect of urbanization on suspended-sediment flux in a selected watershed was investigated, and it became clear that sediment dynamics vary spatially and temporally. The high spatiotemporal variability in suspended-sediment transport allows the determination of sediment sources and a general understanding of erosion in the catchment, which is why the statistical analysis of hydrometeorological data is crucial, as presented in [6,22]. In [23], different hysteresis relationships between suspended-sediment concentration and discharge due to catchment characteristics in a multiple catchment of the middle Yellow River were reported. A comprehensive understanding of the spatial and temporal dynamics of suspended-sediment concentrations requires properly calibrated and tested numerical models, as described in [24].

Measuring the amount and dynamics of suspended sediment in streams remains a complex problem, despite the existence of several established methods. Sediment transport is a highly dynamic process that cannot be fully captured by any measurement technique due to constantly changing conditions in rivers. Therefore, when selecting an appropriate measurement model, it is crucial to consider the temporal and spatial variability in sediment transport in both longitudinal and transversal cross-sections. If an accurate determination of the fractional volume of sediment is required, a combination of direct and indirect measurement techniques is necessary [1,2]. Establishing a comprehensive monitoring system and modelling suspended-sediment transport are critical to finding a systematic, long-term solution to the problem of sedimentation in streams and are the starting point for developing the management strategy.

The article provides an overview of suspended-sediment measurements on the River Drava in Slovenia between the years 2005 and 2018 and an analysis of suspended-sediment dynamics at different temporal scales (between different years, seasonal, and during a high-water event). Furthermore, an analysis of suspended-sediment dynamics during a high-water event is presented and a prediction of the origin of sediments in the river is made. In addition, an overview of the current management of suspended sediment in the River Drava is given and some future topics are proposed.

2. Study Area

The River Drava, which is the fourth-largest tributary on the right bank of the Danube, is extensively used for hydropower generation, with almost the entirety of its water potential energy being harnessed. Originating in South Tyrol, Italy, it flows through Austria, Slovenia, and Croatia, and ultimately merges with the Danube at Osijek [25]. The River Drava stretches for a length of 117.7 km in Slovenia and has a catchment area of 4662 km^2. The river has an average discharge of 292 m^3/s and is joined by several tributaries, including the Meža and Dravinja, with respective discharge rates of 12 m^3/s and 11 m^3/s. Additionally, the river has numerous torrential tributaries along its entire length. The Drava is home to a total of 22 hydropower plants located in Austria, Slovenia, and Croatia, with eight plants situated in Slovenia. The Zlatoličje and Formin areas in Slovenia feature two artificially constructed side channels (Figure 1).

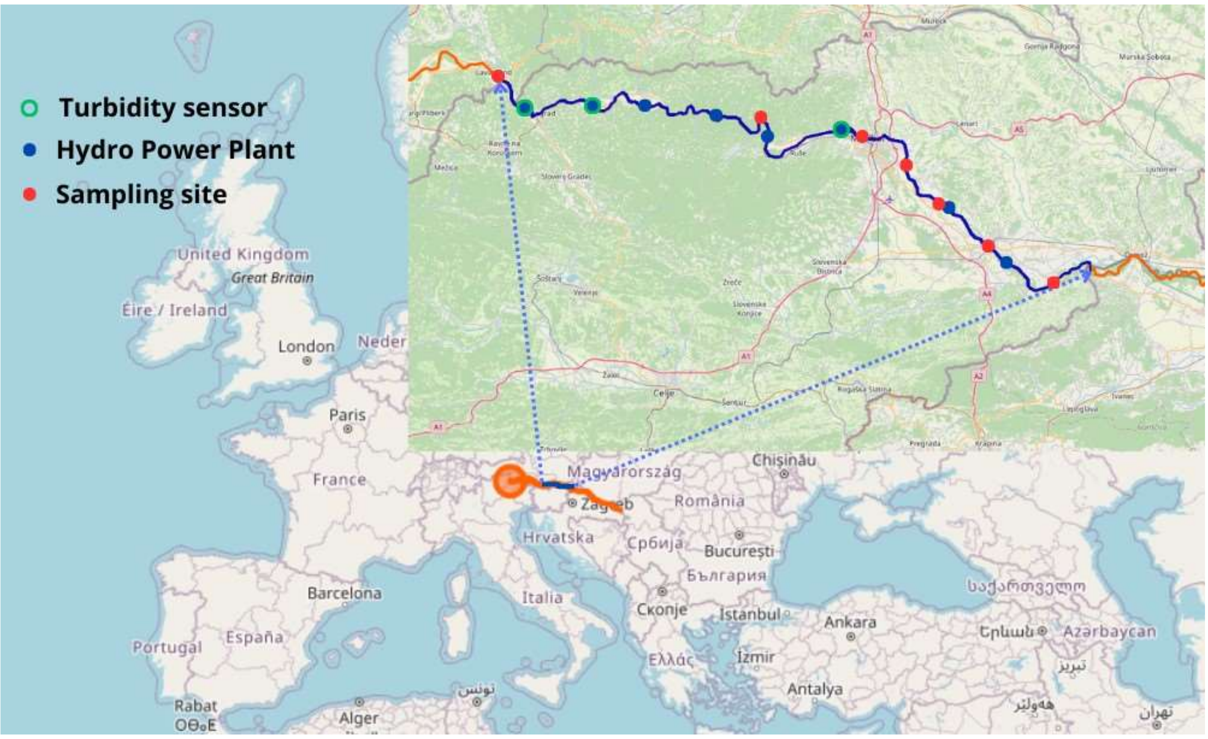

Figure 1. The River Drava in Slovenia; hydropower plants on the River Drava in Slovenia (blue dots); turbidity sensors (green circles); and monitoring sites presented in the current study (red dots).

