ASSESSING SEDIMENT REGIME ALTERATION OF THE LOWER DRAVA RIVER

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Abstract: Alterations to the sediment regime of the lower Drava River were assessed using the rescaled adjusted partial sums (RAPS) method and possible causes of these changes are discussed in this paper. The sudden alteration to sediment regime and the sharp decreases of suspended sediment concentration (SSC) at the two gauging stations in the lower Drava River began in the 1980s. Suspended sediment load decreased about 65% between 1967–1981 (0.922×10^6 t/year) and 2003–2017 (0.323×10^6 t/year) for the Botovo station. For the Donji Miholjac station, suspended sediment load decreased about 81% between 1971–1981 (1.383×10^6 t/year) and 2007–2017 (0.263×10^6 t/year). The construction and operation of reservoirs were the main reasons for these sharp alterations. SSC and flow discharge (Q) relationships were assessed by proposing a new form of a sediment rating curve (SRC). Compared with the traditional SRC approach, the new form of the SRC can better capture seasonal dynamics of SSC at daily and monthly time-scales.

Keywords: sediment load; flow discharge; reservoir operation; sediment rating curve; Drava River (Croatia)

PROCJENA PROMJENA REŽIMA SUSPENDIRANOG NANOSA NA DONJEM TOKU RIJEKE DRAVE

Sažetak: Promjene režima suspendiranog nanosa na donjem toku rijeke Drave izučavani su primjenom metode RAPS (Rescaled Adjusted Partial Sums). Rezultati analize pokazali su da je do nagle promjene režima nanosa i smanjenja koncentracije suspendiranog nanosa (SSC) na dvije vodomjerne postaje na rijeci Dravi došlo početkom osamdesetih godina dvadesetog stoljeća. Pronos suspendiranog nanosa na postaji Botovo smanjen je u razdoblju 2003. - 2017. (0.323×10^6 t/god) u odnosu na prethodno razdoblje 1967. - 1981. (0.922×10^6 t/god) za oko 65%. Pronos suspendiranog nanosa na postaji Donji Miholjac smanjen je u razdoblju 2007. - 2017. (0.263×10^6 t/god) u odnosu na prethodno razdoblje 1971. - 1981. (1.383×10^6 t/god) za čak oko 81 %. Glavni razlog smanjenja je izgradnja akumulacija za potrebe rada tri hidroelektrane u Hrvatskoj. Odnos između SSC i protoka (Q) korišten je za izradu krivulje pronosa suspendiranog nanosa (SRC) u novim uvjetima. Analize ukazuju da su SRC u novim uvjetima osjetljivije na sezonsku dinamiku od onih u prethodnom razdoblju.

Ključne riječi: pronos suspendiranog nanosa; protok vode; akumulacija; krivulja pronosa suspendiranog nanosa; Rijeka Drava (Hrvatska)

1 INTRODUCTION

Suspended sediment concentration (SSC) and sediment load are important characteristics in river geomorphology and are closely related to the geological settings of river systems [1-3]. Since suspended sediment carries contaminants, including phosphorus and heavy metals [4, 5], it affects the water quality of rivers [6]. Additionally, suspended sediment impacts light attenuation in waterbodies, which further influences the development of aquatic communities [7-9]. Thus, the assessment of SSC and sediment load is of great significance for sustainable management of river systems.

In the past few decades, with the impacts of anthropogenic activities, including damming [10-13], land use change [14, 15], and climate change [11, 14], sediment regime in many rivers has been dramatically altered. For example, Dai et al. [16] found that dam construction and bank reinforcements along the Yangtze River resulted in a decline in SSC delivered by the Yangtze River into the East China Sea. The change of sediment regime in rivers may cause serious consequences, including the prevention of burrowing benthos from finding suitable habitats [17] and negative impacts on delta evolution [18]. Therefore, understanding how sediment regime has changed under complex conditions is very important.

The Drava River is one of the largest tributaries of the Danube River. It originates in Italy, crosses Austria, Slovenia, Hungary and Croatia, and finally joins the Danube River downstream of Osijek, Croatia (Figure 1). Previously, Bonacci et al. [19], Bonacci and Oskoruš [20], and Tadić and Brleković [21] analyzed the hydrological regime of the lower Drava River. Additionally, Bonacci and Oskoruš [22], and Tamás [23] analyzed human impacts on water regime in the lower Drava River, and sediment transport in the Drava River, respectively. In the current study, long term observation data were used to assess sediment regime in the lower Drava River, which allows explanation of the processes of river evolution. Furthermore, models were developed to estimate SSC and flow discharge (Q) relationships at different time-scales; such relationships can be used to inform river management and for designing restoration. Since the Drava River is a large tributary of the Danube River, the results in this study can also be used to inform river management in the Danube River basin.

