Chapter 7
Sediment Transport of the Drava River

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Abstract Sediment transport data collection on the Croatian-Hungarian section of the Drava River started in 1961 at the Barcs and Drávaszabolcs (Hungary) gauging stations, in 1980 at Donji Miholjac and Botovo (Croatia) stations, in 1991 at Terezino Polje (Croatia), and in 1998 at Bélavár (Hungary). In the present study, recent data measured after the construction of the last hydropower plant on the river have been used and analyzed. Sampling and analysis methodology is described, and an overview of the sediment transport processes along the river is given. The conclusion is that typical river morphological processes like armouring on the upstream reach and riverbed erosion downstream of reservoirs can be identified. For a detailed analysis and reliable prediction, a more systematic approach and a regular and well-designed field data collection and monitoring activity would be needed.

Keywords Drava river · Sediment sampling · Suspended load
Bedload · Bed material

7.1 Introduction

The most important parameters describing fluvial sediment transport are sediment load, Q_s, meaning the amount of sediment (volume or mass) passing through a given cross-section during a specified time; sediment yield, G_s, which is the mass of sediment passing by during a specified period of time; and, for suspended sediments, sediment concentration, c_s, which is the ratio of the mass of sediment and the volume of the water in which it is contained.

The measurement of fluvial sediment is based on sampling procedures, as a result of which, relying on protocols, sediment load and concentration can be calculated. Based on regular sediment measurement, it is essential to estimate the

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D. Lóczy (ed.), *The Drava River*, Springer Geography,
https://doi.org/10.1007/978-3-319-92816-6_7

correlations between flow characteristics and sediment parameters, for different water regime conditions. The best way to achieve this is to draw up sediment rating curves (Graf 1984).

Sediment transport data collection on the Drava River started in 1961 at Barcs and Drávaszabolcs stations (Hungary), in 1980 at Donji Miholjac and Botovo stations (Croatia), in 1991 at Terezino Polje (Croatia) and in 1998 at Bélavár (Hungary) (VITUKI 2003). In the present study, recent data measured after the construction of the last hydropower plant on the river have been used and analyzed.

Sediment investigation of the Drava River in recent times included different sampling campaigns as well as regular monitoring activities of both Hungarian and Croatian water management bodies. In frame of the Hungary-Croatia IPA Crossborder Co-operation Programme 2007–2013 (HU-HR) project number HUHR/1001/1.1.2/0009, entitled “Drava morphological monitoring” there was a possibility to examine the morphological conditions of the river, and the repeated measurement of hydraulic characteristics. The project featured a co-operation between the South-Transdanubian Water Management Directorate and the Croatian Water Management Organization (Hrvatske Vode), and was selected for support in 2011. The work was strongly related to the requirements of the EU Water Framework Directive, which implies that during preservation work and action in order to maintain the good status of the waterbodies, the regular monitoring of certain Drava reaches has to be carried out, with the purpose to follow the changes in the status of the river. The present study highly relies on the results of this project (Rákóczi et al. 2012). While the above-mentioned project included comprehensive analyses of sediments and bed material, reference is also made to the suspended sediment investigations of Croatian authorities, which were analyzed by Gilja et al. (2009).

It has already been reported in recent literature that the amount of suspended sediment along the Drava River has been greatly reduced, which can cause serious consequences (Bonacci and Oskoruš 2010 and Chap. 9 in this volume; Kiss et al. 2011). This, according to several authors, can be attributed to the massive construction on the Drava River since 1975, in the form of numerous hydrotechnical works, including various hydroelectric power plants.

7.2 Methods

In frame of the project of 2012, measurements were carried out at five cross-sections along the Hungarian-Croatian common reach of the Drava river: Botovo, Bélavár, Barcs, Drávaszabolcs, and Belišće. The measurements comprised three discharge measurements, suspended and bed-load sampling, and bed material sampling and were carried out in May, June and August, respectively. In situ measurements were performed by the South-Transdanubian Water Directorate (Pécs, Hungary), while the laboratory analysis of the sediment and bed material samples was carried out by Eötvös József College (now the Faculty of Water Sciences, National University of Public Service, in Baja, Hungary).