The River Drava is significantly regulated along its entire path through Slovenia, which also strongly impacts suspended-sediment dynamics. The historical political structure of the countries through which the Drava flows affected the management and research activities on this river, which were neglected until the political upheavals of 1989–1990 and the end of the Serbian–Croatian war in 1995. However, there are few published studies that incorporate parameters of the river environment that have been published in the past [26]. Recently, some studies have been carried out on the River Drava on the possible reuse of sediments in the construction sector [13,27,28].

The national hydrological monitoring of surface waters required by the European Union under the European Water Framework Directive (Water Framework Directive 2000/60/EC) includes the measurement of water level, water velocity, flow, geometry of cross-sections, water temperature, as well as the suspended-sediment concentration in the water. The Slovenian Environment Agency regularly monitors suspended sediment in only the primary watercourses in Slovenia. However, the River Drava is not included in this monitoring program.

3. Materials and Methods

3.1. Monitoring of the Transport of Suspended Sediment in the River Drava in Slovenia

The first investigation of suspended sediment on the Slovenian part of the River Drava was undertaken at the monitoring station in Ptuj in the period from 1956 to 1975. Sampling was not performed randomly. At the Ptuj water monitoring station, suspended-sediment samples were taken between 1965 and 1975. The maximum value of concentration of suspended sediments was recorded during the flood on 20 August 1966, at 2802 g/m^3. A detailed analysis of the dependence of concentration of suspended sediments on other hydrologic parameters was not performed. The total amount of suspended sediment was not determined due to a lack of samples [29]. Thereafter, no further measurements were made as part of the national hydrological monitoring.

Today, the monitoring of suspended sediment is carried out by Dravske elektrarne (DEM)—the operator of the hydropower plants on the River Drava—at four sites using turbidity sensors. Turbidity measurements [30] at the four sites in the hydropower plants reservoirs started gradually in 2011 in the reservoir of the Dravograd hydropower plant, in 2012 at two other sites in Vuzenica and Mariborski otok, and in 2013 at the fourth site in Markovci (Figure 2) [10,29].

Figure 2. (**a**) Point-integrated sampler; (**b**) nozzle enabling isokinetic sampling; (**c**) crane with winch and steel cable; (**d**) lowering the sampler to take a sample; (**e**) measuring with ADCP; (**f**) simultaneous sampling and measurement with an ADCP.

Within the Slovenian–Austrian Cross-border Cooperation Program 2008–2013 (SI-AT), entitled "Drava-Mura Crossborder Initiative—DRA-MUR-CI", within one of the work packages, the transport of suspended sediment (measurements and modelling) was carried out at selected monitoring sites of the River Drava, namely Šturmov potok, Zavrč, Ptuj, and Studenška brv Maribor (Figure 1). Furthermore, in the year 2018, measurements of suspended sediment were conducted at Zgornji Duplek and Zlatoličje locations (Figure 1) persistently for one year, including the high-water occurrence in October 2018.

3.1.1. Suspended-Sediment Samplers

Suspended-sediment samplers are used to collect representative water samples in the stream. These samples are then analysed in a laboratory setting to determine the suspended-sediment concentration levels. To ensure the most reliable sampling, some conditions should be met, such as the following: water should enter the nozzle isokinetically (where the velocity and direction of water entering the sampler are the same as in the environment); stream flow patterns should be disturbed as little as possible; standard bottle sizes should be used (e.g., 1 pint or 1 L); and the equipment should be easy to operate and maintain [4,31,32].

There are two different types of samplers for suspended-sediment collection, namely depth-integrated and point-integrated samplers. The depth-integrated sampler is designed to obtain water samples from a vertical column of water by lowering it to the bottom of a stream and, afterwards, raising it back to the surface. The point-integrated sampler, on the other hand, collects the water at a specific point in the stream, which is made possible by the use of a valve that can be activated electrically. Figure 2 shows a point-integrated sampler US P-72 with appropriate equipment, which can be used for the isokinetic sampling of water at any point in the stream and was used for sampling at some of the monitoring sites investigated in this study.

The sampler is made of aluminium, has a length of 0.7 m, and weighs 18 kg. The hydrodynamic shape of the sampler allows it to rotate in the direction of the flow and be immersed at any depth. The diameter of the nozzle is 5 mm. Inside the housing there is a space for a collection bottle with a capacity of 0.95 L. On the side, there is a hole through which air can escape from the bottle while it fills with water. The sampler can be used in streams with a velocity between 0.5 and 2.0 m/s and a depth of 20 m.

3.1.2. Acoustic Method

Acoustic methods in hydrology were developed primarily for measuring the velocity and discharge of watercourses [33,34]. However, we can use the backscatter and attenuation of acoustic signals in water to monitor suspended sediment in water bodies. A calibration within situ measurements is necessary to determine the concentration of suspended sediment from the backscatter. Acoustic backscatter depends on the concentration and size of the scatterers and is also impacted by attenuation due to suspended matter along the water column [31,35,36].