2 MATERIALS AND METHODS

2.1. Study area

In this study, the lower Drava River, between Slovenian and Croatian state boundaries, was evaluated. Daily Q and SSC from two gauging stations (Botovo and Donji Miholjac) were analyzed (Figure 1; data provided by the Croatian Meteorological and Hydrological Service). SSC data were obtained from daily water samples taken from one point (close to the riverbed in water gauging profile). These samples were taken at the same hour every day. Because both sampling sites (Botovo 28 km; Donji Miholjac 178 km) are far from the downstream reservoir Dubrava, possible effects of the operation of Hydro Electric Power Plants (HEPP was minimized. Each sample was poured through a 0.45 μm thick filter paper (320 mm diameter Munktell filter paper). Daily Q was calculated from hourly values based on hourly measurements of water level (WL). The WL-Q RK method was used for hourly calculations of Q. The defined RK varied over time due to morphological changes of the river bed. Consequently, many rating curves were calculated, but only two RK examples per station are presented herein: the newest one, and one in 2009 (Figure 2). The main characteristics of the two gauging stations, including distance from the river mouth, basin area, elevation and the available data period are summarized in Table 1. Table 2 presents the detailed information of three hydroelectric power plants (HEPP) constructed in the lower Drava River. Figure 3 presents the daily SSC and Q time series for the two gauging stations. Table 3 summarizes the statistics of the daily SSC and Q. Q of the two stations generally followed the same temporal pattern with Botovo station having higher extreme values in the flood season (Table 3). Difference of annual mean value of Q between the two stations was small since there were no large tributaries between Botovo and Donji Miholjac. The standard deviations of SSC data were much greater than the averages, which indicates a very big scatter (Table 3) or can also indicate incoherence of the sampling methods used. SSC of the two stations presented large difference, especially during the flood season (Figure 3).

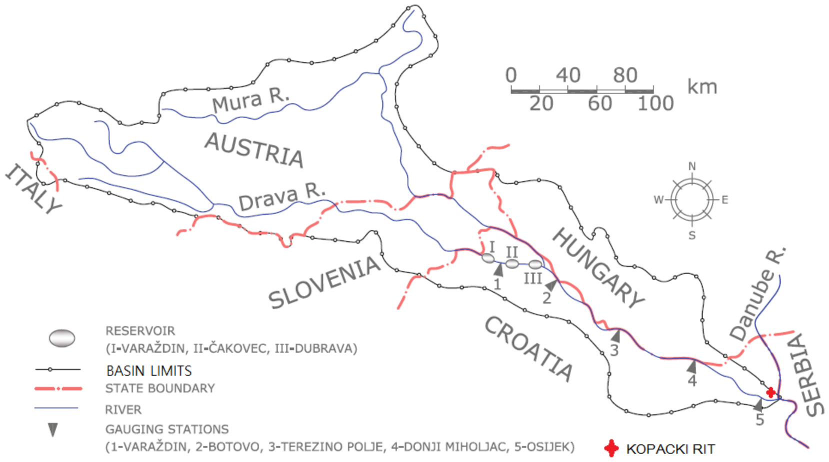

Figure 1 Location maps of the Drava River, with positions of five gauging stations and three HEPP (I-HEPP Varaždin; II-HEPP Čakovec; III-HEPP Dubrava) [20]

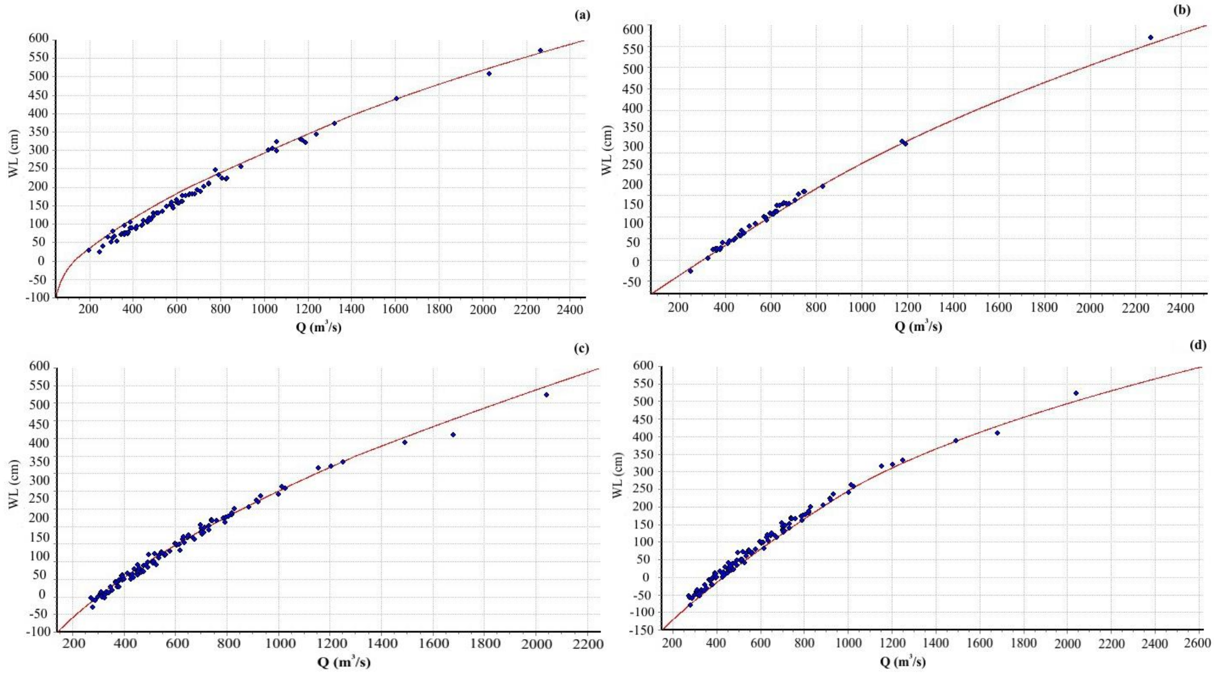

Figure 2 The WL-Q RK relationships for each station: (a) Botovo 2009, (b) Botovo 2017–2019, (c) Donji Miholjac 2009, (d) Donji Miholjac 2017–2019

