Estimation of suspended loads in the Danube River at Göd (1668 river km), Hungary

Tóth, Bence*; Bódis, Erika

Danube Research Institute, Centre for Ecological Research of Hungarian Academy of Sciences

Karolina út 29. 1113 Budapest, Hungary. Phone: +36 1 279 31 00

toth.bence@okologia.mta.hu, bodis.erika@okologia.mta.hu

*Corresponding author

Abstract: Sediment rating curves were used to estimate suspended particulate matter (SPM) loads in the Danube River at Göd (1668 river km), Hungary, in conjunction with a sampling program conducted between 2003 – 2012. Contrary to its water quality significance, only a few studies have focused on the annual transport of SPM in this section of the river. Based on the results, we can state that 1) the SRC method (in certain cases with correction factors) provided reliable estimates of the annual SPM loads in this section of the river; 2) the division of the dataset into seasonal or temperature subsets did not significantly improve the estimations, moreover, annual datasets may provide additional hydrologic information on the water year or the annual water regime; 3) large amounts of the SPM were transported during short, but high

water discharge periods, hence, calendar based-sampling should be supplemented with event-based sampling, and 4) the SPM load of the river has declined by about 50% over previous decades, which is most likely due to the installation of hydropower plants on the upper (German, Austrian, Slovakian) stretches of the Danube River.

Keywords**:** suspended particulate matter, sediment rating curve, Danube River, annual suspended particulate matter loads

1. Introduction

Suspended particulate matter (SPM) in streams and rivers is the solid fraction transported by the flow of water. SPM consists of inorganic (mainly silt and clay mineral grains, authigenic minerals), and organic particles (bacteria, phytoplankton, zooplankton, and plant and animal fragments, e.g., Schönborn, 1992). The concentration of SPM is controlled by a combination of water discharge and available particulate matter supply. SPM tends to settle under low flow conditions, and resuspends when flow increases. Hence, flow essentially determines the qualitative and quantitative properties of SPM, which is in a 'genetic' relationship with bed sediment (Oertel, 1992). SPM causes turbidity and affects the spectral composition of the light penetrating a water body (Dvihally, 1979). SPM also plays a significant role in sorbing various inorganic (e.g., heavy metals) and organic (e.g., PCBs, PAHs) chemical constituents (e.g., Evans, et al., 1990; Oertel, 1994; Lin and Chen, 1998).

Studies focusing on SPM cover a wide variety of investigations including but not limited to: 1) determinations of the relationship between water discharge and SPM concentration and/or load and the spatial and temporal changes in this relationship (e.g., Asselman, 2000); 2) evaluations of the chemical composition of SPM (e.g., Viers et al., 2009); 3) estimations of the annual loads of SPM and sediment-associated chemical constituents (Horowitz, 2010); 4) evaluating the effects of anthropogenic impacts (e.g., hydropower dams; Klaver, et al., 2007); 5) calculations of the *effective discharge* (Wolman and Miller 1960); and 6) investigations of particulate organic matter (Reschke, et al., 2002). Since the amount of sediment delivered by a river contributes to its channel and landscape forming power (i.e., forming depositional zones, erosional zones, deltas), geomorphological processes also can be predicted based on the amount of SPM transported by streams and rivers (Syvitski, et al., 2005).

Many fluvial studies are designed to determine the concentration and load of SPM. Such programs require SPM sampling over a wide range of water discharge. However, most programs lack the resources to collect a sufficient number of samples to accurately estimate the annual SPM load. In the absence of actual samples, SPM concentrations can be estimated using sediment rating curves (SRCs) developed using log transformed data for SPM and Q; these curves can take the form of a power function:

$$c = bQ^a \quad (1)$$

or, a linear equation:

$$\log(c) = \log(b) + a \cdot logQ \quad (2)$$

where: c is SPM concentration (mg L^{-1}), Q is water discharge (m^3 s^{-1}), and 'a' and 'b' are regression coefficients. This approach is widely used in studies focusing on the determination of SPM concentrations and annual loads (Achite and Ouillon, 2007; Horowitz, 2008; Gao and Josefson, 2012). Horowitz (2003) demonstrated that in certain cases, a second or a third order polynomial regression may provide more accurate estimates.

Certain corrections may be necessary when applying this approach. When the regression is fitted to log-transformed data, back-transformation to arithmetic space may cause a marked underestimation. To eliminate this bias, various correction factors may be required (e.g., Bradu and Mundlak, 1970; Duan, 1983; Ferguson, 1986). A second issue is associated with the degree of scatter in the SPM concentration *vs.* water discharge relationship. The reasons for this can be manifold. Hysteresis may lead to differences in the Q-SPM relationship for the falling and rising limbs of a hydrograph, (e.g., Williams, 1989; Eder, et al., 2010). Seasonal differences (e.g. wet and dry periods) also can affect the accuracy of the regression (Asselman 2000). Further, the Q-SPM relationship can change from year-to-year, leading to differently shaped SRC-s, (convex, concave, or linear) as shown by Horowitz (2003) in a study of the Mississippi River (USA), or by Warrick, et al., (2013) in the study of northern California rivers.