The most commonly used device for measuring water velocity and indirectly further parameters is the Acoustic Doppler Current Profiler (Figure 2). All results presented in this article were collected with a 1200 kHz Teledyne RDI WorkHorse Rio Grande. In this ADCP model, five different frequencies (75–1200 kHz) are possible, which differ in sound absorption (sound absorption increases with frequency). The measuring device working with this frequency can be used in rivers with a minimum depth of 0.4 m to 15 m and velocities up to 10 m/s, which are also the conditions at the selected measuring points on the River Drava. By crossing the stream, the water depth and velocity can be measured. With a computer connected to the ADCP via a radio link, all data were recorded and collected in real time. The parameters such as discharge, cross-sectional area, and average velocity are known immediately after the crossing.

Based on the backscattered signal, the information about the concentration of suspended sediment can be calculated. The conversion of the backscattered signal into a concentration of suspended sediments is possible with another piece of conversion software, e.g., Aqua Vision, VISEA-PDT 4.0 (PDT—Plume Detection Toolbox), which allows a direct conversion of the measured data into a concentration of suspended sediments. In addition, the software allows a calibration of the measured backscatter with actual values of concentration of suspended sediments obtained with the direct methods. The theoretical background of the backscatter measured with ADCP is represented by the acoustic equation which links the discrepancy between the received and transmitted sound energy and the lost energy during the propagation of the sound wave [37]:

$$S_v = C + \log 10\,[T_T\, R^2/L\, P_T] + 2\,\alpha\, R + K_C\,(E - E_r) \quad (1)$$

The equation for acoustic backscatter in dB (S_v) is determined by several factors, including a constant value (C) in dB, the temperature (T_T) of the Acoustic Doppler Current Profiler (ADCP) transducer in °C, the slant range (R) along the beam to the scatterers in m, the transmit pulse length (L) in m, the transmit power (P_T) in W, the attenuation coefficient (α) in dB/m, a scale factor (K_C) in dB/count, the relative backscatter (E) equal to echo intensity in the count, and the received noise (E_r) in the count. The values of C, TT, R, and PT are either recorded with the ADCP or provided by the factory. The value of E is derived from the Received Signal Strength Indicator of the receivers, and Er is the noise value when no signal is present. The typical value of Er is 40 counts, and the values of factor KC range from 0.35 to 0.55 dB/count. The attenuation coefficient α is the sum of the water absorption α_w and particle attenuation α_s, which are obtained based on empirical formulas that can be found in the literature [37].

The procedure of conversion of backscatter into a sediment concentration can be summarized in three steps: the conversion of backscatter into dB, the standardization of the instrument, the standardization of the area.

The most important part of the measurement is the calibration with real values of sediment concentration. This can be performed with data from the optical backscatter sensors or with water samples where the sediment concentration is determined in the laboratory and then manually entered into the programme.

4. Results and Discussion

The paper presents the results of suspended-sediment measurements that were collected over a period of 13 years (2005–2018) from four monitoring sites: Šturmov potok, Ptuj, Studenška brv Maribor, and Zgornji Duplek during a high-water event. (Figure 1) During the measurements with different measurement techniques, some experience was gained in order to propose the optimal technique for the monitoring and management of suspended sediments on the River Drava. The hydrological data were obtained from Dravske elektrarne (DEM)—the operator of the hydroelectric power plants on the River Drava—who provide data on discharge; at the Ptuj measuring point, the discharge and water level were measured by the Slovenian Environment Agency site. Different measurement methods were used to determine the suspended-sediment concentration, depending on the available equipment and the conditions at the measurement sites. The suspended-sediment concentration was determined by analysing the collected water samples. A variety of water samplers were used, from the simple water samplers used under severe conditions, such as floods, to the depth-integrated samplers described and shown in the previous chapter. However, to obtain the most representative results of suspended-sediment dynamics in a cross-section, the basic measuring technique was supplemented with the acoustic method. The results presented are divided into three parts: First, the dynamics of suspended sediment at selected sites at mean discharge of the River Drava are presented. In addition, a case study is presented where a combination of direct and indirect methods was applied. Finally, the results of a high-water event in October 2018 are presented.

4.1. Suspended-Sediment Dynamics at Average Discharge

Analysis of the correlation between the concentration of suspended sediments (c in g/m^3) and flow rate (Q in m^3/s) in the River Drava showed that the dependence of these quantities can be adequately described by quadratic functions that vary depending on the measurement location. The concentration of suspended sediment can vary both longitudinally and transversely along the river. In the example of the River Drava, the amount of suspended sediment can be compared at three different distances from the bank

(Profile1, Profile2, and Profile3; Table 1) and at two depths (2 m and 4 m) on a river cross-section at the Šturmov potok monitoring site (Figure 3), where the results from October 2009 and May 2005 are shown.

Table 1. Locations and dates of water sampling from the River Drava, maximum and minimum water flows, and concentrations of suspended material.