7.2.1 Sampling

In the following, the methods of sediment sampling in Hungary are described, as the majority of data and analyses on which the present study is based, refer to Hungary. However, we have to mention that in Croatia, sampling methods are not always comparable, and thus the data obtained from the different measurement methodologies must be very carefully used because of possible inhomogeneity issues. In Croatian methodology, for example, it is a common practice to determine suspended load concentrations from a single, near-surface sample (Gilja et al. 2009).

When sampling suspended load in the whole cross-section, in Croatian practice six verticals and three samples per vertical are used, while in Hungary it is usually three verticals and two samples per vertical. Before analyses, the samples taken from different depths are joined in both countries, thus the results in the grain size distribution give a vertical-average only instead of a 2D distribution in the cross-section.

7.2.1.1 Suspended Load

The most effective way of sampling suspended load is with a pump. An advantage is that it is not needed to regain the sampler onboard between the points. Thus, this method is the fastest, which is an issue, particularly at high velocities and when sampling is done in the navigation route. During sampling, it is very important to ensure that the sampling nozzle faces the flow, the pipe is not bent and to let enough time before taking samples to flush the pipe.

Sampling needs to be carried out with care to adjust the revolutions per minute value (RPM) or the discharge of the pump for the velocity through the nozzle V_{in} should not differ much from the velocity of the flow v at the given point:

$$0.8\,\mathrm{v} \le V_{in} \le 1.5\,\mathrm{v}$$

In case the velocities are outside this range, the RPM of the pump should be accordingly adjusted, or a tap should be installed at the end of the pipe to ensure that intake velocities match. In order to determine intake velocity, the discharge of the pump (q_p) has to be divided by the cross-section area of the nozzle (f_n):

$$v_{\text{in}} = q_{\text{p}}/f_{\text{n}}$$

In practice, we perform sampling with a constant pumping discharge, assigning a fixed intake velocity to different velocity ranges of the flow, keeping the hydraulic coefficient between the values 0.8 and 2.0. This ensures a maximum 20% difference in concentrations, which is acceptable.

7.2.1.2 Bedload

The bedload of rivers is moving intermittently over the surface of the riverbed. As bedload samplers disturb the current, they have an effect on the transported bedload. When choosing the appropriate sampler, we have to minimalize disturbance. Sampling of the bedload usually happens with the Helley-Smith sampler (in fine sediment, e.g. sand) or the Károlyi sampler (in coarser sediment). Both samplers have different sizes and gaps for different river types, depending on the grain size and the mass flow of the sediment.

The samplers are lowered to the bottom of the river, and, depending on the sampling time (usually 10–15 min), based on the mass of the sample taken, bedload transport can be calculated:

$$q_{\text{b}} = \frac{G}{b \cdot T \cdot \rho_{\text{s}}},$$

where

G dry mass of the sample;
b width of the gap of the sampler;
T sampling time and
ρ_{s} density of the bedload sample

In our experience, it is very useful to equip these samplers with an underwater camera, in order to be able to see the clogging of the sampler or anything blocking it; furthermore, to determine the exact sampling time needed to collect a reasonable amount of sediment in the apparatus.

The size of the Károlyi sampler used was: length 1,620 mm, height: 310 mm, wingspan: 200 mm, gap size: 314 × 122 mm, weight: 35 kg.

On the reaches where bedload is mainly sand, the Helley-Smith sampler was also used, fitted with a camera as well. Depending on the expected coarseness of bed material, two different size Helley-Smith samplers were used on the Drava river. For fine sand, a smaller sampler (length: 960 mm, height: 200 mm, wingspan: 400 mm, gap size: 152 × 152 mm, weight: 17 kg), and for coarse sand a bigger (length: 1,550 mm, height: 240 mm, wingspan: 510 mm, gap size: 150 × 150 mm, weight: 35 kg).