Table 1 Main characteristics of the two gauging stations in the lower Drava River

Station name	Distance from the mouth (km)	Basin area (km^2)	Elevation (m a. s. l.)	Observation period
Botovo	227	31.038	121.55	1967–2017
Donji Miholjac	80.5	37.142	88.57	1971–2017

Table 2 Main characteristics of the three hydroelectric power plants (HEPP) in the lower Drava River

HEPP	Varaždin	Čakovec	Dubrava
Start of operation (year)	1975	1982	1989
Installed discharge (m^3/s)	450	500	500
Mean power generation (GWh/year)	476	400	385
Reservoir volume (10^6 m^3)	8.0	51.0	93.5
Reservoir water surface (km^2)	3.0	10.5	16.6
Maximum water level in the reservoir (m a. s. l.)	191.0	168.0	149.6

Table 3 Summary statistics of the daily data sets

Statistical parameters	Botovo		Donji Miholjac	
	Q (m^3/s)	SSC(mg/L)	Q (m^3/s)	SSC (mg/L)
X_{mean}	490.43	23.74	513.22	29.33
X_{max}	2630	701	2281	891
X_{min}	103	0.03	166	0.01
Sx	241.66	31.39	236.10	40.34
Cv	0.49	1.32	0.46	1.38

Note: X_{mean}, mean; X_{max}, maximum; X_{min}, minimum; Sx, standard deviation; Cv, coefficient of variation

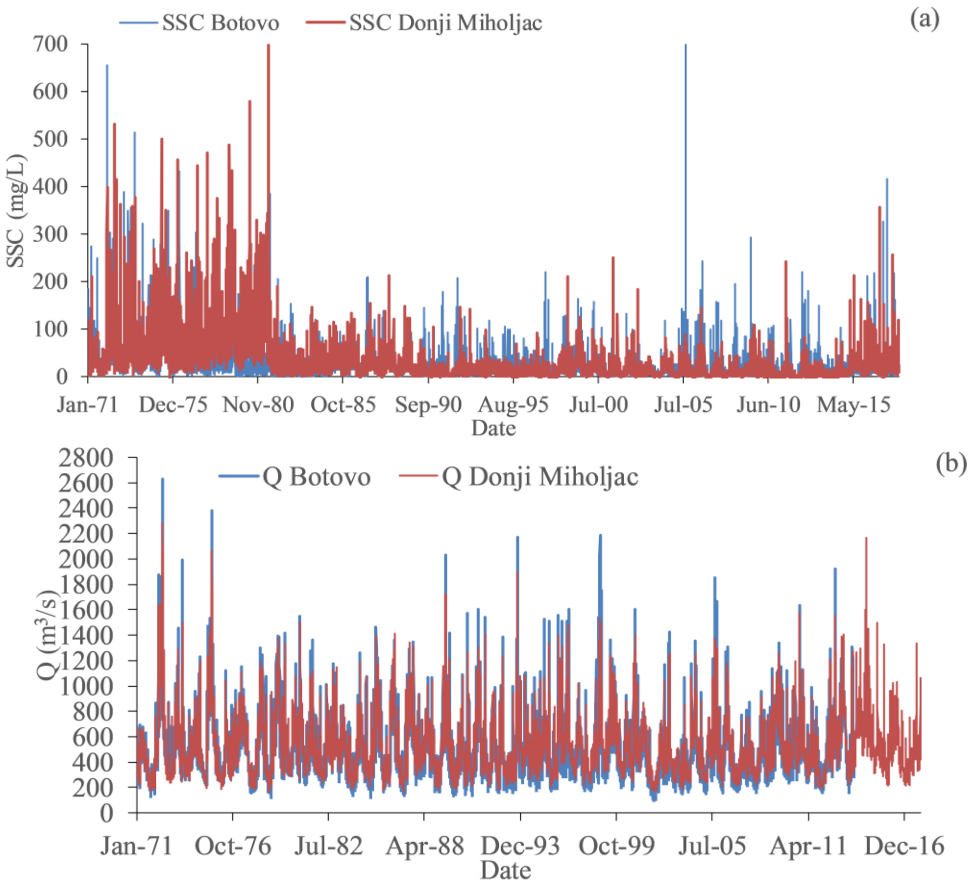

Figure 3 Time series of daily SSC and Q for the two gauging stations: (a) SSC and (b) Q

2.2 Methods

To detect and quantify trends and fluctuations in sampled time series, the widely used rescaled adjusted partial sums (RAPS) method [20, 24-26] was employed in this study. The RAPS method can highlight trends, shifts, data clustering, irregular fluctuations, and periodicities in the time series [24], which can be defined by:

$$RAPS_i = \sum_{n=1}^{i} \frac{T_n - T_m}{S_T} \quad (1)$$

where T_m is the mean value of the time series, S_T is the standard deviation, T_n is the value of a sample, and n=1, 2…, N, N is the number of values in the time series.