Although relatively long-term datasets are available for the Hungarian section of the Danube River, where measurements usually have been collected on a weekly, or biweekly basis, there still is a need to estimate SPM concentrations for the unmeasured periods to facilitate the determination of annual loads. The present study had three objectives. 1) to develop a reliable method for determining the relationship between Q and SPM concentration in the middle section of the Danube river; 2) to evaluate the current sampling strategy that has been applied for several years, to see if modification(s) are necessary; and 3) to develop a hydrological characterisation of the middle section of the river based on an evaluation of the available data and estimated annual loads. Although the Danube is the second longest river in Europe, only a few relatively recent publications focus on its sediment transporting characteristics within the Hungarian section. Baranya and Józsa (2013) evaluated an Acoustic Doppler Current Meter as a potential SPM concentration measuring tool. Others have investigated the contaminants associated with the suspended phases in the river, (e.g., Andrási, et al., 2013; Faludi, et al., 2014). Long-term declines in SPM concentrations in the Hungarian section of the Danube River have been noted by Horváth and T. Bartalis, (1999); Tóth, et al., (2005) and Kiss, et al., (2007) but no actual load data were cited. The present study was designed to address this lack of SPM load data for the investigated section of the river, i.e. ~15 km up- and downstream from the gauging station (where there are no significant tributaries or anthropogenic impacts).

2. Materials and Methods

2.1. Study site and sampling method

The gauging station is located at Göd, at river km 1668 (distance from mouth). Göd is about 20 km upstream of Budapest, the capital of Hungary. The river catchment area at this site is 184 767 km^2 (Lászlóffy, 1965) (Fig. 1.). The upper Danube River basin covers a large part of Southern Germany and the Austrian Alps. Vegetation is characterized by forests (40%), grasslands (27%), and arable land (23%). The texture of the soils in the area are silt loam and sandy loam, the soils in the mountainous areas range from clay to sand (Muerth, et al., 2010). The prevailing land use in the Danube River basin in Slovakia is agriculture (50%) and silviculture (43%) (www.icpdr.org, 2014). The hydrologic characteristics of the river are basically determined by the size and the physiogeographic heterogeneity of the catchment area (the Alps, the North Carpathian Mountains), large-scale weather patterns, (Ludwig, et al., 2003), furthermore, anthropogenic impacts (numerous hydropower plants, river regulation) also are significant.

The average annual water discharge at the sampling site during the study period was 1 595 ± 704 m^3 s^{-1} (avg. ± stand. dev.), based on daily measurements (General Directorate of Water Management, 2011), and ranged between 580 and 5 820 m^3 s^{-1}. In addition, weekly water samples were collected between 2003 – 2011, close to the center line of the river. SPM concentrations were determined gravimetrically on the same day the samples were collected using filtration through pre-dried and pre-weighted 0.45-µm membrane filters (three replicates). Water temperature was measured *in situ*.

Approx place of Figure 1.

2.2. Rating Curve Development

As a first approach, the annual datasets of discharge and SPM concentration were log-transformed and then divided into validation and calibration subsets; the data were found to be normally distributed based on the Shapiro-Wilk test (Statistica 6.0 Software). Linear, or second order polynomial curves were fitted, depending on the model efficiency. Model efficiency was evaluated by comparing model output (i.e., values obtained using the calibration dataset) and the validation data. The criterion defined by Nash and Sutcliffe (1970) was used:

$$NS = 1 - \frac{\sum_{i=1}^{n}(m_i - p_i)^2}{\sum_{i=1}^{n}\left(m_i - m_{avg}\right)^2} \qquad (3)$$

where: m_i is measured, p_i is the predicted concentration of SPM, and m_{avg} is the mean of the measured values. If the NS criterion is 1, it indicates perfect prediction, values lower than 0 show that using the average value for SPM provides better estimations than the model. To reduce the impact of extreme values (because of squared differences) the NS efficiency criterion was calculated using logarithmic values of the measured and predicted concentrations (Krause, et al., 2005).

Differences between predicted and observed concentrations were calculated, as follows:

$$D(\%) = \frac{p_i - m_i}{m_i} \cdot 100 \qquad (4)$$

where p_i is the predicted SPM concentration, and m_i is the measured SPM concentration. Since differences can be both negative and positive, the absolute values were used to characterize the effectiveness of the model. Correction factors described by Bradu and Mundlak (1970), Duan (1983), and Ferguson (1986) also were tested, and applied, when they improved the model (improved the NS criterion). Numerous additional statistical measures can be applied, when evaluating model efficiency (e.g. Hanna and Chang, 2012) e.g. fractional mean bias (FB), normalized mean-square error (NMSE), geometric mean (MG), geometric variance (VG), fraction of predictions within a factor of two of observations (FAC2), or the index of agreement (d) (e.g. Krause, et al., 2005), however, none of these measures can generate perfect models. As NMSE reflects both systematic and unsystematic errors (the lower the NMSE, the better the prediction), and FAC2 is a robust measure (FAC2 should be in the range of 0.5–2) not overly influenced by high or low outliers, these two measures were also used to evaluate the models.

$$\mathrm{NMSE} = \frac{1}{N}\sum_{i=1}^{n}\frac{(p_i-m_i)^2}{\frac{1}{N}\sum_{i=1}^{n} p \cdot \frac{1}{N}\sum_{i=1}^{n} m} \qquad (5)$$

$$FAC2\text{: } 0.5 < \frac{p_i}{m_i} < 2 \qquad (6)$$

where p_i is the predicted SPM concentration, and m_i is the measured SPM concentration.

As an alternative, multiple regression analyses also were evaluated. The significant predictors were chosen by both backward and forward stepwise regression (Statistica

6.0 Software). After this, the entire dataset (2003 – 2011) was divided into seasonal subsets based on the changes in daily water discharge (falling or rising limb of the hydrograph). The fitting and evaluative procedures that were used for the seasonal subsets were the same as previously described for the annual data sets.

3. Results

3. 1. Annual SRCs

With the exception of 2011, every year of SPM data from the calibration subsets displayed normal distributions. Statistically, regression analysis should not be applied where the data are not normally distributed, however, despite this, the model for 2011 appeared to work reasonably well (highest NS and highest r^2 values, Table 1). Linear SRCs provided the best estimations for 2003, 2004, 2006, and 2008 whereas second order polynomial SRCs provided the best results for 2005, 2007, and 2009 – 2011 (Fig. 2, Table 1.). Correction factors only improved the results in four cases; their values always were >1.