7.2.1.3 Bed Material

The sampling of the bed material is usually achieved with a bucket-sampler. Because armouring of the riverbed is to be expected on the river Drava, the edge of the sampler was sharpened to facilitate its penetration into the riverbed (length: 535 mm, diameter: 180 mm, weight: 9 kg).

7.2.2 *Processing of Samples*

The grain size distributions of bedload and bed material were determined using Taylor sieves—separating fractions (0.063; 0.125; 0.25; 1.0; 2.0; 4.0; 8.0; 12.0; 16.0; 24.0; 32.0; 48.0; 63.0; 96.0; 125.0 mm) or by settling velocity method—separating fractions (>0.10 mm; 0.05–0.10 mm; 0.02–0.05 mm; 0.01–0.02 mm; 0.005–0.01 mm; <0.005 mm). Drying was carried out at 105 °C. After that, dry matter content measurement (analytical precision) was done. In a case when the ratio of fractions with diameters less than 0.15 (0.1) mm is higher than 10%, hydrometry method must be used to establish the grain size distribution.

For suspended load, which is usually contained in about 5L water samples, the first important step is to measure the exact amount of the sample, to know from how much water we will measure sediment concentrations. The samples are then left to settle. When the sediment settles in the bottom of the containers, the excess water is carefully sucked from the containers and approximately 0.5L is left. The amount of clean water removed is precisely measured and recorded in the protocol. The samples are dried in electronic oven for 24 h at 105 °C temperature. Then, we measure the weight of each sample and its dry matter content on a precision scale. Concentration is calculated as

$$C_{\mathrm{ss}} = \frac{m_{\mathrm{d}}}{v_{\mathrm{s}}},$$

where

m_{d} dry matter weight and
v_{s} total volume of the sample

In the case of suspended load, too small a grain size for screening, the grain size determination is done with a special Atterberg-type settling device, which is operating on the principle of the Stokes equation. The main part of the settling velocity meter is a cylindrical glass tube with an inner diameter of 35–40 mm. There are six level markings on the tube. On the bottom of the tube, there is a stricture and a tap. It ends in a ca 4 mm diameter rider. On the top of the tube, there is a funnel with a throttle. With the throttle open, the tube is filled up with distilled water, and the sample is also poured into the tube through it. There is a vent in the axis of the throttle, connected with a 0.1–0.2 mm diameter nozzle, to secure that outflow velocity does not exceed 0.2–1 cm s^{-1}. The tube has to be mounted on a stand with its axis vertical.

Before filling the samples in the tubes, we leave them dissolve in aqueous solution of sodium metasilicate to avoid coagulation. Then we fill the tubes with sodium metasilicate solution and we pour the samples into it. The grain size fractions are <0.10 mm; 0.10–0.05 mm; 0.05–0.02 mm; 0.02–0.01 mm; 0.01–0.005 mm and >0.005 mm. The grain size distributions of the different samples can be drawn up as percentages from the data as a distribution curve. We read the values of d_m, d_{eff}, d_g, d_{10}, and d_{60} from the diagram and we calculate U unevenness factor ($U = d_{60}/d_{10}$), according to the Hungarian measurement standard.

7.2.3 Analyses

Concentrations of suspended load and grain size distribution curves of suspended sediment, bedload and bed material were determined from each sample. Total yields were estimated if a simultaneous discharge measurement was available.

For a better description of sediment transport processes, we determined the correlation between discharge and suspended sediment concentration. In this, all available sampling results were used (2004–2016) and the Barcs station, with the longest time series, was selected as an example.