Sample No.	Location	Depth (m)	Date	Flow Q (m^3/s)	Suspended-Sediment Concentration c (g/m^3)
			DRAVA Šturm		
1	Profile 1	2	14 October 2009	441	12.0
2	Profile 1	4	14 October 2009	441	12.0
3	Profile 2	2	14 October 2009	441	14.0
4	Profile 2	4	14 October 2009	441	12.0
5	Profile 3	2	14 October 2009	441	11.0
6	Profile 3	4	14 October 2009	441	14.0
7	Profile 1	2	14 January 2010	314	4.5
8	Profile 1	4	14 January 2010	314	3.0
9	Profile 2	2	14 January 2010	314	4.0
10	Profile 2	4	14 January 2010	314	4.0
11	Profile 3	2	14 January 2010	314	4.0
12	Profile 3	4	14 January 2010	314	5.0
13	Profile 1	2	20 April 2010	239	4.0
14	Profile 1	4	20 April 2010	239	3.0
15	Profile 2	2	20 April 2010	239	4.0
16	Profile 2	4	20 April 2010	239	4.0
17	Profile 3	2	20 April 2010	239	3.0
18	Profile3	4	20 April 2010	239	4.0
19	Profile 1	0	17 June 2010	556	54.0
20	Profile 1	1	17 June 2010	556	49.0
21	Profile 2	0	17 June 2010	556	53.0
22	Profile 2	1	17 June 2010	556	54.0
23	Profile 3	0	17 June 2010	556	50.0
24	Profile 3	1	17 June 2010	556	49.0
25	Profile 1	2	16 September 2010	429	17.0
26	Profile 1	4	16 September 2010	429	13.0
27	Profile 2	2	16 September 2010	429	16.0
28	Profile 2	4	16 September 2010	429	15.0
29	Profile 3	2	16 September 2010	429	15.0
30	Profile 3	4	16 September 2010	429	15.0
31	Profile 1	0	31 January 2011	312	5.0
32	Profile 1	1	31 January 2011	312	1.0
33	Profile 2	0	31 January 2011	312	3.0
34	Profile 2	1	31 January 2011	312	1.0
35	Profile 3	0	31 January 2011	312	1.0
36	Profile 3	1	31 January 2011	312	3.0
37	Profile 1	0	22 March 2011	169	6.0
38	Profile 1	1	22 March 2011	169	5.0
39	Profile 2	0	22 March 2011	169	14.0
40	Profile 2	1	22 March 2011	169	14.0
41	Profile 3	0	22 March 2011	169	20.0
42	Profile 3	1	22 March 2011	169	20.0
43	Profile 1	0	15 May 2012	301	19.0
44	Profile 1	2	15 May 2012	301	19.0
45	Profile 2	0	15 May 2012	301	14.0
46	Profile 2	2	15 May 2012	301	14.0
47	Profile 3	0	15 May 2012	301	20.0
48	Profile 3	2	15 May 2012	301	20.0

Table 1. *Cont.*

Sample No.	Location	Depth (m)	Date	Flow Q (m^3/s)	Suspended-Sediment Concentration c (g/m^3)
			DRAVA—Ptuj		
61	left	0	5 May 2011	391	8.0
62	left	2	5 May 2011	391	6.0
63	middle	0	5 May 2011	391	8.0
64	middle	2	5 May 2011	391	9.0
65	right	0	5 May 2011	391	7.0
66	right	2	5 May 2011	391	9.0
67	left	0	9 June 2011	536	67.0
68	middle	0	9 June 2011	536	53.0
69	right	0	9 June 2011	536	50.0
70	left	0	20 June 2011	631	185.0
71	middle	0	20 June 2011	631	234.0
72	right	0	20 June 2011	631	246.0
73	left	0	18 August 2011	345	15.0
74	left	2	18 August 2011	345	13.0
75	middle	0	18 August 2011	345	31.0
76	middle	2	18 August 2011	345	34.0
77	right	0	18 August 2011	345	40.0
78	right	2	18 August 2011	345	40.0
79	left	0	22 July 2011	988	97.0
80	middle	0	22 July 2011	988	110.0
81	right	0	22 July 2011	988	110.0
82	left	0	13 September 2012	796	95.0
83	middle	0	13 September 2012	796	95.0
84	right	0	13 September 2012	796	64.0

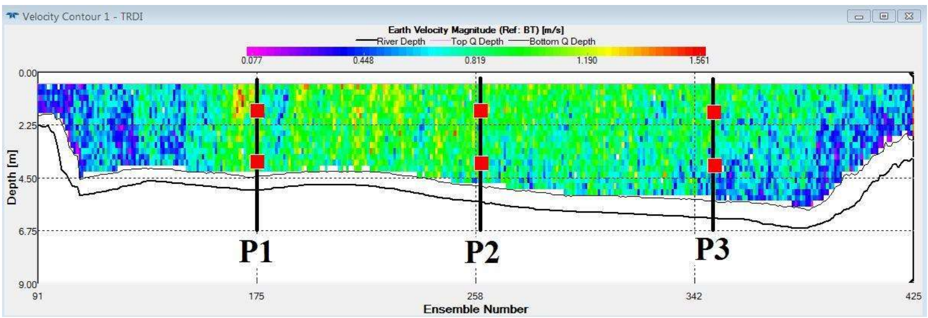

Figure 3. Measured velocity profile, profiles and points where the water samples were taken (red squares).

The results presented in Figure 4 show that the amount of suspended sediment is almost the same at both depths of the river and that there is no significant difference between the selected profiles. Evaluations of the relationship between the discharge and concentration of suspended sediments and of the annual suspended-sediment amounts were performed.

The grain size distribution curve of a composite sample showing the weight fractions of the individual material fractions smaller than the specified grain sizes at the Drava—Šturm measuring point is shown in Figure 5. The examination of the grain size shows that most of the suspended material in the Drava belongs to silt (0.002–0.060 mm), less than 10% is clay fraction (<0.002 mm), and about 8% is fine sand (>0.06 mm).

