ENVIRONMENTAL EFFECTS OF INDUSTRIAL DREDGING ON ALLUVIAL RIVERBEDS

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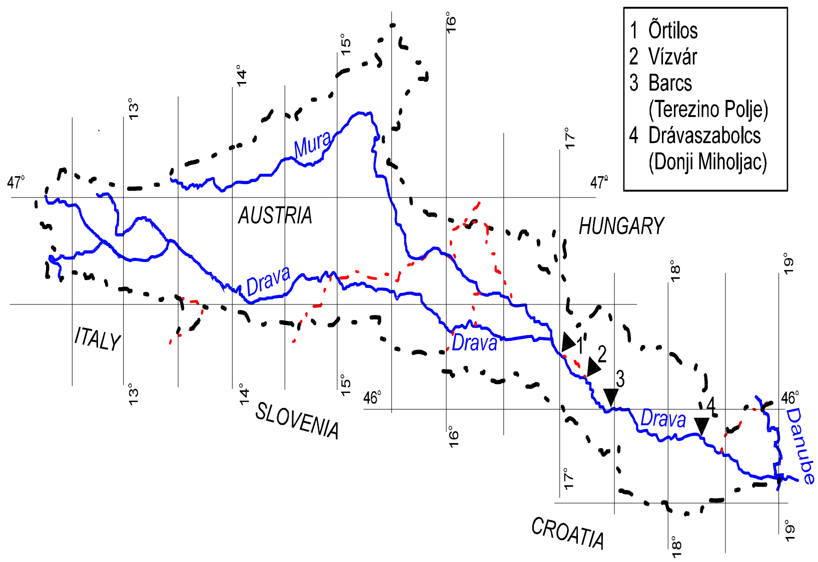
Abstract: Several hydropower plants built in Austria and Croatia influence the natural flow and sediment regime of the Croatian-Hungarian reach of River Dráva. The subsequent river channel deformations have recently been increased by gravel and sand excavations in both countries. The bed-load balances of the sub-reaches between four sediment-measuring stations were determined in contrast to the annual dredged volumes. The annual rate of riverbed degradation was estimated using these balances and the shift of discharge rating curves at each station.
Keywords: riverbed degradation, bed-load balance, dredging, shift of rating curve.

UMWELTAUSWIRKUNGEN VON INDUSTRIELLEN BAGGERUNGEN IN ALLUVIALEN FLUSSBETTEN

Zusammenfassung: Das natürliche Abfluss- und Feststoff-Regime der kroatisch-ungarischen Draustrecke wird von den Österreich und Kroatien errichteten Laufkraftwerken beeinflusst. Die dadurch erzeugten Flussbettveränderungen wurden in letzter Zeit durch die in beiden Staaten durchgeführten Flussbettbaggerungen noch weiter verschärft. Die Bilanz des an den durch vier Feststoffmessstationen erfassten Flussstrecken ermittelten Geschiebes wurde mit dem jährlich gebaggerten Volumen des Flussbettmaterials verglichen. Das jährliche Tempo der Flussbettvertiefung wurde anhand der Geschiebebilanzen sowie der Verschiebungen der Schlüsselkurven der einzelnen Messstationen geschätzt.
Schlüsselwörter: Flussbettvertiefung; Geschiebebilanzen; Flussbettbaggerung; Verschiebung von Schlüsselkurven.

1. Introduction

The degradation of the river channel in River Dráva has been started several centuries ago and its annual rate is changing according to the intensity of human interventions. This gradual deepening of the riverbed not only directly influences the life conditions of the fluvial flora and fauna but decreases the frequency of floodplain inundations and decreases the ground water level in the riparian regions. The aim of this paper is to estimate the annual rate of this process by different methods.



The natural sediment transporting capacity of River Dráva is considerable, due to its high slopes in its mountainous reach. Even in the lower course, at the confluence with its most important tributary, R. Mura (238 rkm), the water surface slope is about 0.4 m/km. It drops to 0.15 m/km downstream of *Bélavár* (198,7 rkm) only, where the coarse gravel bed material is gradually refined to coarse sand till *Barcs* (152.7 rkm). From here, the slope remains almost unchanged over the fine sand-bed reach downstream to *Drávaszabolcs* (77.7 rkm) (Figure 1).

River Mura, originally a sediment-laden stream, too, has a slope of about 0,6 m/km upstream of the confluence. Its bed-load contribution to the one of R. Dráva is moderate, due to the river barrages existing in Austria and Croatia. The flow discharge and sediment measuring station is at *Letenye,* situated 20 km upstream of the confluence. Unfortunately, bed-load sampling has been stopped here in 1980, thus, estimated data on annual bed-load transport can not be supported by actual measurements for the last 25 years.