Altogether the data of five cross-sections were used, out of which in the upstream four the data of some formerly executed repeated discharge measurements and sediment samplings from the period 1998–2002 were available (VITUKI 2003). In this case, comparative analyses to detect eventual changes were also carried out.

7.3 Results

7.3.1 Suspended Load

Suspended load in the river is highly dependent on the water regime, and is highly changeable. At Barcs, suspended sediment yield ranged from 697 to 35,5016 g s^{-1} (n = 70), while at Drávaszabolcs from 1,298 to 124,481 g s^{-1} (n = 70) in the period from 2004 to 2016. At Botovo, the measured values fell between 1,029 and 137,095 g s^{-1} (n = 45), According to the findings of the detailed analyses in 2012, the suspended load (or concentration) of the river was increasing from Botovo downstream. The increase was even more prominent from Barcs to Drávaszabolcs, then, until Belišće (54 fkm) it decreased a little, and almost equalled to the values measured at Barcs. The growth of the suspended sediment load can probably be attributed to the nearby location of the Croatian Hydropower Plant at Donja Dubrava, the reservoir of which entraps the majority of the arriving suspended sediment, thus forwarding a relatively clear, sediment-free flow downstream the dam. Because of the relatively high deficit in the sediment transport capacity, the suspended sediment is entrained from the bed. Upstream of Barcs, however, bed material is mainly gravel and the process is limited by the low ratio of fine fractions in the bed material. Downstream Barcs bed material is finer and a larger amount of sand can be taken into suspension, increasing the concentration rapidly. A little more downstream the sand riverbed starts to widen, which results in sediment deposition and the decrease of the concentration of suspended load.

In 2003, the average of the grain size diameter of the suspended sediment was 0.058 mm at Botovo (227.5 river km), and practically the same: 0.06 mm at Bélavár (198.5 rkm) in 1999, when sampling was performed on the recession of a floodwave. At Barcs (154.1 rkm) 0.105 mm and at Drávaszabolcs (78 rkm) 0.15 mm was recorded, which means that the grain size of the suspended load was indeed increasing downstream. A possible explanation for this phenomenon can be that on the two upstream stations the sediment supply is source-limited for two reasons. The same reasons described above explaining the changes in concentrations can be attributed for the changes in grain size parameters as well: the settling of suspended load in the reservoirs, and the relatively large grain size of bed material, from where the river cannot bring fine fractions into suspension, even at high velocities (VITUKI 2003) (Fig. 7.1).

Based on the measurements carried out in 2012, we can conclude that the grain size distribution of the suspended load on the investigated Drava reach became rather homogeneous and did not change much along the river (Fig. 7.2).

The average diameter of the suspended load seemed to have decreased since 2003, but, considering the relatively low discharges at the time of the 2012 sampling (between 356 and 706 $m^3\ s^{-1}$), and the grain size distribution of the later measurements until 2016, the change in the diameter is not significant. In the latest samplings the average diameter ranged from 0.1 to 0.17 mm at Barcs and

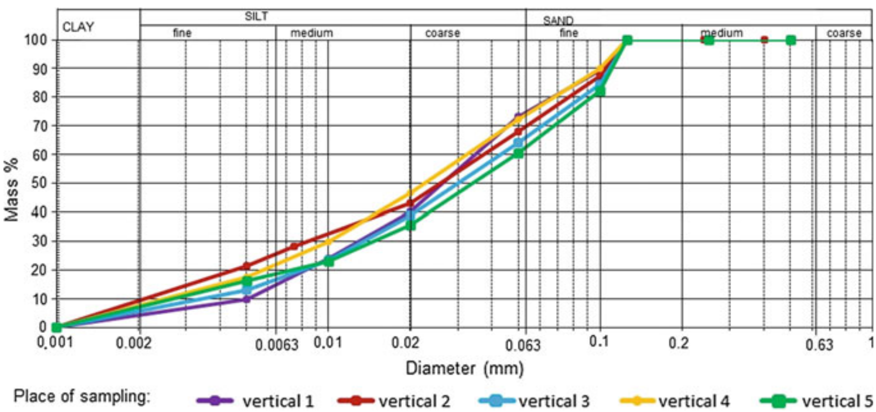

Fig. 7.1 Typical grain size distribution of suspended load of the Drava river at Barcs (29.08.2012)