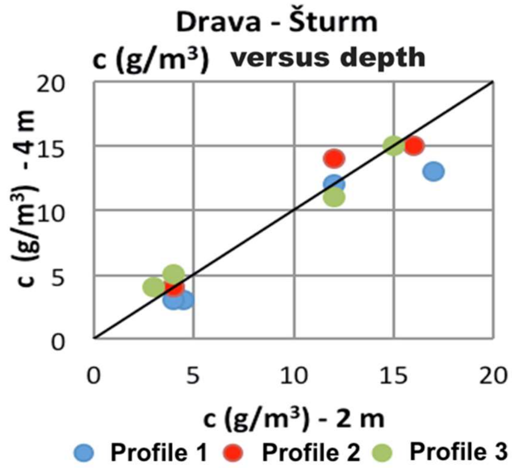

Figure 4. The ratio between the concentrations of suspended material at depths of 2 m and 4 m, measured in three profiles of the River Drava (Profile 1, Profile 2, and Profile 3) at the monitoring site Šturmov potok.

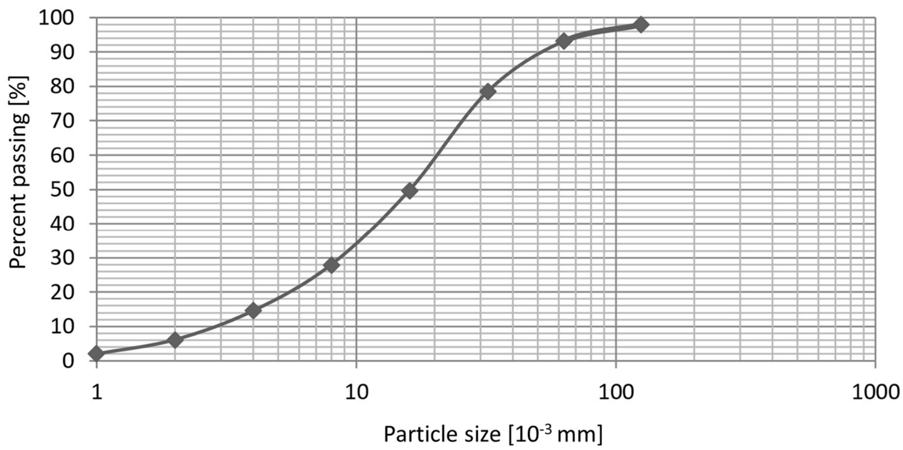

Figure 5. Grain-size distribution curve of suspended material of a composite sample at the Drava Šturm measuring point.

4.2. Prediction of Suspended-Sediment Transport

4.2.1. Q/c Curve

Based on long-term measurement results, we can predict the transport of suspended sediments in a selected cross-sectional profile of a watercourse. If we know the water flow (Q) in a geometrically defined cross-section and with measured velocity vectors, as well as simultaneously determined concentrations (c) of suspended particles at selected points of the profile, we can predict the concentration over the entire profile and simulate the Q/c diagram. With the known Q/c function and a time-dependent flow Q(t), we can determine the annual balance (B) of transport of suspended particles and use the annual trends of flow Q to statistically predict the transport of suspended material through the selected profile. The described interdependencies are shown in Figure 6 for the Drava—Ptuj and Drava—Šturm locations, where the graphs also include the functional dependence, with R^2 (coefficient of determination) representing the fit estimate of the function to the measured values.

Figure 6. Q/c and Q/H (water level) relationships for Šturmov potok and Ptuj measuring sites.

4.2.2. Annual Quantities of Suspended Sediments

The cumulative amounts of suspended-sediment transport can be determined using a suspended-sediment transport model and measured and historical runoff data. Figure 7 shows the hourly measurements of the flow rate of the River Drava in the years 2005 and 2010 in m^3/s (data from ARSO) in the first blue diagram. From the discharge data, the total of suspended sediment c in the water body in kg was calculated for each hour. The middle diagram shows the quantities. The bottom diagram summarizes these quantities, and the final value gives the aggregate annual total of suspended sediment in the river for 2005 and 2010 in the Šturm profile.

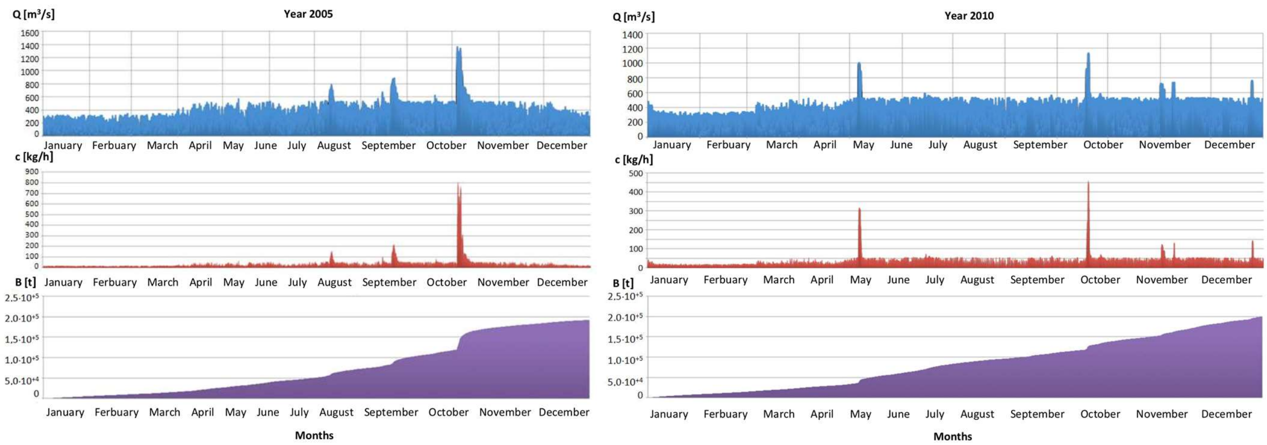

Figure 7. Flow rate, suspended-sediment concentration, and suspended-sediment annual balance B(t) at the Šturm monitoring station in 2005 and 2010.