To quantitatively analyze SSC-Q relations at daily and monthly time-scales, the widely used sediment rating curve (SRC) was employed. The SRC was used to regress sediment load, in particular SSC in river systems, from Q [27-30]. Normally, a power equation is used:

$$SSC = aQ^b \quad (2)$$

where a and b are regression coefficients. In the SRC method, the coefficients a and b are constants without physical significance; however, some researchers still attribute meaning to them, relating them to the severity of erosion and transport processes [27, 30].

2.3 Model performance index

Model performances were evaluated using the following two indicators: the coefficient of correlation (R) and the root mean-squared error (RMSE):

$$R=\left[\frac{\frac{1}{n}\sum_{i=1}^{n}(O_i-O_m)(P_i-P_m)}{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i-O_m)^2}\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i-P_m)^2}}\right] \tag{3}$$

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i-P_i)^2} \tag{4}$$

where n is the number of data samples, O_i and P_i are the observed and predicted values. O_m and P_m are the average values of O_i and P_i.

3 RESULTS AND DISCUSSION

3.1 Variations of Q, SSC, water level, and suspended sediment load

Figure 4 presents temporal variations of RAPS values for annual averaged Q, SSC and the amount of suspended sediment at the two gauging stations. For Botovo station, a sharp drop of Q, SSC and suspended sediment load began from 1982 (Figure 4(a)), thereby dividing the time series into two sub-periods: the first from 1967 to 1981, and the second from 1982 to 2017. Interestingly, with the decrease of Q, SSC and suspended sediment load, the water level (WL) began to increase (Figure 4(a)), which clearly indicates a change to the river bed [22]. Figure 5 shows the relations of Q and WL at Botovo station for the two sub-periods, 1967–1981 and 1982–2017. Before 1982, WL was linearly correlated with Q (R^2=0.96), indicating a stable river bed during this period (Figure 5(a)). The linear correlations between WL and Q became weak (R^2=0.50) for the second sub-period. Seasonal dynamics of SSC and Q were further assessed through the climatological year, which was defined by averaging for each day of the year all measurements available over the observation period for that specific day [31]. For the two sub-periods, peak values of SSC and Q were both apparent during the summer period (Figure 6). In the first sub-period (1967–1981), SSC correlated well with Q (R^2=0.80) with a power function (Equation (2)). However, for the second sub-period (1982–2017), the correlation between SSC and Q became weak (R^2=0.62). Monthly averaged SSC and Q in the period 1967–1981 exhibited similar seasonal characteristics (Figure 7). However, monthly averaged SSC and Q in the period 1982–2017 exhibited different seasonal patterns after August (Figure 7). Notably, the average monthly mean SSC value in the flood season during the period 1982–2017 was even smaller than that in the dry season during the period 1967–1981.

For Donji Miholjac station, a sharp decrease of SSC and suspended sediment load also began in 1982 (Figure 4(b)), dividing the time series into two sub-periods: the first from 1971 to 1981, and the second from 1982 to 2017. However, Q and WL did not exhibit a clear trend. For Donji Miholjac station, WL was linearly correlated with Q (R^2=0.95), indicating a stable river bed in these 47 years (Figure 8). When expressed on a climatological year, both SSC and Q were concentrated in the summer period during the flood season (Figure 9). Additionally, for the first sub-period (1971–1981), high SSC values were observed in spring and SSC was poorly correlated with Q (R^2=0.38) with a power function (Equation (2)). However, for the second sub-period (1982–2017), the correlation between SSC and Q became stronger (R^2=0.56). Monthly averaged SSC in both periods exhibited seasonal characteristics, following the pattern of Q (Figure 10). Notably, the average monthly mean SSC value in the flood season during the period 1982–2017 was far smaller than that in the dry season during the period 1971–1981.

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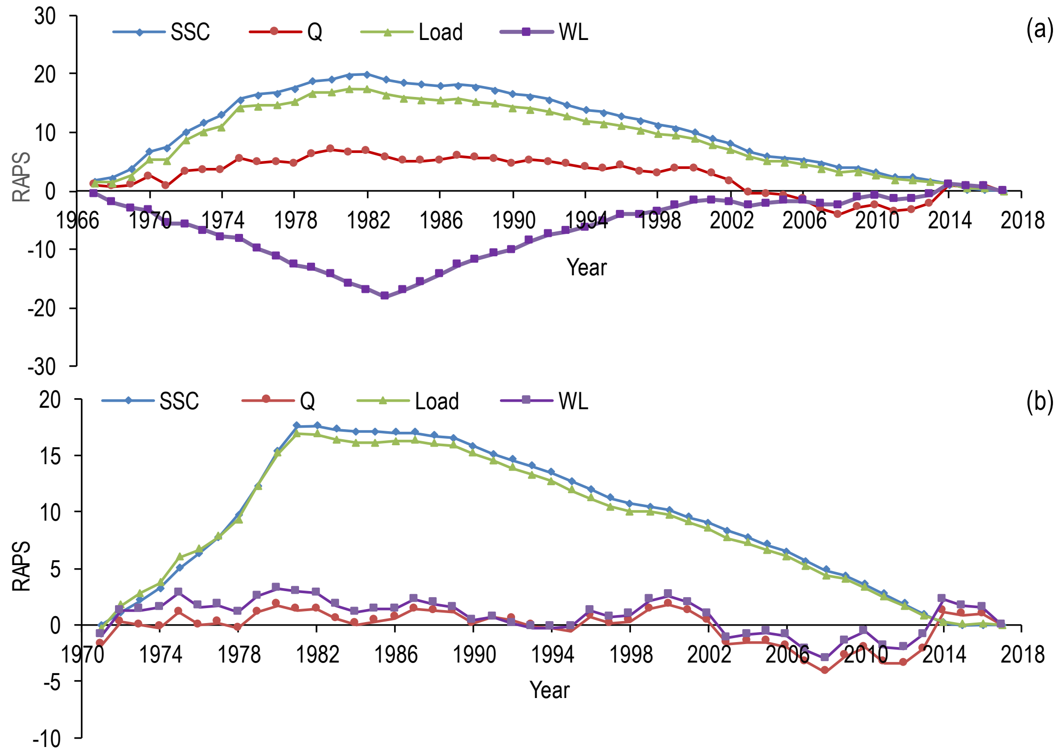