Average differences between predicted and measured values ranged between 26 and 54%. It should be noted that when the SPM concentration range was ≤ 5 mg L^{-1}, relatively small differences between the measured and predicted values, when expressed as a percentage, were quite high. However, these large errors are relatively insignificant in terms of estimating annual loads because the contributions for these periods also are relatively low. If the percentage errors in annual SPM load are excluded for those periods when the concentrations were ≤5 mg L^{-1}, the range in estimation error declined to between 20–43%. NMSE values ranged between 0.12 and 0.34, and only 1–3 data pairs fell out of the range of FAC2, with the exception for 2003. The estimations were relatively inaccurate for 2003 based on the NS, NMSE, and FAC2 values; however, the average difference (D%) between predicted and measured values was not markedly high. There is a strong positive correlation ($r=0.82$, $p<0.05$) between the average annual SPM concentration (predicted data) and the average annual water yield, and there is a moderate positive correlation ($r=0.52$, $p<0.134$) between the average differences between predicted and measured SPM concentration (D_{avg}) and the average annual water yield.

#Approx place of Table 1. #

#Approx place of Figure 2.#

Based on the annual SRCs that were developed, annual SPM load can be calculated using the following formula:

$$\text{Annual SPM load (t)} = \sum_{i=1}^{365} c_i \cdot Q_i \cdot 86400 \cdot 10^{-6} \qquad (7)$$

where: c_i is the SPM concentration (mg L^{-1}), Q_i is the water discharge (m^3 s^{-1}), 86 400 and 10^{-6} are the necessary conversion factors to express the annual SPM load in tonnes

d^{-1}. Table 2 contains annual estimates of the range of SPM concentration, the average SPM concentration, and the annual SPM loads.

#Approx place of Table 2. #

Based on a flow-duration curve for the study period (250 $m^3 s^{-1}$ flow classes) and the modelled interrelationship between discharge and SPM load, it is possible to determine the product of the instantaneous data. When the product reaches its maximum value, it identifies the discharge rate (*effective discharge*) that is responsible for the majority of the transported SPM, (Wolman and Miller, 1960; Sichingabula, 1999; Biedenharn, et al., 2000) (Figure 2.). For the Danube River, between 2003 – 2011, this value was 1750 $m^3 s^{-1}$, which is slightly higher than the average value determined for the study period (1595 $m^3 s^{-1}$, based on daily measurements).

#Approx place of Figure 3.#

Cumulative plots of the SPM load (Figure 4.) show that ~40% of the total load was transported during periods when discharge was >2500 $m^3 s^{-1}$ (10% duration); furthermore, the river carried a significant amount of SPM (~12% total load for the period) when discharge >4000 $m^3 s^{-1}$, even though it occurred on only 53 days during the 9-year long study period.

#Approx place of Figure 4.#

3.2. Results from the multiple regression analysis

Based on both stepup and stepdown regression modeling, two independent variables, (water discharge, water temperature) were significant predictors of SPM concentration. No significant correlation was found between the two variables. Obviously, water temperature does not affect SPM concentration directly. However, it may reflect biological activity and/or some seasonal characteristics. For example, the formation of biological detritus (which is a part of SPM; e.g. leaf breakdown rates) generally is greater at higher temperature (e.g., Abelho, et al., 2005). On the other hand, heavy rainfall, which may cause substantial soil erosion in the catchment area, is more typical during warmer seasons in the temperate zone. Statistically, the inclusion of this variable appears reasonable, based on the Akaike information criterion (AIC decreased from 240.3 to 219.0, and from 172.1 to 168.7 in the falling and rising limb, respectively.) Using the multiple regression approach the average differences between predicted and measured values decreased slightly in the falling limb (from 38.6% to 38.3%) and markedly in the rising limb (from 41.9% to 38.3% and 37.1 %). NMSE values decreased by 0.1 and 0.05 (falling and rising limb, respectively), and less data pairs were out of the range of the criterion FAC2 (falling limb: decreased by 3, rising limb: decreased by 4). (Table 3.).

Approx place of Table. 3.

3.3. Seasonal SRC-s and temperature classes

All the data in the seasonal subsets displayed normal distributions (falling and rising limbs were handled separately). Linear regression produced the best predictions in all the seasonal subsets of the falling limb and in the spring subset of the rising limb, second-order polynomial regression provided the best model in case of the winter, summer and autumn subsets of the rising limb. (Table 4.).

#Approx place of Table 4.#

Since seasonal water temperature data displayed an overlap (Fig. 5.), we created three temperature classes both for falling and for rising limbs and investigated whether this subdivision could produce better predictions.

#Approx place of Figure 5.#

Regression coefficients were similar in the T1 and T2 subsets (falling limb), and a second-order polynomial regression provided the best NS values in all the three temperature subsets of the falling limb. The rising limb temperature subsets generated different shaped regression curves (second- order polynomials in the T2 and T3 subsets, linear regression in the T1 subset). Although relatively high NS values were associated with the T1 subset, accompanied by only small differences between predicted and measured data, it should be noted that the rising limb T1 subset did not contain a sufficient amount of validation data; hence, this result is tentative at best. Correction factors improved the model only in the two T3 subsets (Table 5.).

#Approx place of Table 5.#

4. Discussion

In the Danube River, almost all the yearly datasets displayed normal distributions of the log-transformed data and the SRC method appeared to provide usable estimates of SPM concentration in the absence of actual samples for the study period (2003 – 2011). Even in the one case where the data were not normally distributed (2011), the SRC approach still appeared to work well. According to Horowitz (2003), differences between predicted and measured values that are within ±15 – 20% fall within measurement error. On the other hand, Gray and Simões (2008) consider ±30 – 50% an acceptable error. Our annual SRCs produced an error range of 20 – 42% with an average of 35%, our seasonal SRCs provided an error range of 25 – 51% with an average of 38%, and our temperature class SRCs provided an error range of 22 – 54% with an average of: 31%.