4.2.3. Studenška Brv, Maribor Measuring Site

A case study of the suspended-sediment concentration in a selected River Drava profile, using indirect acoustic measurements (with an ADCP) and point sampling (direct method), is presented. Combining these methods is necessary to obtain a representative picture (temporal and spatial distribution) of sediment transport through the river profile.

The measurement was performed on the profile of the River Drava in the area of Studenška brv in Maribor. The ADCP was operated from a bridge (Figure 2) with data collected and monitored in real time on a connected laptop. A wireless connection was established between the instrument and the laptop. Simultaneously, water samples were collected using a spot sampler (Figure 2) and later analysed in a laboratory.

The measured velocity profile and the profiles where the water samples were collected are shown in Figure 8. The actual flow rate at the time of measurement was 287 m^3/s. The streambed was characterized by uneven depths, with the greatest depth of 7.5 m reached near the left bank. There were two prominent points in the profile where the depth was shallowest (5.5 m), namely in the area of the bridge piers. These piers visibly influenced the dynamics of the water flow and caused significant sediment deposition at this location.

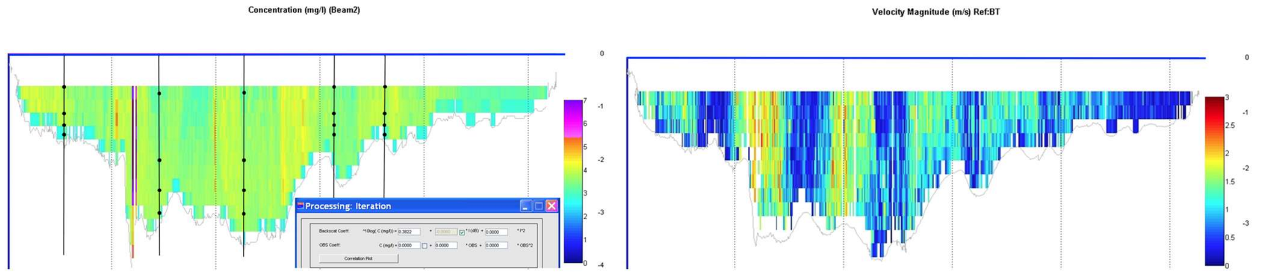

Figure 8. Sediment concentration in mg/L showing sample collection sites and iteration with calculation of coefficients A and B in Equation (1) and velocity profile at Studenška brv measuring site.

The concentrations of suspended sediments in the collected samples were measured and are presented in the Table 2. The concentration was determined using a method in accordance with the Slovenian standard SIST EN 872:2005, which is further described in [11].

Table 2. Suspended-sediment concentration c in collected samples according to SIST EN 872:2005.

Sample	Depth [m]	Concentracion [mg/L]
V1-1	0.3	0.0090
V1-2	0.9	0.0066
V1-3	1.2	0.0116
V1-4	1.4	0.0098
V2-1	0.4	0.0052
V2-2	1.2	0.0038
V2-3	1.6	0.0038
V2-4	1.9	0.0030
V3-1	0.7	0.0022
V3-2	2.1	0.0014
V3-3	2.8	0.0020
V3-4	3.3	0.0048
V4-1	0.7	0.0020
V4-2	2.1	0.0028
V4-3	2.8	0.0034
V4-4	3.3	0.0026
V5-1	0.4	0.0104
V5-2	1.2	0.0060
V5-3	1.6	0.0066
V5-4	1.9	0.0026

The backscatter signal and the concentration of suspended particles both depend on the attenuation of the particles, and conversely, the attenuation of the particles depends on the concentration of the suspended particles. Therefore, the concentration values must be optimized in an iterative process, which was performed automatically by the program VISEA-PDT [37].

The relationship between the absolute value of the backscatter signal and the concentration of suspended sediments is given by the expression:

$$10 \log (C) = A\ I + B, \tag{2}$$

C is the concentration of suspended sediments in mg/L, I represents the measured absolute backscatter in dB, and A and B are constants resulting from the measured values of the sediment concentration of the samples.

The actual value of the concentration of suspended sediments was determined in an iterative substep, since both the strength of the sound signal reflection and the concentration of suspended sediments depend on the attenuating particles. The loss of sound energy due to absorption by particles and scattering in the water was taken into account.

The use of an Acoustic Doppler Current Profiler to determine the concentration and distribution of suspended sediment over a river profile has proven to be a good alternative to other methods when used in conjunction with appropriate software that allows the conversion of acoustic signals to the concentration of suspended sediments. This approach allows the presentation of a comprehensive picture of sediment transport through a selected cross-section of a water body.

4.3. High-Water Event Dynamics of Suspended-Sediment Concentration

The aim of this case study was to investigate the concentration of suspended sediment in the River Drava during a flood event. The detailed description of the measurement procedure and the results have already been published in [38], but in order to give a comprehensive picture of sediment transport in the Drava, some main conclusions are summarised below.