Figure 4 Temporal variations of RAPS values for annual averaged Q, SSC, WL, and suspended sediment load at the two gauging stations: (a) Botovo and (b) Donji Miholjac

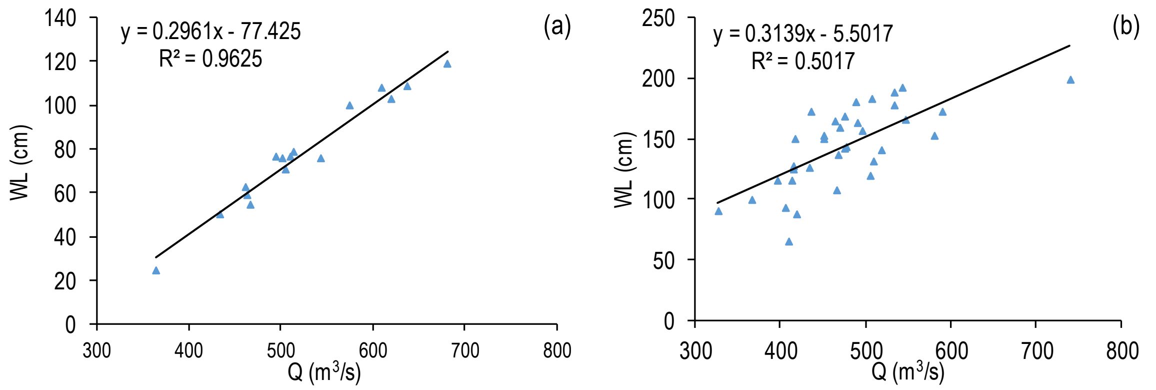

Figure 5 Flow discharge and water level relations at Botovo station: (a) 1967–1981, (b) 1982–2017

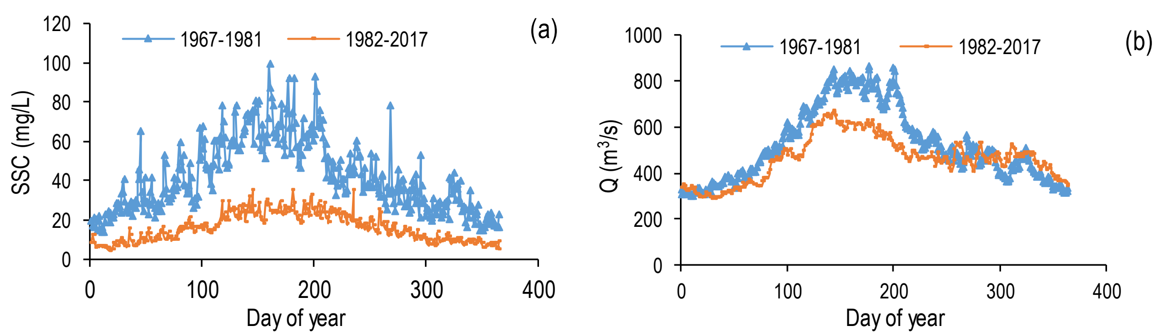

Figure 6 Seasonal variations of daily averaged SSC (a) and Q (b) at Botovo station for the climatological year

