ASSESSMENT OF THE BALANCE AND MANAGEMENT OF SEDIMENTS OF THE DANUBE

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Abstract

The paper attempts to analyse the quantitative balance of sediment (historical and current situation) in the Danube with a special focus on the extraction of sediment for the maintenance of waterways and commercial dredging as well as the retention in impoundments of hydropower plants. It includes an analysis of the water tables and their development in the river, and a description of the most important impacts on the hydromorphological system of analysed stretches highlighting the importance of sustainable management of sediments in order to preserve and improve the hydromorphological situation.

Keywords: *sediment balance, sediment extraction, channel incision, hydromorphology.*

1 INTRODUCTION

This article based on the WWF working paper "Assessment of the balance and management of sediments of the Danube waterway" (published in second quarter 2008) founded by WWF Germany. It reviewed data sources on sediment household, channel incision and dredging for the Danube and selected tributaries.

At the beginning a description of different time periods of substantial changes in the sediment transport of rivers in the Danube River Basin should given:

1. 10,000 B.C. to 1,000 A.D.: After the last Ice Age the rivers deposited huge quaternary sediment layers along the foothills of the mountains. During that time period, the rivers formed most of the landscape that is visible today, in particular different terrace systems. The lowest terraces in these systems form today's potential floodplains. The thickness of quaternary gravel layers differs greatly in various catchments of the northern and eastern Alps as well as in the Carpathians.
2. 1000 A.D. to 1500 A.D.: Due to intensive deforestation and increasing agricultural land use, huge amounts of fine sediment reached the rivers and created the so-called floodplain loams in the lower courses. This effect is still present in smaller catchments under specific agricultural practises. This period is also known to have the highest flood marks ever measured at riverine towns in Central Europe.
3. 1500-1700: The first flood protection measures and river regulations ("high water regulations") reduced the floodplain along some river stretches.
4. 1700-1850: Intensive "mean water regulation" was undertaken in order to increase transport capacity. These regulatory methods included river

shortening/straightening (meander cut-off) and riverbed narrowing. As a result, slope and shear stress were increased.

5. 1850-1900: "Low water regulation" (for waterway transport) and other regulation works were implemented. Also, sediments were extracted to be used as construction material for urbanisation.
6. 1900-1950: Construction of power plant chains in the upper river stretches (the Danube and its tributaries) caused a substantial reduction of bed load as well as increased sedimentation in impoundments. Dredging was increased along the entire Danube for waterway transport and construction purposes.
7. 1950-1990: The largest dams were built (Iron Gate I and II, Gabcikovo, Wien-Freudenau (construction began in 1992)), and along with smaller dams on several tributaries, they aggravated the sediment deficit. The amount of dredged material increased until the late 1980s (most of the pre-fabricated multi-storey buildings in "socialist" countries in the Central and Eastern Europe were built with aggregates from river beds), but decreased thereafter.
8. Since 1990: The political changes in Central and Eastern Europe led to a decrease in industrial production, transportation and dredging. Also, no additional large dams were built in the catchment. However since the enlargement of the European Union, economic prosperity has come back to the region, slightly increasing waterway transport. In recent years, several plans to improve navigation and to construct new power plants have been made. The EC also plans to improve waterway transport (TEN-T plans) and to support renewable energies, including hydropower. Dredging today is carried out for navigation reasons, the operation of hydropower plants, flood protection and commercial reasons.

1.1 Method

The original study based on the review of data on sediment balance, gravel and sand extraction, channel incision, legal framework for dredging as well as case studies for quantitative sediment management in other European river basins. National consultants from the middle and lower Danube countries (Slovakia, Hungary, Serbia, Romania and Bulgaria) provided detailed information on their respective river sections and for selected tributaries. Mostly existing data was used, supported by internet research and personal interviews with international and local experts and consultants.

Calculation of the historical sediment transport and sediment balance for the Danube based on the existing quantitative data is very difficult. The existing data covers only the last 50 years, with few samples before World War II. Additionally, the sampling methods differ across the countries. It is difficult, therefore, to estimate the near-natural sediment transport capacity in relation to periods 4 and 5 and, in particular, to period 3 (compare list in the introduction).