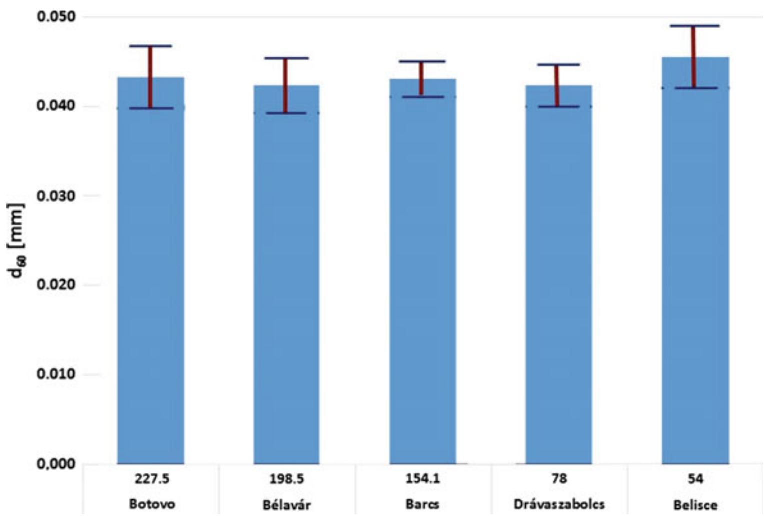

Fig. 7.2 Average grain size of the suspended sediment along the Drava river in 2012 (with standard deviation)

0.12–0.17 mm at Drávaszabolcs during a relatively high discharge, which correspond to the values determined in 2003 (Fig. 7.1).

7.3.2 Bedload and Bed Material

The bedload of the Drava river downstream of Botovo is seemingly very changeable, but this phenomenon can be attributed to the periodic armouring of the riverbed, which can make it very stable. Depending on the water regime, the process lasts from a few days to some weeks. The armour layer resists the flow and prevents particles from being washed away from the surface of the riverbed. At Barcs, bed material is finer and the armouring process is no more prevalent. Thus, here bedload transport is higher, as well as at Drávaszabolcs. The widening of the riverbed on the lower slope reaches until Belišće causes a decrease in bedload transport similarly to suspended load concentrations.

The variation in average grain sizes of bedload samples does not allow well-based conclusions. As bedload sampling was only performed on three occasions in both sampling periods, there are insufficient data available for detailed analyses. At the two upstream sections, the grain size distributions of bed material are very similar. Grain sizes are much larger than at the lower three which are on the sand-bed reach of the river. Bedload and bed material grain sizes are very similar.

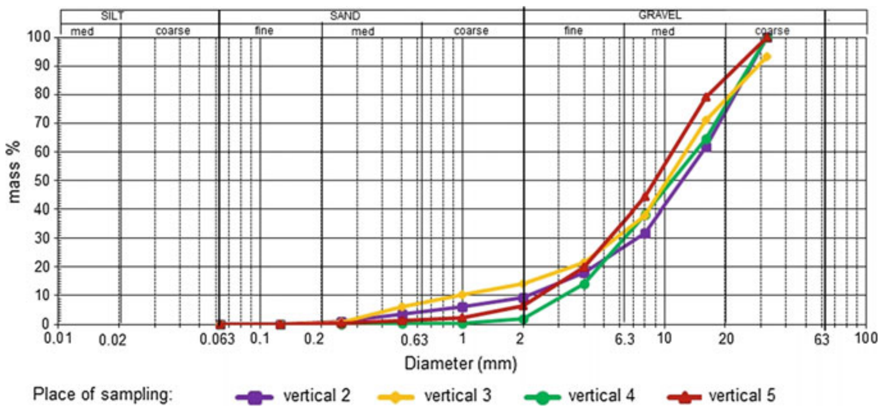

Fig. 7.3 Typical grain size distribution of bed material at Botovo (08.05.2012)

The shapes of the grain size distribution curves at Botovo indicate that there is a constant riverbed erosion process going on and armouring is predominant (Rákóczi et al. 2012) (Fig. 7.3).