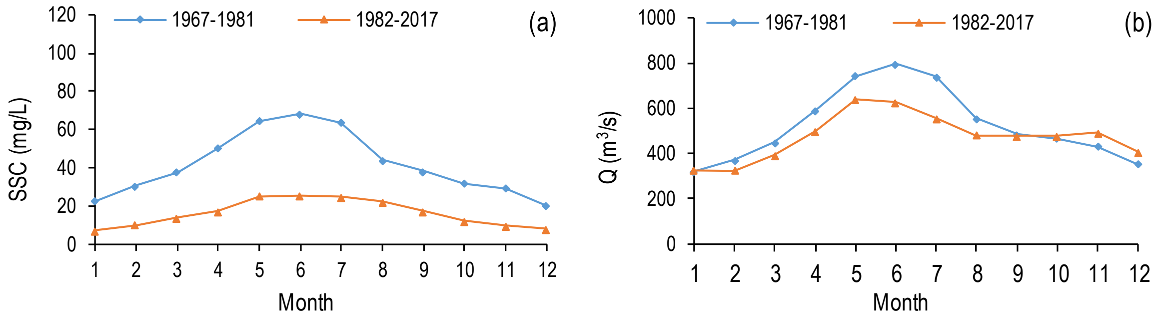

Figure 7 Monthly averaged SSC (a) and Q (b) at Botovo station

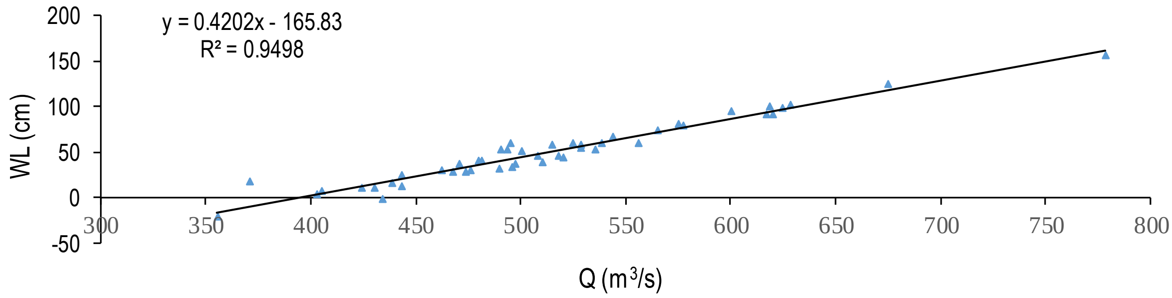

Figure 8 Flow discharge and water level relationship at Donji Miholjac station

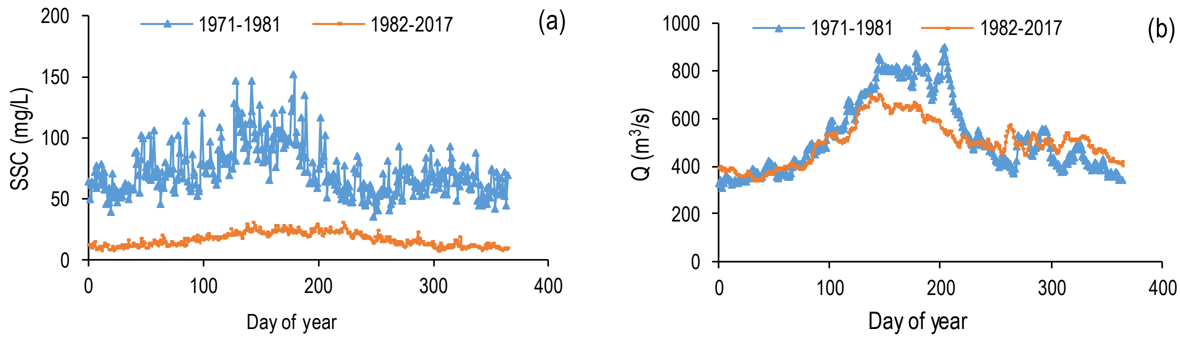

Figure 9 Seasonal variations of daily averaged SSC (a) and Q (b) at Donji Miholjac station for the climatological year

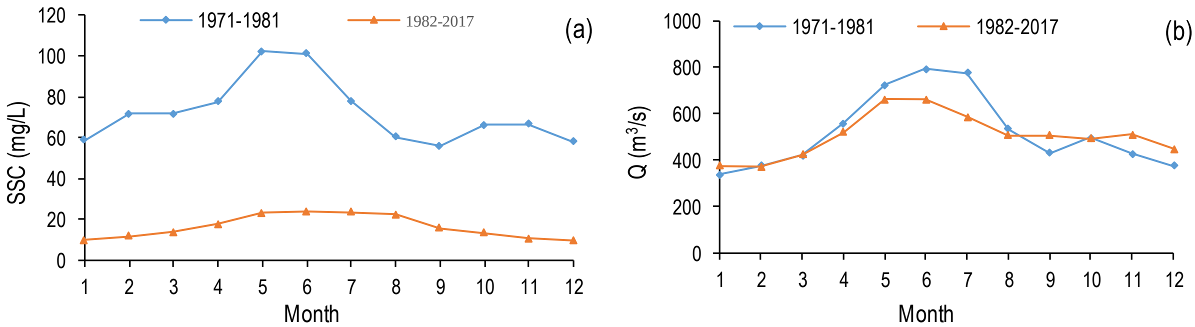

Figure 10 Monthly averaged SSC (a) and Q (b) at Donji Miholjac station

The sudden alteration of sediment regime and the sharp decreases of SSC at the two gauging stations in the lower Drava River began from the 1980s. Suspended sediment load decreased about 65% from 1967–1981 (0.922×10^6 t/year) to 2003–2017 (0.323×10^6 t/year) for the Botovo station. For the Donji Miholjac station, suspended sediment load decreased about 81% from 1971–1981 (1.383×10^6 t/year) to 2007–2017 (0.263×10^6 t/year). In previous studies, in the time series of many climate-related variables (e.g. Q, WL, and water temperature), a rather sudden change, or an inflection point, had been observed around the mid-1980s [19-21, 32-35]. Results of the current study further confirmed this conclusion. Based on the operating times of the three reservoirs in the lower Drava River (Table 2), it can be concluded that the sharp decreases of SSC and sediment load are greatly impacted by the construction and operation of reservoirs. In addition, the management of about 80 km of the lower Drava River bed and the adjacent catchment from the 1980s by "river training" measures, also plays an important role [22]. Regional climate change as well as other anthropogenic influences (i.e. material excavation) could be additional reasons for this decreasing trend [20]. Kopački Rit is located at the confluence of the Drava River and the Danube River. It is one of the most important and well-preserved natural wetlands in Europe. Compared to the wetland area of 37 000 ha that existed in the 18th century, there has been a substantial reduction of flood retention capacity along the left bank, downstream to Osijek, which may have been caused by the regulation works employed to deal with the sharp decreases of SSC and sediment load from the Drava River to the Danube River [22]. This issue may bring serious consequences, which should be considered.