One of the main problems is the availability of long-term mean quantitative values, in addition to the methodological problems in comparing the different data sources on sediment balance. Furthermore, major floods strongly influence the amount of annual sediment transport, but this influence has mostly not been monitored due to the transport characteristics during flood pulses.

2 RESULTS

2.1 Sediment transport

As the source of the Danube is situated in the Black Forest highlands with an altitude of less than 1,000 m, little bed load is transported in the very upper stretches. However, with the confluence of the major alpine tributaries (the Iller, Lech, Isar and in particular the Inn Rivers), the transport of bed load increases considerably. The highest values of bed load are observed in the Austrian stretch of the Danube, due to additional supply by alpine tributaries (e.g. Traun and Enns Rivers).

Downstream from Györ, Hungary, the Danube transports mainly sandy gravel fractions. Downstream from Budapest, the gravel gradually disappears from the bed load. From there on, gravel is only deposited in smaller amounts at the confluence with certain tributaries (e.g. Hron). As lowland rivers, the Tisza and Sava bring a lot of fine suspended material, but no gravel. The Velika Morava, as well as some of the Carpathian rivers (i.e. Olt or Siret), transport larger amounts of medium to fine sediments, and gravel in smaller quantities.

Figures 1 and 2 (next pages) display the overall amount and distribution of the gravel fractions of the bed load and suspended load in the Danube River, based on non-harmonised national and international datasets.

2.1.1 Bed load

In the past, the river received most of the bed load within the Bavarian and Austrian stretches. Due to the construction of many power plants and reservoirs in the upper catchment and many other tributaries, the flux of coarse sediments (gravel) has decreased to nearly zero in several stretches. Consider the following example of bed load decrease near Vienna: At the very end of the 19th century and after strong mean water regulations, the increased amount of transported bed load was about 1.7 million t/yr (before 1850 the average transport is estimated at about 900,000 t/yr according to Schmautz et al. 2000), from the beginning of the 20th century till the 1960s, it was 1 million t/yr, between the 1960s and 1980s - 600,000 t/yr and in 1995, before the construction of the last power plant in Austria "Freudenau", it reached about 300,000 t/yr. Without the current artificial feeding of an average 160,000 t/yr, the bed load transport would be very low and only further downstream slightly increasing, mostly because of bed incision. But downstream of the Gabcikovo dam and after the confluence with the old Danube, huge amounts of fine gravel are transported (up to 400,000 t/yr, with 7-10 mm grain size instead of 25 and 30 mm grain size near Devin at the Austro-Slovakian border).

Naturally, the gravel bed load downstream from Gonyu (rkm 1,792) decreases slowly due to the reduced slope and flow velocity of the river and consists mostly of fine gravel. However, on the middle and lower Danube, local confluences of tributaries can change the substrate when they add gravel to the Danube. For example, the Hron joins upstream of the Danube bend, introducing grain sizes of up to 70 mm, and where Velika Morava enters, it brings grains of up to 60 mm. Also in the former Iron Gate stretch, the substrate changes and gravel and rock occur naturally over many kilometres. Along the lower Danube, tributary confluences, as well as erosion along cliffs, introduce coarser material, which is of great importance for sturgeon spawning. Also the bed load coming from tributaries along the lower Danube is considerably reduced by dams in the catchments.