At Bélavár, armouring is less developed, and can only be observed near the right bank (vertical 5). In all the other verticals no significant erosion or deposition is shown by the bed material. Dynamic equilibrium is assumed (Fig. 7.4).

More downstream, where the slope of the river considerably decreases, sand becomes dominant in bed material. At Barcs, depending on the water regime, fine and medium gravel can also be observed, but amounting to less than the half of the samples, usually below 20%. At Drávaszabolcs and Belišće medium sand prevails in the composition of bed material, and gravel can be seldom observed. These two latter sections show a near-equilibrium riverbed (Rákóczi et al. 2012) (Fig. 7.5).

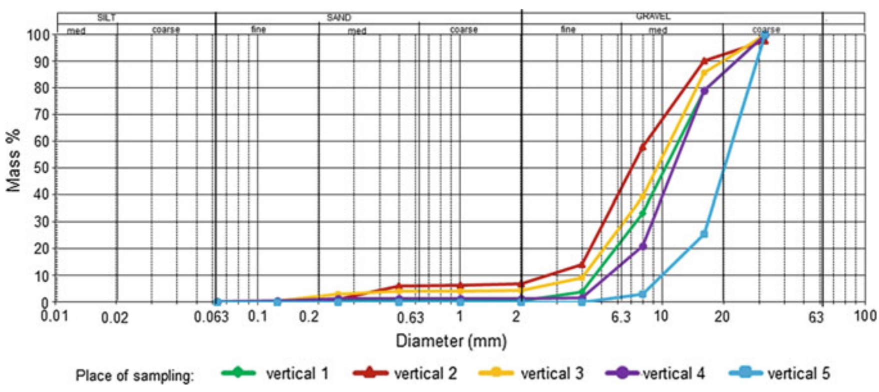

Fig. 7.4 Typical grain size distribution of bed material at Bélavár (09.05.2012)

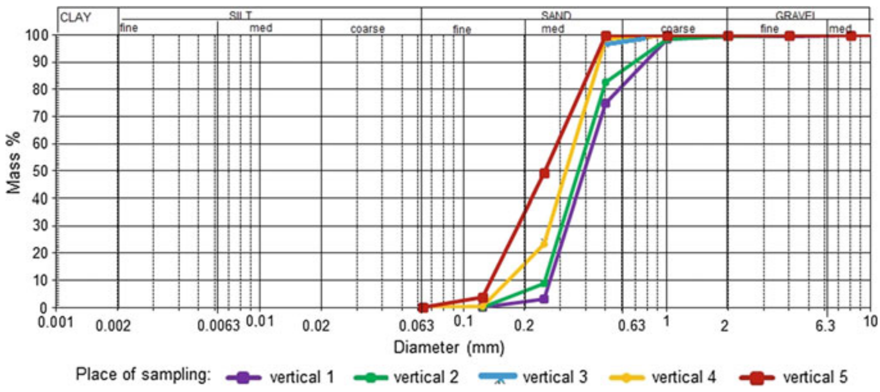

Fig. 7.5 Typical grain size distribution of bed material on the lower reaches (30.08.2012)

The grain size distributions of bedload and bed material are similar. At the upstream two sections, where gravel is predominant, average grain sizes are between 9.5 and 12.8 mm, at Barcs, between 2 and 3 mm, at Drávaszabolcs between 0.4 and 0.5 mm and at Belišće around 0.3 mm (Fig. 7.6).