During high-water events characterized by large flow rates, measuring sediment transport in rivers poses significant challenges due to hazardous conditions, large woody debris, and other floating objects on the river surface. It is a known fact that more than 50% of suspended sediment is transported during high-water events. Since such situations usually occur in very short periods of time, predicting them and collecting samples are very difficult if the system is not automated. However, when conditions are optimal, classical sampling methods are uneconomical, and errors in sampling and calculating the final concentration of sediment increase. Traditional measurement techniques such as Acoustic Doppler Current Profilers, hydrometric wings, and sediment samplers face considerable difficulties or are even impractical. Therefore, the introduction of invasive and automated methods for determining suspended-sediment concentration is crucial [2,39–43]. As alternative measurement approaches or modifications to existing techniques, some novel technologies, such as remote sensing methods or automated sampling systems, may provide potential solutions by enabling measurements from a safe distance or offering enhanced instrument resilience to debris interference.

The investigation of a high-water event occurred at the Duplek Bridge site, located between the cities of Maribor and Ptuj. At this site, the outflow channel is separated from the riverbed at the Melje Dam to supply the Zlatoličje Hydropower Plant. The maximum capacity of the derivation channel is 500 m^3/s, and when this capacity is exceeded, the extra water flows into the natural riverbed. This area's required ecological river discharge is 10 m^3/s in winter and 20 m^3/s in summer.

In the autumn of 2018, a high-water event commenced on 29 October when the discharge of the River Drava surpassed 500 m^3/s. The discharge within the natural riverbed began to escalate from 10 m^3/s and reached a peak discharge of 1391 m^3/s, lasting for a duration of three days. Discharge data were obtained from the Melje Dam's automated measuring station at the Dravske elektrarne site and were accessible online in real time.

In order to determine the concentration of suspended sediments relative to discharge during the high-water event, water samples were collected manually using 1000 mL plastic bottles from the bridge. The sampling period continued until 4 November 2018, with only one sample per day collected during the last four days when the discharge was below

500 m^3/s and decreased significantly. The collected samples were filtered through glass microfiber filters, and the concentration of suspended sediments was determined according to the standard SIST EN 872:2005 [44]. Filter trays were dried in an oven and weighed using an analytical balance (RADWAG AS 220.R2).

The results of the suspended-sediment measurements during the high-water event in October 2018 are shown in Figure 9. The minimum discharge value was 92 m^3/s on 5 November 2018, at 15:13, while the maximum was 1391 m^3/s on 30 October 2018, at 18:33. The minimum concentration value was 105 mg/L on 5 November 2018, at 15:13, while the maximum was 2450 mg/L on 31 October 2018, at 00:28. The suspended-sediment concentrations were found to be different at rising water levels from those measured at the same water level at falling water levels. The suspended-sediment dynamics in watercourses rely on various factors, including energy conditions determined by discharge levels, sediment availability, precipitation intensity, land use, and vegetation cover. These factors influence the typical hysteresis effects that are observable when studying the relationship between runoff and sediment concentration. Figure 9 displays the correlation between the concentration of suspended sediments and discharge for a specific stretch of the River Drava during a high-water event in October 2018. A counter-clockwise hysteresis loop was observed, indicating that sediment sources were located at the area's far end, contributing to surface runoff, which suggests that sediments reached the stream during the falling limb [38]. However, the hysteresis loop may also have occurred due to material eroded in a catchment that did not reach the stream during the previous flood event and settled on the slope. The surface runoff then transported these sediments during the next high-water event. Reports of high values of suspended-sediment concentration during a falling limb are associated with bank collapse [45].