With the exception of 2003, an extremely dry year, all the NMSE and FAC2 measures showed reliable models. These various results are not markedly different from each other; however, they do exceed the differences attributable solely to measurement error. This may have resulted from the high variability in discharge and SPM concentrations that occurred during the study period.

In the Rhine River (near the German-Dutch border), Asselman (2000) demonstrated that the highest NS efficiency criteria can be obtained by splitting the entire dataset into seasonal subsets based on water level change (discharge), and applying a correction factor. However, Asselman's study did not investigate annual SRCs. Asselman's values (0.57 – 0.72) are higher than those for our seasonal predictions (0.24 – 0.61, average: 0.40); however, the author also stated that NS values only can be compared for the same gauging stations. Hence, we can state that the NS criteria for our annual SRCs (0.24 – 0.71, average: 0.49), or for our temperature class SRCs (0.25 – 0.78, average: 0.55) showed slightly, but not significantly better estimations than our seasonally generated SRCs (0.24 – 0.61, average: 0.41), based on the NS criterion. However, despite the NS criteria, and the differences between predicted and measured data, the division of the data into various subsets did not appear to bring about a significant improvement. Although in certain cases (e.g. rising limb, summer subset) all the model performance measures indicated very good estimations, the subdivision – with regard to the entire dataset – can not be considered either a simpler, or a better approach in our study. The multiple regression approach improved all the model efficiency measures in comparison with the entire dataset (*cf.* table 1. all years, and table 3.), however, this subdivision does not appear to provide markedly better estimates, than the annuals SRCs. One of the potential benefits of using the annual SRC approach is that it may provide additional hydrologic information on the basis of the shapes of the annual curves: a convex curve indicates that the river probably is 'sediment-starved' (Horowitz 2003), which can be caused, for instance, by severe natural floods in the previous time interval and/or by various anthropogenic activities. Interestingly, the Danube River generated unusually high water levels in 2002, 2006, and 2010, but only the 2011 SRC displayed an obvious convex shape (Figure 2.). Based on that result, it appears that the Danube only became supply-limited in 2011 but not in 2002 nor 2006. Since floods can be caused by a variety of factors, and the catchment at Göd is quite extensive (>180.000 km^2) this kind of characterisation may not be possible at this time, but deserves some further investigation.

The annual rating curves for only 3 out of the 9 years within the study period showed improvement with the application of a correction factor to deal with the potential bias associated with converting from logarithmic space to arithmetic space. Further, there was no single valid correction factor. All the correction factors were positive, indicating a negative bias; however, based on this study, none of the applied correction factors could be considered more or less effective.

There was no obvious relationship between the applied model performance measures; however, in the case of the most inaccurate (e.g. year 2003, or falling limb, autumn) and the most accurate (e.g. rising limb, summer) models, the measures were coherent with each other.

Based on the annual SRCs, annual SPM loads ranged between 0.72 – 2.2 Mt y^{-1} (average = 1.6 Mt y^{-1}) during the study period. These annual loads are on a par with the Dnieper (Russia) and Vistula (Poland) Rivers (Julien, 2002), the Rhine River (German-Dutch border; Asselman, 2000), the Seine River (France; Meybeck, et al., 2003), and the Lena River (Russia; Håkanson, et al., 2005).

In 1971, Bogárdi's monograph reported an average SPM concentration of 100 mg l^{-1} for this section of the Danube between 1931 – 1940. In 1993, Rákóczi reported an annual load of 3.27 Mt for this section of the Danube River. Relative to the current results, it appears as if the annual SPM loads in the river have declined by about 50% since the 1990s. The apparent reason for this decline is the installation of numerous hydropower dams in the upper stretches of the river. This rationale for the current decline in both SPM concentration and annual loads is in accord with similar findings elsewhere (e.g., Syvitski, et al., 2005; Walling, 2006; 2008).

Our examination of the cumulative data for 2003 – 2011 clearly highlight the significant contribution of short-term, high flow events to the annual SPM loads in the Danube River. This once again tends to confirm the old adage that 90% of fluvial SPM is transported during 10% of the time (e.g., Horowitz, 2003). Hence, it would seem that event-based sampling, rather than calendar-based sampling (the current norm) probably would provide more accurate estimations of annual SPM loads. However, the interrelationship between the accuracy of our estimated annual SPM loads and the annual water yield means that in wet years, the accuracy of the predictions might decline. Since climate change appears to manifest itself in more extreme weather phenomena (Andersen, et al., 2006; Steele-Dunne, et al., 2008; Guo, et al., 2014), annual weather and water yield data also should be taken into account when developing SRC models. The calculated effective discharge for this study is similar to the average measured discharge; and may indicate that these intervals may be hydrologically significant.

5. Conclusions

1) SPM concentrations and annual loads for the Danube River at Göd (1668 river km) during the study period could be estimated reasonably well using the annual SRC method; the annual estimates showed improvement in only a limited number of cases through the application of correction factors.

2) The division of the entire dataset into seasonal or temperature subsets did not markedly improve the accuracy of the annual SPM load estimates.

3) The calculated effective discharge of the Danube River at Göd was close to the average annual discharge; however, a significant amount of the annual loads of SPM occurred during short, but markedly elevated discharge events.

4) This implies that some improvement in the estimation of annul SPM loads could be achieved through the continued use of calendar-based sampling supplemented with specific event-based sampling.

5) Based on the results of this study, the SPM content of the Danube River has declined by close to 50% during the last two decades, probably as the result of the installation of numerous hydropower dams in the upper stretches of the basin.