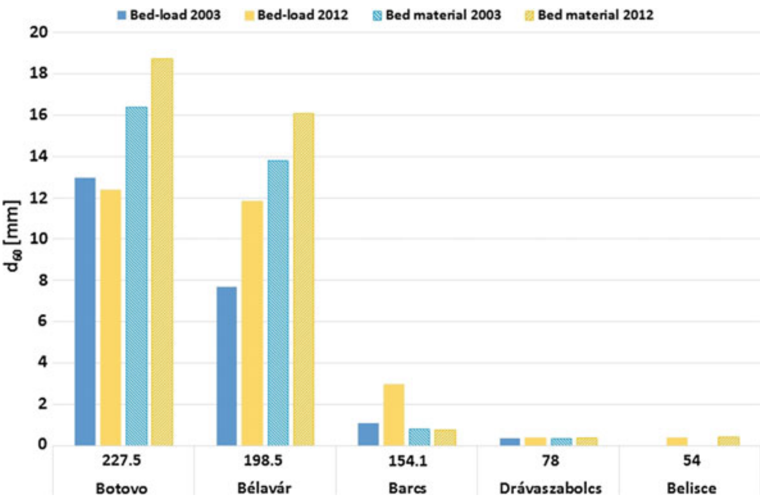

Fig. 7.6 Bedload and bed material grain sizes along the Drava river in 2003 and in 2012

7.3.3 Connections Between Discharge and Sediment Transport

Establishing mathematical correlation between discharge and sediment load makes it possible to assess the change in sediment regime if discharge changes (Gilja et al. 2009). However, as sampling requires human presence and is a rather resource-demanding procedure, data are scarce and connections are not very well correlated, especially at high stages/discharges (Fig. 7.7).

The number of sediment samplings over the investigated period is relatively low and does not cover the high waterlevel range sufficiently to establish a reliable correlation between sediment concentration (or sediment load) and discharge. Sediment sampling during high discharges cannot only be difficult because of the lack of resources. As floodwaves are usually short, the time interval between flood forecast and the occurrence of the peak waterlevels is sometimes too short to organize these complex measurements. It is also to be noted that navigating and anchoring a measurement boat on the Drava river during high waterlevel can also be dangerous or even impossible because of the high velocities, especially on the upstream reach (Rákóczi et al. 2012).

Despite the low number of data, the division of the time series into shorter time periods suggests a certain increase in the suspended load concentrations (quantities), especially in the higher discharge ranges. However, the trend cannot be proven significant; in order to establish it a reliable database of sediment measurements would be needed in the future (Fig. 7.8).

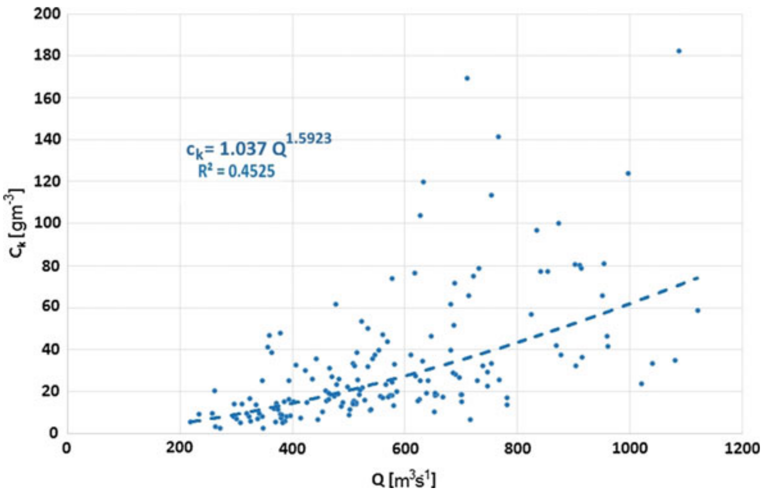

Fig. 7.7 Suspended load concentration plotted against discharge at Barcs, 1991–2016 (n = 164)