3.2 Modeling of SSC and Q relationships

Figure 11 shows the correlation coefficients between monthly averaged SSC and Q for each year at the two gauging stations. For Botovo station, in 84% of cases, the correlation coefficients between monthly averaged SSC and Q in each year exceeded 0.6, which indicates that using Q for regression of monthly averaged SSC is generally fine at this station. However, at the Donji Miholjac station, only 66% of the correlation coefficients between monthly averaged SSC and Q in each year exceeded 0.6, and in some years, the correlation coefficients were lower than 0.0, indicating that using Q for regression of monthly averaged SSC may not be appropriate at this station. The difference is probably linked with the spatial and temporal dynamics of the anthropic pressures in the river channel and the associated channel processes. The management of about 80 km of the lower Drava River bed and the adjacent catchment by "river training" measures [22] greatly altered the sediment regime at the Donji Miholjac station. Using the traditional SRC method, the regression formulae were derived for each gauging station at monthly intervals, to give:

$$SSC=0.006Q^{1.34} \quad R=0.65 \quad RMSE=15.69 \text{ (Botovo)} \tag{5}$$

$$SSC=0.189Q^{0.89} \quad R=0.29 \quad RMSE=29.70 \text{ (Donji Miholjac)} \tag{6}$$

The result of Botovo station was acceptable (R=0.65, RMSE=15.69 mg/L). However, for Donji Miholjac station, the result was poor (R=0.29, RMSE=29.70 mg/L). In order to improve modeling performance, SSC was regressed using the SSC from the previous month (SSCt-1), and Q in the same month (Q_t). The results of the new regression were far better, with larger R and lower RMSE values. For both stations, R values exceeded 0.8 and RMSE values decreased significantly, especially for the Donji Miholjac station:

$$SSC_t = 0.541SSC_{t-1}+0.0005Q_t^{1.6} \quad R=0.80 \quad RMSE=12.32 \text{ (Botovo)} \tag{7}$$

$$SSC_t = 0.836SSC_{t-1}+0.0005Q_t^{1.453} \quad R=0.866 \quad RMSE=15.52 \text{ (Donji Miholjac)} \tag{8}$$

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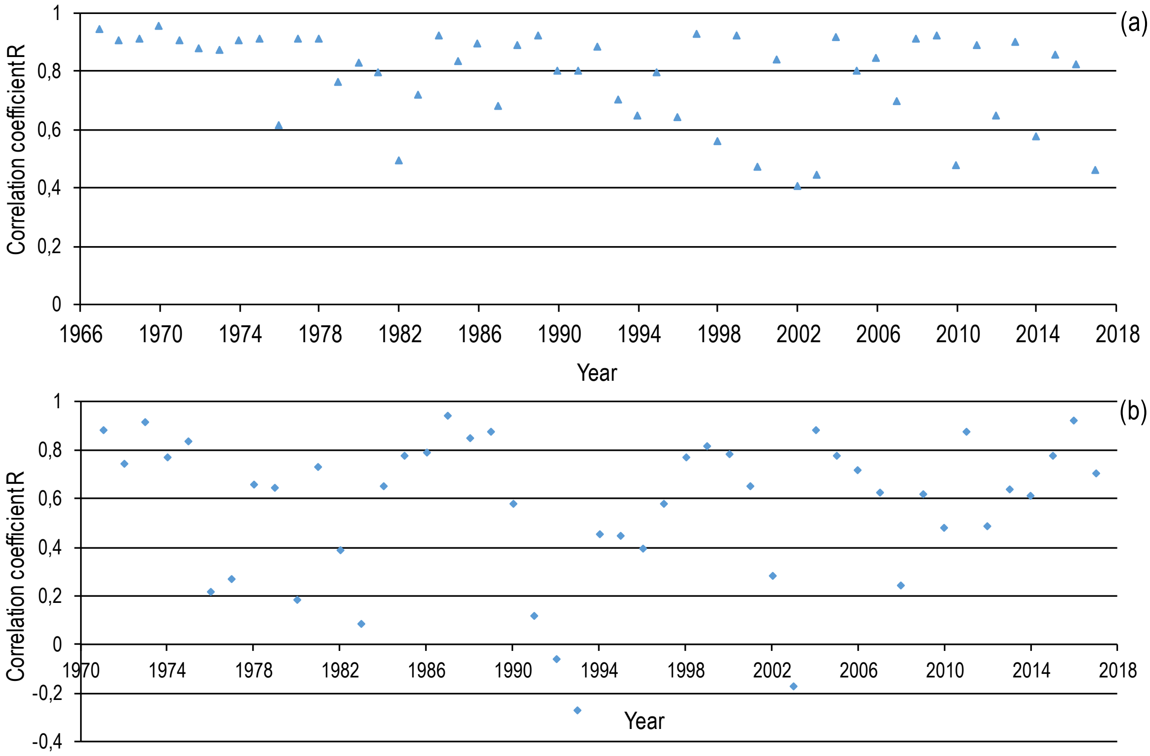

Figure 11 Correlation coefficients of the regression of monthly averaged SSC and Q for each year at the two gauging stations: (a) Botovo and (b) Donji Miholjac