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http://icpdr.org/main/danube-basin/slovakia

Table 1. Regression coefficients of rating curves for the Danube River at Göd (1668 river km), Hungary, between 2003 and 2011, and model efficiency measures.

Water year	$\log c = a \cdot \log Q + b$		$\log c = a \cdot (\log Q)^2 + b \cdot \log Q + d$			**CF**	**NS**	$\overline{\lvert D \rvert}$ **%**	$\overline{\lvert D \rvert}_s$ **%**	r^2	N_{Cal}	N_{Val}	NMSE	FAC2
	a*	**b**	**a**	**b**	**d**									
2003	1.0509	-2.0919				-	0.24	30.1	30.1	0.28	23	22	0.50	10
2004	1.3043	-2.9325				B-M	0.56	46.9	31.2	0.54	24	23	0.25	3
2005			-1.4408	10.194	-16.473	-	0.46	53.6	37.0	0.43	20	21	0.34	3
2006	1.1815	-2.4518				-	0.58	52.8	43.3	0.51	20	19	0.17	3
2007			2.9687	-18.305	29.504	B-M	0.24	45.4	45.4	0.31	20	17	0.14	2
2008	1.8295	-4.6784				-	0.65	25.8	19.9	0.48	21	20	0.12	2
2009			-1.2131	9.0378	-15.148	-	0.59	40.0	40.0	0.62	20	20	0.12	1
2010			-3.222	22.549	-37.78	1.212	0.37	37.7	37.7	0.30	20	14	0.24	2
2011			-13.474	85.414	-133.89	-	0.71	40.5	33.7	0.76	20	14	0.22	1
All years	1.4146	-3.2353				1.167	0.41	47.2	41.9	0.43	180	178	0.33	29

c: suspended particulate matter (SPM) concentration (mg L^{-1}). Q: discharge (m^3 s^{-1}). a, b, d: regression coeff. CF: correction factor (B-M refers to Bradu Mundlak, individual value for all predicted SPM concentrations), NS: Nash-Sutcliffe efficiency criterion, D: Difference between predicted and observed concentration. D_s: Difference between predicted and observed concentration for those periods when the SPM concentrations were ≥5 mg L^{-1}. r^2: coeff. of determination, N_{Cal}, N_{Val}: number of data pairs in the calibration and validation subsets, respectively, NMSE: normalized mean-square error, FAC2: number of cases when p_i/m_i is out of the range of 0.5–2.

Table 2. Annual suspended matter concentration ranges, average values and loads in the Danube River at Göd, Hungary (2003–2011).

	min	**max**	**average**	**St.dev.**	**cv%**	**Load**
	(mg L^{-1})					**(Mt year^{-1})**
2003	6.4	41.8	15.1	6.7	44.4	0.72
2004	6.7	42.4	17.7	7.8	44.1	0.96
2005	9.0	36.2	23.3	8.5	36.4	1.44
2006	8.9	99.2	25.8	17.9	69.2	2.07
2007	20.1	176.7	25.0	16.3	65.4	1.44
2008	4.3	47.5	14.4	7.8	53.9	0.79
2009	7.7	48.1	23.4	10.7	45.7	1.55
2010	7.7	56.6	32.8	14.5	44.2	2.20
2011	0.1	29.7	19.7	9.1	46.0	0.86

Table 3. Regression coefficients of the sediment rating curves for the Danube River at Göd (1668 river km), Hungary, between 2003–2011, and model efficiency measures.

Subset	$\log c = a \cdot (\log Q) + b \cdot T + d$			CF	NS	$\overline{\lvert D \rvert}$	$\overline{\lvert D \rvert}_s$	AIC	r^2 r^2_{logQ} r^2_T	N_{Cal}	N_{Val}	NMSE	FAC2
	a	b	d			%	%						
Fall	1.424	0	-3.2634	1.159	0.46	51.1	38.6	240.3	0.46	101	103	0.29	16
Rise	1.18	0	2.5086	1.175	0.39	56.8	45.5	172.1	0.36	77	77	0.30	15
Fall T	1.21	0.013	-2.715	-	0.56	44.1	38.3	219.0	0.55 0.45 0.14	101	103	0.19	13
Rise T	1.06	0.016	-2.33	1.139	0.53	42.8	37.1	168.7	0.51 0.36 0.20	77	77	0.25	11

Subsets: Fall, rise: falling and rising limb, only predictor is water discharge. Fall T, Rise T: falling and rising limbs, predictors are water discharge and temperature. c: suspended particulate matter (SPM) concentration (mg L^{-1}). Q: discharge (m^3 s^{-1}). T: water temperature (^oC). a, b, d: regression coeff. CF: correction factor (B-M refers to Bradu Mundlak, individual value for all predicted SPM concentrations), NS: Nash-Sutcliffe efficiency criterion, D: Difference between predicted and observed concentration. D_s: Difference between predicted and observed concentration for those periods when the SPM concentrations were ≥5 mg L^{-1}. AIC: Akaike information criterion. r^2: coeff. of determination, N_{Cal}, N_{Val}: number of data pairs in the calibration and validation subsets, respectively, NMSE: normalized mean-square error, FAC2: number of cases when p_i/m_i is out of the range of 0.5–2.

Table 4. Regression coefficients of the sediment rating curves for the Danube River at Göd (1668 river km), Hungary, between 2003–2011, and model efficiency measures.