2. Bed-load transport in the investigated reach of River Dráva

Regular bed-load measurements were started at Barcs and at Drávaszabolcs in 1969, however, the data collection has been discontinued in 1983. This interruption was all the more unfortunate, because in 1982 and 1989 two run-of-river hydropower plants have been constructed on the Croatian reach of River Dráva, upstream of the section dealt with in this paper. Besides, in 1982, both countries started regular dredging activities in various parts of the river with the purpose of improving the conditions for navigation and/or obtaining construction material.

In 1998, a demand has aroused to continue the sediment data collection parallel with the modernization of measuring methods and equipment. For the sake of this study, two new cross-sections for the sediment and flow discharge measurements were selected and established at *Botovo* (227.2 rkm) and at *Bélavár* (198.7 rkm) supplementing the stations *Barcs* (152.7 rkm) and *Drávaszabolcs* (77.7 rkm) established in 1961 (Figure 1). The length of the recently investigated reach of Dráva River extends from Botovo to Drávaszabolcs (about 150 km). The details of the bed-load samplers and the tracing method were described elsewhere (Rákóczi and Szekeres 1999).

2.1. Bed material samples and their connections to bed-load samples

Besides some pilot bed material sampling near the two new sediment measuring stations, the local District Water Authority systematically sampled the bed material within the study reach of R. Dráva between 1998 and 2000. The samples were taken at every river km section in 5 points. In Figure 2, showing the distribution of the cross-sectional average grain-sizes along the river, the striking difference of the gravel-bed and sand-bed reaches upstream and downstream of Barcs is clearly visible. Along the Botovo-Barcs reach, several mm changes in grain-sizes can be seen. The reason of it might be the dredging activity, however, the planform of R. Dráva reveals that the finer grains are more characteristic to the fords and the coarser ones to the pools of curvatures of the river channel.

The influence of the flow regime on the *armouring* process, characteristic to the surface layer of gravel beds, is demonstrated by change of grain-size composition of the riverbed at Bélavár. Here the average grain diameters varied from 16 to 20 mm in 2000, while in 1998 they were found around 14 mm. In the Botovo region, this effect is enhanced by the daily peak power generation at the nearby *Donja Dubrava* Croatian hydropower station resulting in repeated sudden water level and flow velocity fluctuations with high riverbed erosion capacity.

Further examples can be obtained for the bed material - bed-load connection and for the variation of average grain sizes along the cross-sections in Figures 3. and 4. summarizing the results of the sediment measurements. The former shows at Botovo station that at mean flow (467 m^3/s) a fully developed armouring could occur on the right- and the left-hand side of the section (2, 3, 4, 5 and 8 sampling points), where the grain sizes are high. The bed-load sampling was not successful at these places, only at the 6. point, where the armouring process was not yet complete. Figure 4. demonstrates that at Bélavár the partial bed-load movement became effective along the entire cross-section at higher flows (983 m^3/s) only, when the erosion-protective armour layer had broken up. In the fine-sand bed section of Drávaszabolcs, obviously no resistant armouring could develop, however, at Barcs there were found some signs of armouring on certain places and flow discharges. The reason for several surprisingly low bed-load discharges measured at Barcs even by medium flow discharges could be a temporary lack of sediment supply from the direction of Bélavár due to increased dredging activities over there.

2.2. Annual bed-load transport

The collection of bed-load data in the gravel-bed reaches was hindered by the armouring process on the bed surface and the results influenced by the various sources of error characteristic for the sampling in gravel- and sand-bed river reaches alike (Rákóczi and Szekeres 2002). After repeated checking the measured data and omitting unlikely results, graphical correlations between water and bed-load discharges (bed-load rating curves) could be established for the sediment measuring stations. As an example, the graphical correlations for the data measured at station Barcs is given in Figure 5. Using the multi-annual time series of daily mean flow discharges and the bed-load rating curves, the annual bed-load transport values were calculated for each station. The results are shown in Table 1. For comparison, also the data *calculated* for Letenye station are given. The reasons for the absence of measured sediment data were described in Chapter 1. By all means, the annual transport values at Letenye are well surpassed by the transport measured at Botovo. It should be considered that several hydropower plants have been constructed also on the River Mura, retarding most part of bed-load arriving from upstream. Besides, the station Letenye is situated 24 km upstream of the confluence with River Dráva, therefore, the unknown bed-load supply from R. Mura to R. Dráva can not be important.