Using the traditional SRC method, regression formulas were derived for each gauging station at a daily time-scale:

$SSC=0.053Q^{0.993}$ R=0.54 RMSE=26.87 (Botovo) (9)

$SSC=0.153Q^{0.843}$ R=0.27 RMSE=38.80 (Donji Miholjac) (10)

The results of both stations were poor and consequently SSC was regressed using the SSC from the previous day (SSC_{t-1}), and Q in the same day (Q_t). The results of the new regression were better, with higher R values and lower RMSE values. For both stations, R values exceeded 0.7. Figure 12 presents the comparison of modeled and observed SSC values for 2015–2017 at the two gauging stations. The new SRC formula captured the seasonal dynamics of SSC, especially for lower SSC values. However, the new SRC formula failed to accurately model extreme SSC values (Figure 8), which has been a general problem for various models [28, 36-38]. Compared with the traditional SRC method, which employs only Q to obtain SSC, the new SRC formula is more stationary since it considered SSC values from the previous day or month. The poor performance of the traditional SRC method also indicated that the power function in Equation (2) may not be applicable for all river stations, which has also been discussed in [38].

$SSC_t = 0.585SSC_{t-1}+0.0005Q_t^{1.22}$ R=0.73 RMSE=21.54 (Botovo) (11)

$SSC_t = 0.71SSC_{t-1}+0.0422Q_t^{0.852}$ R=0.74 RMSE=27.30 (Donji Miholjac) (12)

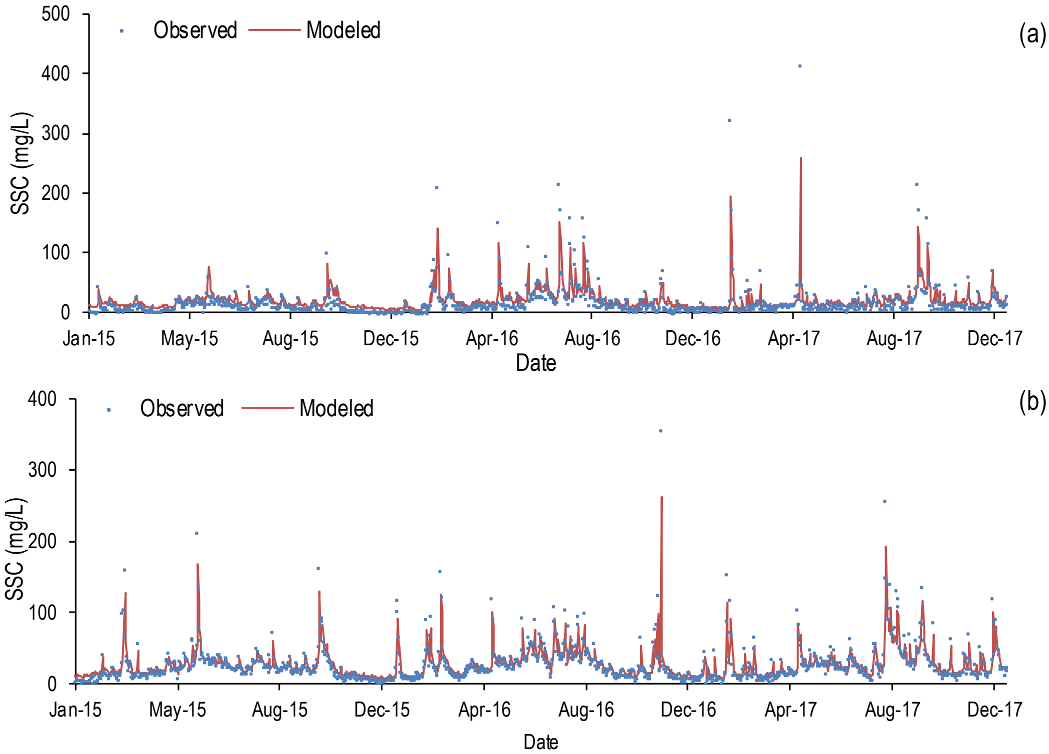

Figure 12 Comparison of modeled and observed SSC values for the time period of 2015–2017 at the two gauging stations: (a) Botovo and (b) Donji Miholjac

4 CONCLUSIONS

Using the RAPS method, the alteration to the sediment regime of the lower Drava River was assessed and its possible causes were discussed. Suspended sediment load decreased about 65% between 1967–1981 (0.922×10^6 t/year) and 2003–2017 (0.323×10^6 t/year) for the Botovo station. For the Donji Miholjac station, suspended sediment load decreased about 81% between 1971–1981 (1.383×10^6 t/year) and 2007–2017 (0.263×10^6 t/year). The sudden alteration of sediment regime and the sharp decreases of SSC at the two gauging stations began from the 1980s. This indicates that the change was mainly caused by the construction and operation of reservoirs, and the implementation of river training measures. The SSC-Q relationships were assessed by a new formulation of the SRC. Compared with the traditional SRC approach, the new form of SRC performed far better, with higher R values and lower RMSE values, and was able to better capture seasonal dynamics of SSC at daily and monthly time-scales. The results in this study can be used in designing river management and rehabilitation measures for the Drava River.

While SSCt was regressed from SSC_{t-1}, SSC_{t-2},..., as well as Q_t, Q_{t-1}, Q_{t-2} using Excel Solver, modelling accuracy was not improved. Therefore, the best form is presented in this paper.

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