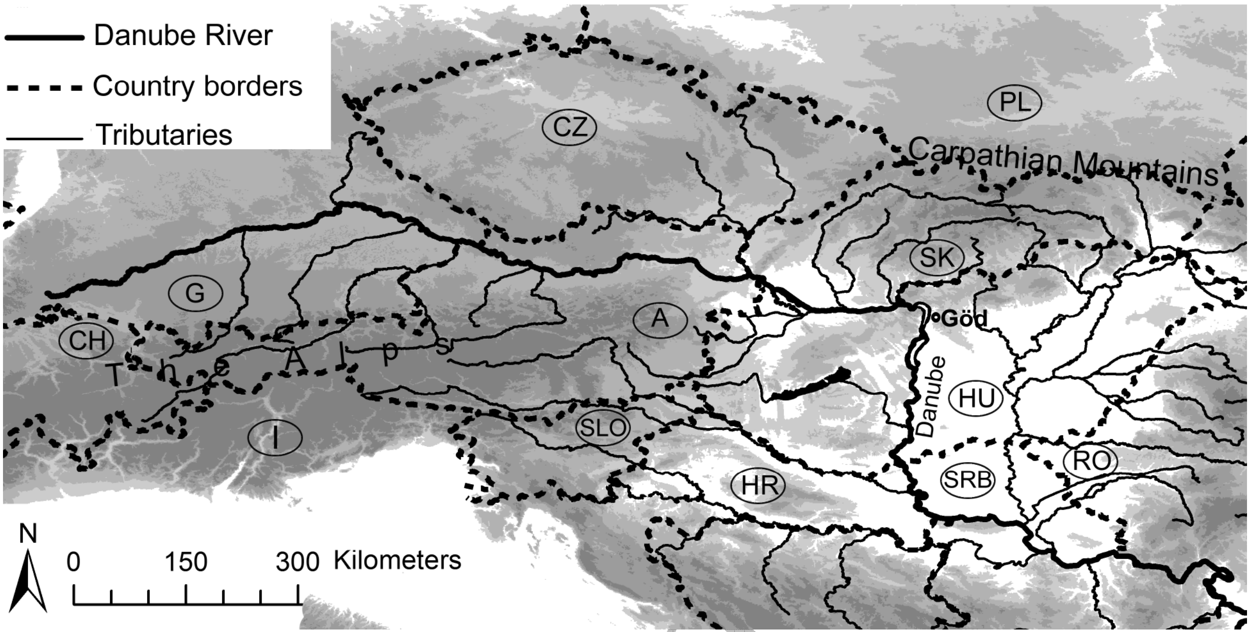
	Subset	$\log c = a \cdot \log Q + b$		$\log c = a \cdot (\log Q)^2 + b \cdot \log Q + d$			CF	NS	$\overline{\lvert D \rvert}$ %	$\overline{\lvert D \rvert}_s$ %	r^2	N_{Cal}	N_{Val}	NMSE	FAC2
		a	**b**	**a**	**b**	**d**									
Fall	Wi	1.7736	-4.4026				1.294	0.42	38.4	38.4	0.35	20	20	0.59	3
Fall	Sp	0.6367	-0.7403				1.097	0.28	50.9	50.9	0.30	29	29	0.17	4
Fall	Su	0.5926	0.4498				B-M	0.42	27.7	27.7	0.40	33	32	0.11	1
Fall	Aut	1.5436	-3.606				1.097	0.39	71.5	50.2	0.42	30	30	0.49	7
Rise	Wi			2.143	-12.001	17.579	B-M	0.24	76.9	45.0	0.31	18	7	0.20	3
Rise	Sp	1.0259	-1.9698				-	0.31	35.1	35.1	0.30	21	21	0.51	6
Rise	Su			0.6919	-3.1741	4.4431	B-M	0.58	24.7	24.7	0.61	20	15	0.15	0
Rise	Aut			2.9876	-16.793	24.443	1.098	0.61	61.8	31.6	0.60	19	12	0.17	0

Subsets: Wi: winter, Sp: spring, Su, summer, Aut: autumn. c: suspended particulate matter (SPM) concentration (mg L^{-1}). Q: discharge (m^3 s^{-1}). a, b, d: regression coeff. CF: correction factor (B-M refers to Bradu Mundlak, individual value for all predicted SPM concentrations), NS: Nash-Sutcliffe efficiency criterion, D: Difference between predicted and observed concentration. D_s: Difference between predicted and observed concentration for those periods when the SPM concentrations were ≥5 mg L^{-1}. r^2: coeff. of determination, N_{Cal}, N_{Val}: number of data pairs in the calibration and validation subsets, respectively, NMSE: normalized mean-square error, FAC2: number of cases when p_i/m_i is out of the range of 0.5–2.

Table 5. Regression coefficients of the sediment rating curves for the Danube River at Göd (1668 river km), Hungary, between 2003–2011, and model efficiency measures.

	Subset	$\log c = a \cdot \log Q + b$		$\log c = a \cdot (\log Q)^2 + b \cdot \log Q + d$			CF	NS	$\overline{\lvert D \rvert}$	$\overline{\lvert D \rvert}_s$	r^2	N_{Cal}	N_{Val}	NMSE	FAC2
		a	b	a	b	d			%	%					
Fall	T1			-0.5816	5.0268	-8.8201	-	0.47	54.0	30.0	0.51	24	23	0.64	3
Fall	T2			-0.8659	6.9265	-12.04	-	0.58	48.0	44.6	0.56	41	40	0.23	11
Fall	T3			-0.0168	0.7808	0.9161	1.06	0.25	32.1	32.1	0.29	50	49	0.20	2
Rise	T1			2.0786	-11.387	16.279	-	0.74	21.3	21.3	0.49	19	9	0.04	0
Rise	T2	1.4776	-3.495				-	0.78	29.7	29.7	0.66	25	25	0.21	0
Rise	T3	1.1168	-2.1849				B-M	0.49	29.7	29.7	0.48	27	26	0.16	0

Subsets: T1: 0–5 °C, T2: 5–15 °C, T3: 15–25 °C. c: suspended particulate matter (SPM) concentration (mg L^{-1}). Q: discharge (m^3 s^{-1}). a, b, d: regression coeff. CF: correction factor (B-M refers to Bradu Mundlak, individual value for all predicted SPM concentrations), NS: Nash-Sutcliffe efficiency criterion, D: Difference between predicted and observed concentration. D_s: Difference between predicted and observed concentration for those periods when the SPM concentrations were ≥5 mg L^{-1}. r^2: coeff. of determination, N_{Cal}, N_{Val}: number of data pairs in the calibration and validation subsets, respectively, NMSE: normalized mean-square error, FAC2: number of cases when p_i/m_i is out of the range of 0.5–2.