Table 1. Annual bed-load transport of Dráva and Mura Rivers (t/yr)

Year	Botovo	Bélavár	Barcs	Dráva-szabolcs	Letenye
1986	165 587	56 887	117 776	283 545	52 611
1987	126 122	42 059	91 638	228 289	51 937
1988	46 849	14 960	35 117	107 287	13 512
1989	184 710	65 619	128 513	306 357	176 374
1990	52 595	17 389	38 497	96 144	19 727
1991	160 236	54 937	114 182	298 318	63 756
1992	84 295	27 879	61 607	169 380	38 098
1993	144 226	51 819	99 605	231 717	60 910
1994	45 052	14 374	33 798	106 131	11 938
1995	67 872	22 309	49 867	141 590	23 150
1996	178 755	61 605	126 979	322 580	102 050
1997	40 936	13 031	30 757	83 811	11 879
1998	186 499	66 332	129 645	248 529	23 112
1999	121 850	40 571	88 633	241 491	52 042
2000	142 105	49 017	100 896	238 799	19 044
2001	43 353	13 721	32 684	86 067	2 873
2002	62 599	20 927	45 456	108 366	23 962
2003	10 358	3 110	8 119	27 448	607
Average	***109 038***	***37 261***	***77 979***	***194 024***	***43 940***

Depending on the flow regime within the 1986-2003 period, the total mass of bed-load transport varied between 10 000-186 000 t/year at Botovo, 3 000-66 000 t/year at Bélavár, 8 000-130 000 t/year at Barcs and 27 000-320 000 t/year at Drávaszabolcs. Along the reach between Botovo and Barcs the dynamic bed-load supply depends heavily on the flow regime, the effects of the Croatian hydropower plants and on the volume of annual dredging from the river channel. Here the supply shows a decreasing tendency with the increasing distance from Botovo. The supply increases from Barcs to Drávaszabolcs, mainly due to the erosion of soft banks here.

3. Re-supply of dredged bed material in natural ways

Disregarding the unknown and probably not significant amount of gravel bed-load entering the River Dráva from R. Mura, the gravel supply for the section Botovo-Barcs is *not renewable,* because the Croatian river barrages hamper the bed-load supply to arrive here. The possible sources of bed-load transport measured at Botovo are the rearrangement of bed material and intermittent selective erosion processes along the 27 km long reach of River Dráva from HPP Donja Dubrava to Botovo. During higher floods when the gates of the barrage are open, some fine gravel might arrive to this reach rolling down toward Botovo, however, this amount is not significant according to the grain-size composition of bed-load samples. Following an occasional beak-up of armoured bed and from bed material loosened by eventual dredging operations, measurable bed-load transport occurs at station Bélavár. The gravel masses of river channel dredging in the Botovo-Bélavár section are not known. They can only be estimated from the difference of average annual bed-load masses at these stations: 109 038 - 37 261= 71 777 t (Table 1).

The annual dredged bed material masses are given in Table 2. subdivided according to the two riparian countries and to the sand and gravel material. No distinction is made however, regarding the purpose of excavations, e.g. river training or construction industry. It can be seen that in the period 1986-2003 Hungary and Croatia together excavated 6 899 000 t bed material, 5 560 000 t of which was gravel. The former figure equals 328 000 t/yr, the latter 265 000 t/yr in the average, while the average annual bed-load transport varies from 37 000 t (Bélavár) to 78 000 t (Barcs). These data demonstrate that the bed-load transport balance here is negative, i.e. R. Dráva can not compensate the material dredged from the river channel. The higher transport at Barcs can be explained by the fact that the slope of the river drops remarkably downstream of Bélavár as mentioned in Chapter 1. Consequently, R. Dráva deposits a significant part of its bed load, which is intermittently transported further toward Barcs. Geophysical surveys have shown that the river is able here to re-fill dredged pits in a relatively short time, moreover, to build temporary deposits up to 0.5 m thick over the original bed surface.

Table 2. Annually dredged bed material masses in River Dráva (t/yr)

	Hungarian dredging			***Croatian dredging***			
Year	***sand+ gravel***	***gravel 184,2-185,0 rkm***	***sand+ gravel 152,7-157,1 rkm***	***sand+ gravel***	***gravel since 1993***	***since 1993 sand***	***Total dredging***
1982	171 000			472 680			**643 680**
1983	192 420			438 300			**630 720**
1984	238 277			396 000			**634 277**
1985	180 000			316 800			**496 800**
1986	160 200			244 534			**404 734**
1987	206 460			90 000			**296 460**
1988	190 800			180 000			**370 800**
1989	218 880			297 000			**515 880**
1990	116 460			177 059			**293 519**
1991	41 904			109 834			**151 738**
1992	51 696			255 861			**307 557**
1993	60 714			172 211	130 372	41 839	**232 925**
1994	54 000			458 860	375 957	82 903	**512 860**
1995	81 104			428 094	428 094	0	**509 198**
1996	67 000			279 724	228 352	51 372	**346 723**
1997	64 899	1 890	63 009	470 736	262 181	208 555	**535 635**
1998	115 967	63 844	52 123	558 356	361 800	196 556	**674 323**
1999	175 946	124 733	51 214	560 317	166 059	394 258	**736 263**
2000	201 568	147 254	54 313	238 973	238 435	538	**440 541**
2001	188 041	142 834	45 207	128 833	99 497	29 336	**316 874**
2002	230 771	169 956	60 815	21 775	14 364	7 411	**252 545**
Subtotal of marked values		***1 899 729***			***3 659 398***		***6 898 576***