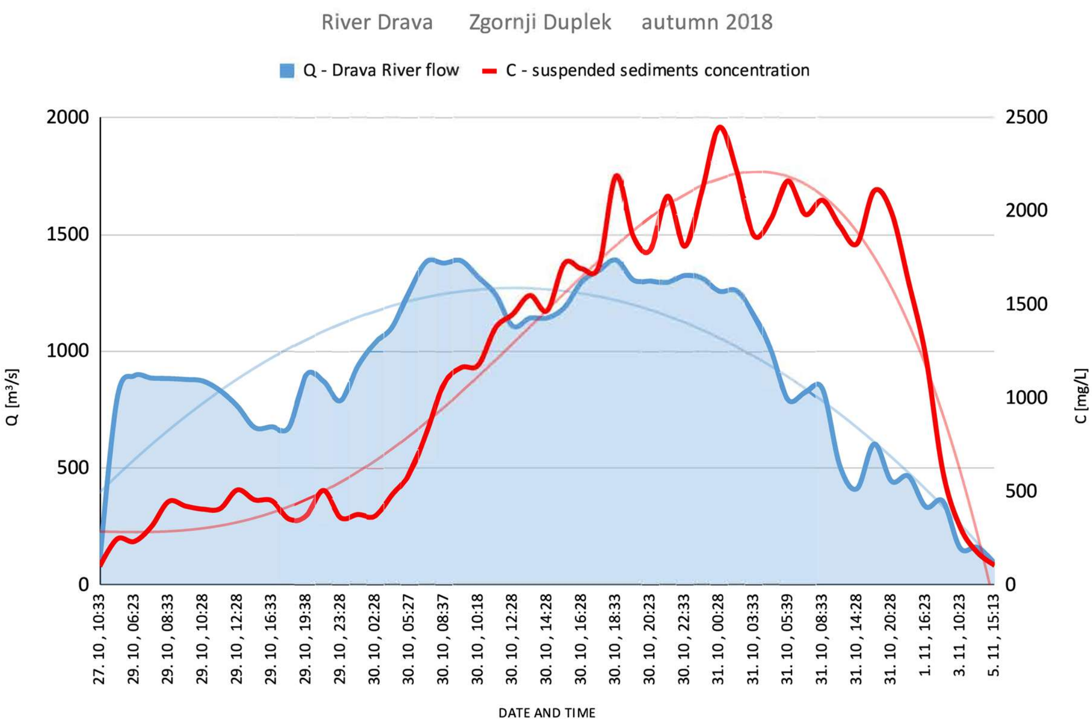

Figure 9. The relationship between the concentration of suspended sediments (C) and water discharge values (Q) was investigated. Time evolution of the water discharge Q and concentration of suspended sediments C for the high-water event in October 2018 (based on [38]).

To determine the main factors contributing to the increase in concentration of suspended sediments during the falling limb, additional land use and precipitation intensity data must be analysed.

From the results, it is clear that on this part of the River Drava, most of the material is transported during high-water events, which can lead to various problems and damages in the flooded areas, e.g., the pollution of agricultural land and reduced performance of returning waves. Special attention and additional measures to protect these areas are required.

4.4. Possible Measures for the Management of Suspended Sediment in the River Drava

Sedimentation in the reservoirs of the Slovenian River Drava is an important issue for hydropower plant operators as it affects the efficiency of the plants. It is estimated that between 30,000 and 40,000 m^3 of sediment accumulate in the reservoirs annually [27]. It was determined from the observations that the volume of reservoirs is decreasing. It was noted that the total volume of the reservoirs decreased by 32% from the commissioning of the hydropower plants to 2014. In addition, the usable volume of the reservoirs has reduced by about 33,000 m^3 annually [13].

Historically, river sediments have been treated as waste and managed in a variety of ways, including landfilling or reintegration into rivers and aquatic systems [13,28,46]. However, some alternative solutions for the treatment and reuse of river sediments from the River Drava have been developed [27,28]. An investigation into whether the sediments from the River Drava are appropriate as a filling material in the construction of levees and its further potential was given in reference [27].

In reference [13], a solution to the problem of sedimentation in the reservoirs of the River Drava in Slovenia was proposed. Sedimentation in reservoirs due to changed hydraulic conditions strongly affects the efficiency of hydropower plants. Based on the particle size distribution of the suspended sediment, most of the material is fine-grained, so flooding the sediment into the core of the stream at higher flow velocities and further flushing would be the most appropriate action. However, the proposed solution does not comprehensively solve the sedimentation problem, as the problem is only shifted downstream.

An effective sediment management measure in streams is sediment fences [47], which are temporary sediment barriers made of permeable fabric that trap and retain small amounts of sediment generated by construction activities or unsecured areas. These fences cause the water to slow down, allowing sediment to settle in a sediment basin in front of the fence. However, they are unsuitable for high waters and require regular maintenance, inspection, and sediment removal.

Sediment traps [48,49] are used to retain sediment from construction sites, but they are unsuitable for functioning water courses.

To minimize the sediment transport of fine-grained material, sediment curtains of impermeable materials [50–52] are an efficient alternative. They can extend to the bottom and prevent sediment passage over the entire height of the curtain or only to a certain depth to prevent the transport of suspended sediment in the upper part of the water column.

5. Conclusions

The suspended-sediment dynamics in the River Drava were studied using different measurement methods and under different conditions (mean discharge and flood events). The problem of sedimentation in the River Drava is of particular importance for hydropower utilisation, as it leads to the clogging of reservoirs and reduces the efficiency of hydropower plants.

The results at selected gauging stations show that the dependence of discharge and the concentration of suspended sediments can be described with the aid of rating curves, which can be used to determine the cumulative amounts of suspended-sediment transport. The concentration of suspended sediments in the River Drava is subject to temporal and spatial fluctuations, which can only be recorded with a suitable combination of indirect and direct measurement methods. An example of a combination of the acoustic method and point sampling in a selected cross-section was shown, giving a representative picture of suspended-sediment transport through the cross-section.

The findings from the analysis of the high-water event in October 2018 suggest that the correlation between the concentration of suspended sediments and runoff follows a clockwise hysteresis loop. This phenomenon can be attributed to several factors, including the sediment sources being located far away from the area where surface runoff is generated, or the sediment being deposited on the slope without being washed away. Nevertheless, additional research is necessary to identify the source of the suspended sediment in the stream during the high-water event.

In order to establish an efficient model of suspended-sediment dynamics in the River Drava, continuous monitoring should be established. In addition to the existing turbidity sensors at four hydropower stations, physical samples and other methods should be used to obtain a representative picture of the selected cross-section that could be used for further predictions of sediment transport. Based on an accurate model of sediment transport, sediment management can be determined in terms of flooding sediments into the core of the stream or constructing sediment fences, sediment traps, or sediment curtains. However, all measures should be sustainable and not adversely affect other users and life in the vicinity of the river.

Author Contributions: Conceptualization, J.K.S., R.J. and M.N.P.; Methodology, J.K.S. and M.N.P.; Investigation, J.K.S., R.J. and M.N.P.; Writing—original draft, J.K.S. and M.N.P.; Writing—review & editing, J.K.S., R.J. and M.N.P.; Visualization, J.K.S. and M.N.P.; Supervision, R.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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