Danube River
Country borders
Tributaries
CZ
PL
Carpathian Mountains
SK
G
A
CH
The Alps
Göd
Danube
HU
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SLO
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SRB
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Kilometers

Fig. 1.

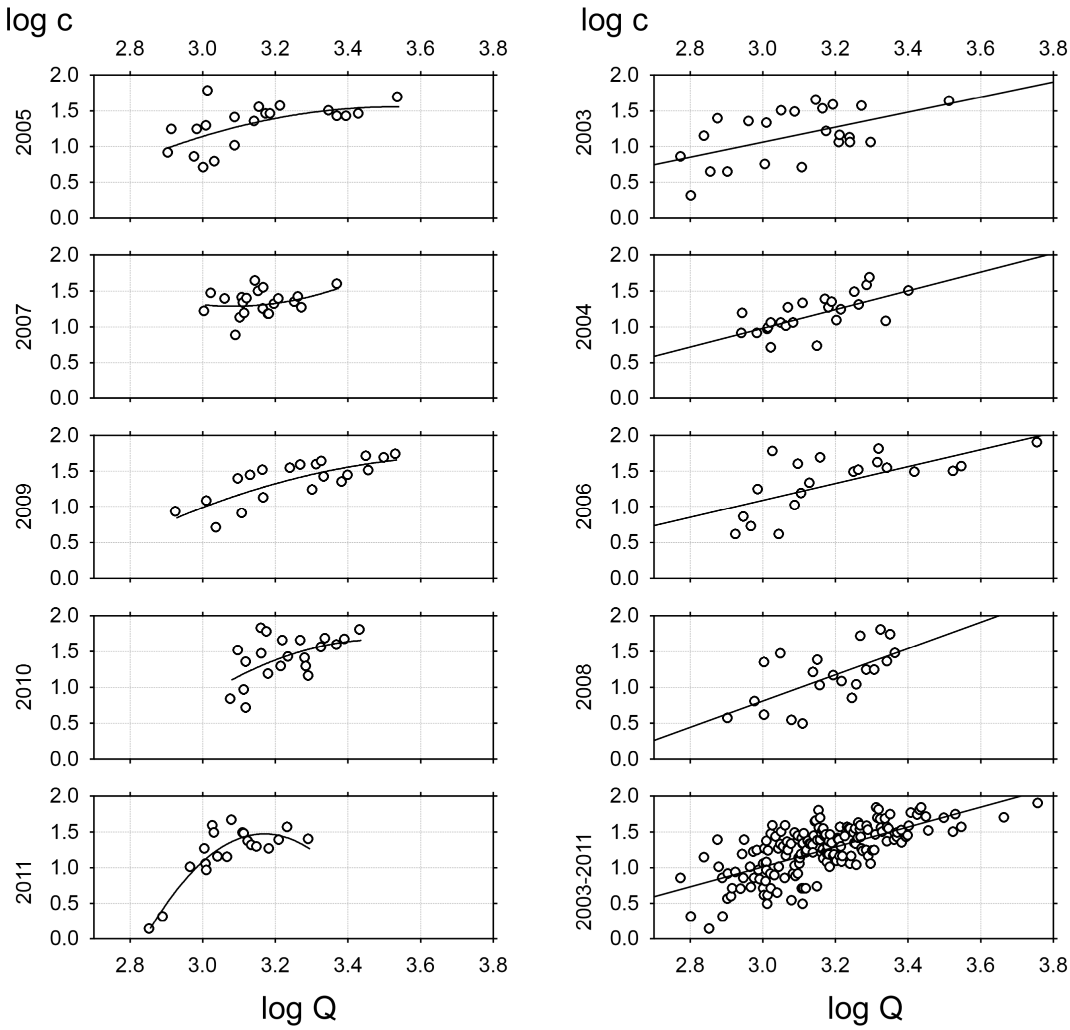

log c
log c
2005
2007
2009
2010
2011
2003
2004
2006
2008
2003-2011
2.8 3.0 3.2 3.4 3.6 3.8
0.0 0.5 1.0 1.5 2.0
log Q
log Q

Fig. 2.