The river reach Barcs-Drávaszabolcs also shows a negative bed load balance i.e. in contrast to the 78 000 t/yr average annual bed-load transport entering the reach at Barcs, 194 000t/yr is leaving at Drávaszabolcs. This is due to the riverbed and bank erosion along this section. The sand excavation has an average annual value of only 101 000 t/yr. By converting the above data into m^3/yr dimension, *the average annual bed degradation* was obtained as follows:

- Along the 46 km long reach from Bélavár to Barcs, taking a river channel width of 140 m, the degradation is 0.35 cm/yr from the bed-load balance and 2.8 cm/yr due to the dredging;
- Along the 70 km long reach from Barcs to Drávaszabolcs, the two kinds of degradations are 0. 58 cm/yr and 0. 50 cm/yr.

4. Checking the rate of riverbed degradations by the changes of hydrological parameters

Figure 6. shows the characteristic annual *flow discharges* (maximum, mean and minimum values) for the 1970-2000 period at station Barcs. It can be seen that the trends of the low and mean flows are almost unchanged. The trend of the peak discharges shows a definite decrease presumably caused by the construction of the Croatian hydropower plants. This assumption is supported by the slightly increasing second trendline (dotted) referring to the 1976-2000 period. This analysis suggests that if the annual minimum and mean *water levels* have a decreasing tendency, *the only reason for it can be the degradation of bed level.*

The trends of annual low, mean and high flow gauge heights are to be seen in Figure 7. also for the station Barcs. It can be seen that all the three trends of characteristic water levels definitely decrease due to the lowering of riverbed The same applies also to station Őrtilos (a Hungarian gauge station near Botovo) where the drop of mean flow levels is 1.20 m and at Barcs this value is 1.60 m during 43 years. These data correspond to 2.8 and 3.7 cm/yr respectively. The drop of low flow levels calculated in a similar way is 3.9 cm/yr at Őrtilos and 4.6 cm/yr at Barcs. In case of station Drávaszabolcs the rate of decrease is less, probably due to the backwater effect from River Danube and to the moderate intensity of dredging: 2.4 cm/yr and 3.0 cm/yr.

The results of these estimations can also be checked by the evaluation of shifting processes of flow discharge rating curves. The upward shift means aggradation and the downward shift the degradation of riverbeds. As an example, the flow discharge rating curves at Barcs is presented in Figure 8. for the period 1972-2000. Between 1972 and 1982 a deepening of about 4.0 cm/yr can be deducted. From that time till 2000 the annual rate of degradation was 3.0 cm/yr in the 400 m^3/s discharge range and 2.0 cm/s in the 1000 m^3/s range. This means 0.8-1.0 m bed level drop within the investigated 30 years interval.

At Drávaszabolcs higher rates of bed degradation (5.0-8.0 cm/yr have occurred between 1971-1979, maybe due to the narrowing of the river channel by a series of spur dikes. This has accelerated the deepening process, which later gradually decreased to 1.5-2.0 cm/yr. The latter values are similar to the ones obtained earlier (1.1 cm/yr) by the bed-load budget method.

5. Conclusions

The degradation of the river channel in River Dráva has been started several centuries ago and its annual rate is changing according to the intensity of human interventions. Cutoff of numerous riverbends around the begin of the XXth century decreased the length of the river and increased its slope, i.e. its erosive capacity. Construction of flood protecting dikes along the river and narrowing its width by spur dikes has further increased the celerity of riverbed deepening. Three hydropower plants erected in the Croatian reach since 1975 have drastically changed the flow- and sediment regime of the study reach of R. Dráva. The gravel and sand dredging operations carried out in various sections of the river by Croatia and Hungary since 1986 have accelerated the degradation process. This gradual deepening of the riverbed not only directly influences the life conditions of the fluvial flora and fauna but decreases the frequency of floodplain inundations and decreases the ground water level in the riparian regions. The present paper succeeded to estimate the annual rate of this process by different methods and to separate the effects of the various human interventions. The environmental consequences make it necessary to decrease the dredging activities to a reasonable level in order to let this precious environment with various water habitats to recover and survive.

6. References

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