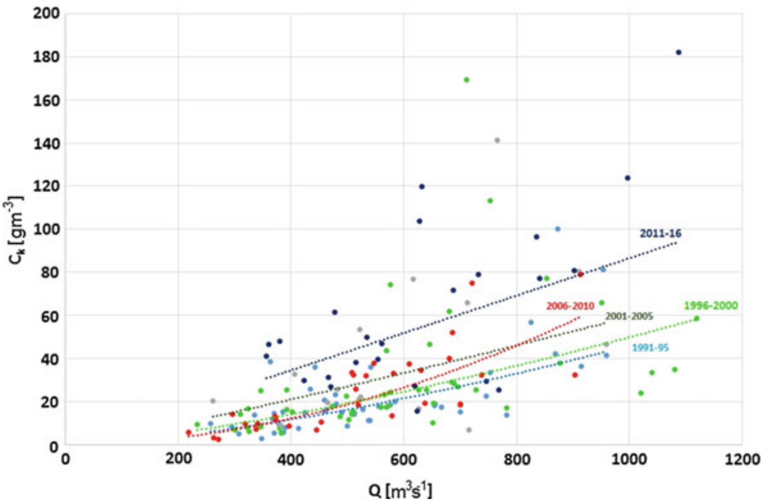

Fig. 7.8 Suspended load concentration plotted against discharge at Barcs, 1991–2016 (n = 164) divided into time periods

7.4 Conclusions

According to several authors, sediment transport of the Drava is supply-limited downstream of reservoirs, but a more thorough investigation is needed to describe the phenomenon correctly and to predict its future consequences. However, we found evidence of riverbed erosion on the lower reach, supporting the statement that the construction and operation of three Croatian dams and their reservoirs are mainly responsible for the downstream deficit of suspended sediment yield. On the upstream reach, intensive armouring of the riverbed is observed, which also needs a more detailed future investigation, with particular emphasis on the collection of a more detailed set of field data (e.g. thickness of the sand layer over the armoured gravel bed) in order to be able to evaluate the ongoing processes using the newest methodological findings (e.g. Kuhnle et al. 2017). Climate change and/or variability as well as other anthropogenic influences (material excavation) could be additional reasons for these phenomena (Bonacci and Oskoruš 2010; Rákóczi et al. 2012).

Today the goal of the sediment sampling is not only to describe sediment transport in the flow, but further to provide calibration and validation data for numeric modelling. Sediment measurements are different in the different countries in Europe (Schwarz et al. 2008). Methodologies and samplers vary, both for field and laboratory analyses. Even in Hungary, sampling and laboratory techniques have been modified several times in the past. Also, sediment sampling was never really systematic, and the sampling campaigns did not follow the hydrological processes. That is why sediment data can hardly be compared. The data series are inhomogeneous and cannot be statistically analyzed. Sampling has to be carried out as to be able to obtain a true picture about the changes of sediment transport across the flow, along the flow and with respect to variability with depth. The sampling points have to be determined based on morphological and flow conditions. Discharge measurement has to be executed in parallel to sediment sampling. For a few years, water autorities in both Hungary and Croatia have been using Acoustic Doppler Current Profilers (ADCP) for the measurement of the discharge. This opens up new possibilities for future analyses. Despite this fact, we still have to emphasize that the availability of hydromorphological data is extremely important for assessments under the Water Framework Directive, also to support ecological status evaluation. However, the lack of information on some large rivers, including the Drava, is evident. The changes in the hydrological and sediment regime of river systems induced by hydromorphological alterations are not well understood, so in the near future there is an urgent need for a harmonised database (Schwarz 2008 and Chap. 5). To this end, the first step is to intensify and reorganize hydromorphological monitoring, including sediment sampling and data management.

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