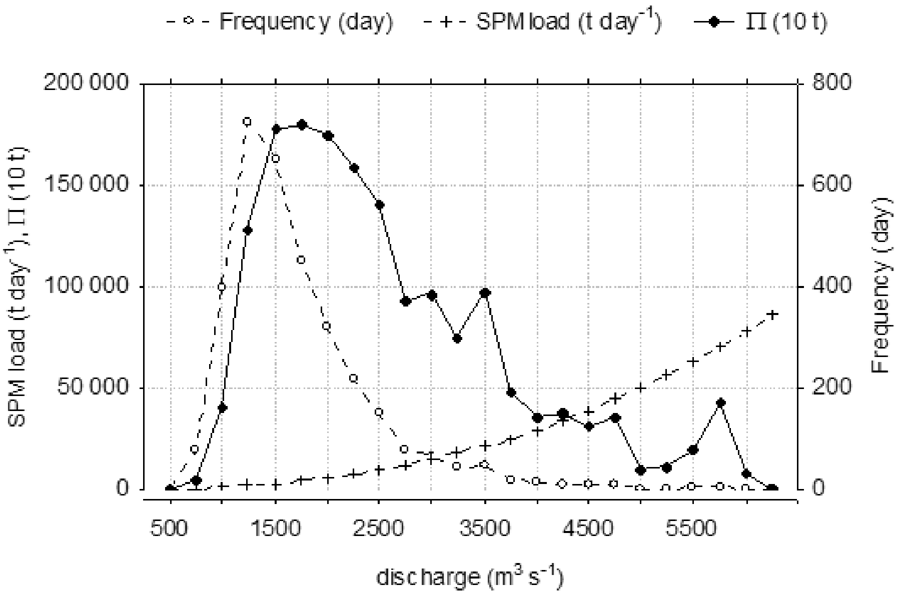
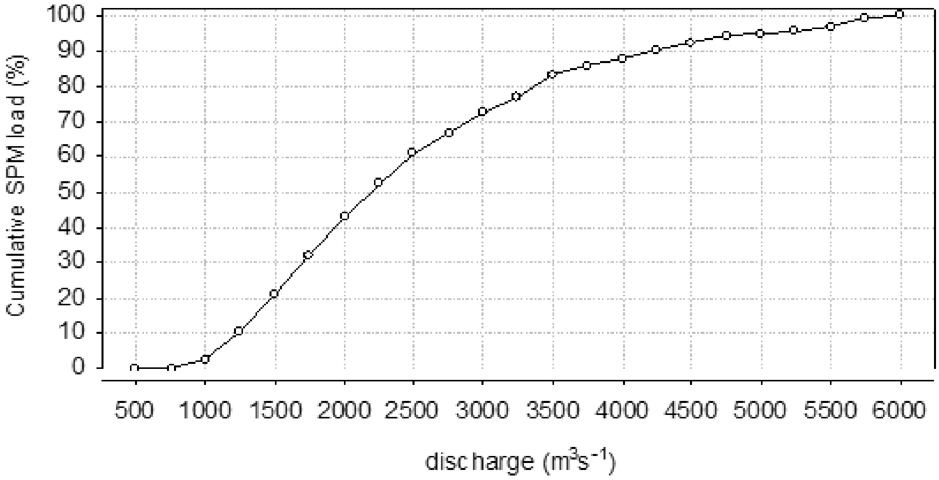

- ○ - Frequency (day)
- + - SPM load (t day-1)
—◆— Π (10 t)
SPM load (t day-1), Π (10 t)
Frequency (day)
discharge (m3 s-1)
200 000
150 000
100 000
50 000
0
800
600
400
200
0
500
1500
2500
3500
4500
5500

Fig. 3.


Cumulative SPM load (%)
100
90
80
70
60
50
40
30
20
10
0
500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000
discharge (m^{3}s^{-1})

572

Fig. 4.

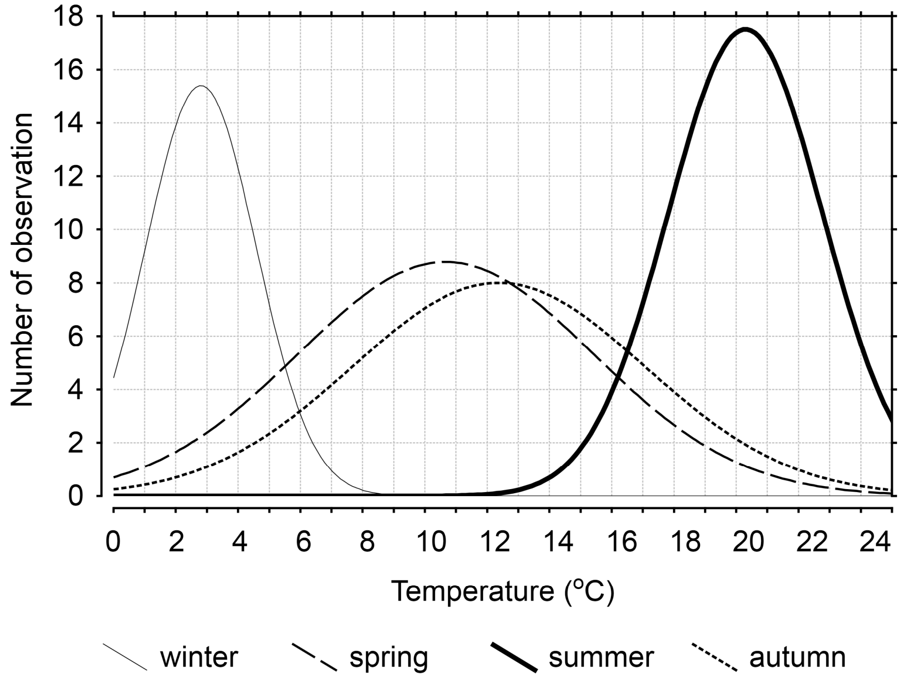


Fig. 5.

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Figure captions

Figure 1. Map of the Danube catchment area, with the gauging station at Göd (1668 river km).

Figure 2. Annual sediment rating curves at Göd, Danube River, Hungary. ‘Q’ stands for water discharge (m^3 s^{-1}), ‘c’ for the suspended particulate matter concentration (mg L^{-1}) of the water.

Figure 3. Flow-frequency distribution, suspended particulate matter (SPM) load, and the product (Π) of the instantaneous data at Göd (Danube River, Hungary), 2003–2011. The highest Π value shows the *effective discharge* of the river.

Figure 4. Cumulative suspended particulate matter load expressed as percentage plotted versus discharge in the Danube River at Göd (1668 river km), Hungary, 2003–2011.

Figure 5. Distribution of water temperature data in different seasons in the Danube River during 2003–2011, at Göd (1668 river km), Hungary.