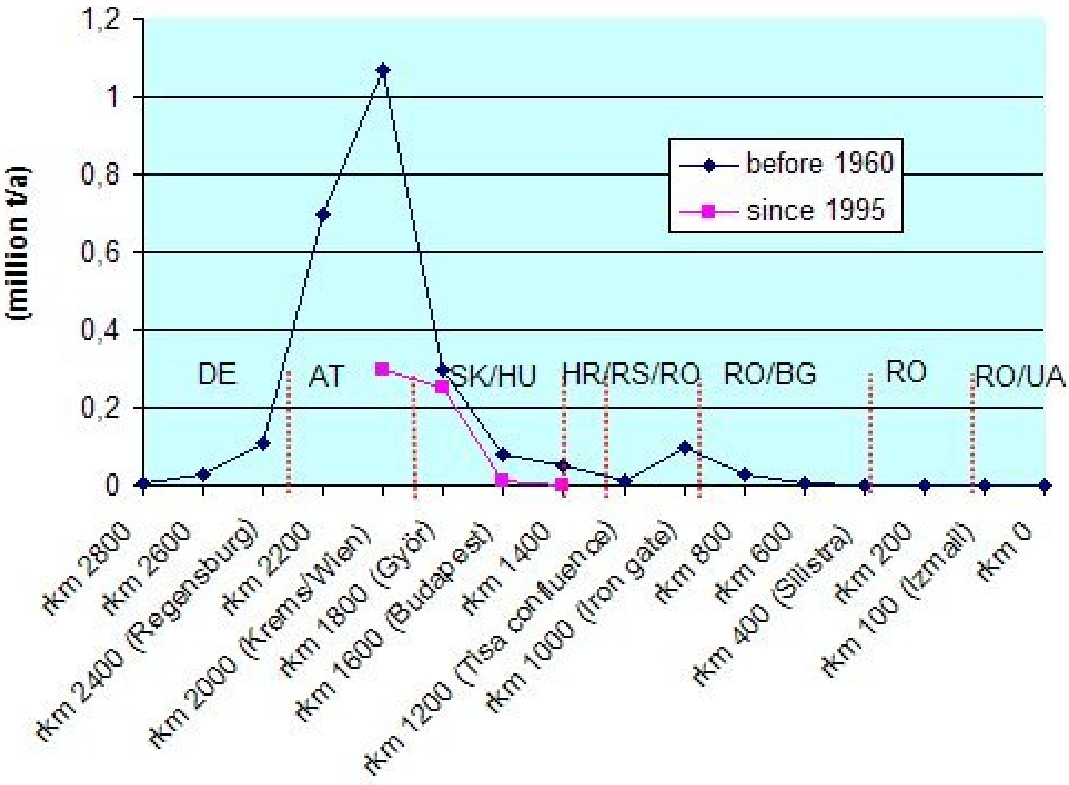


Figure 1: Gravel fractions of the bed load transport within the Danube. NOTE: It is important to show the national borders to point out the different data sources and missing harmonisation of the data. Recent bed load data was only available from Vienna to Budapest. The data is based on the following sources: for the period before 1960, on Danube wide summaries by Laszloffy (1967); from 1993 the Danube Monography (Unesco/IHP 2003); and for Austrian and Slovakian data since 1995 - Holubova et al. 2006 and Zottl & Erber 1999.

After the construction of hydropower plant chains along the Inn and the Danube in Bavaria and Austria, the bed load decreased considerably. Since about 1995, Austria has been artificially supplying gravel downstream from the Wien-Freudenau power plant.

It is important to mention that the gravel fraction is only one part of the bed load. For the Serbian Danube stretch, the sandy bed load can be estimated at 5-10% of the total load. It amounts to almost 0.5 million t/yr. Large dunes on the riverbed are observed, which is a form of bed load movement. For the Romanian Danube, Batuca et al. (2005) gave the value of 3-5% (dune-linked transport) of the total load (0.6 million t/yr) having grain sizes from 0.21-0.25 mm.

Regarding morphological changes the entire upper course was modified (excluding the narrow gorges and breakthrough sections in particularly from multi-channel or braided and anabranching river types into mono channel systems. The entrance of the Danube into the Pannonian plain is characterised by various morphological transition types from braided, sinuous anabranching to meandering stretches. The Gabcikovo power plant with large bypass canal completely changed the morphological conditions: backwater stretches up to Bratislava, and the old Danube bed remains with small residual water. Downstream from Budapest the river morphology in the past was characterised by meandering types, and further downstream to the Drava confluence – by strongly meandering conditions. Most of those stretches were completely modified by river rectification and meander cutoffs; e.g. from Budapest to the Drava confluence, the length of the river was reduced by more than 50%. The increased gradient and flow velocity also changed the morphodynamics over large parts of the river.

2.1.2 Suspended load

For the suspended load, the retention in the upper catchment by river barrages or any kind of impoundment is not as efficient as for the bed load. In particular during floods huge amounts of fine sediment are transported from the upper to the lower catchment.

In the lower Danube the transport of suspended load currently reaches only 30% of the previous load before the construction of the Iron Gate dams (see Fig. 2). In the delta region, only 34% of the natural sediment load remains (18 instead of 53 million t/yr).

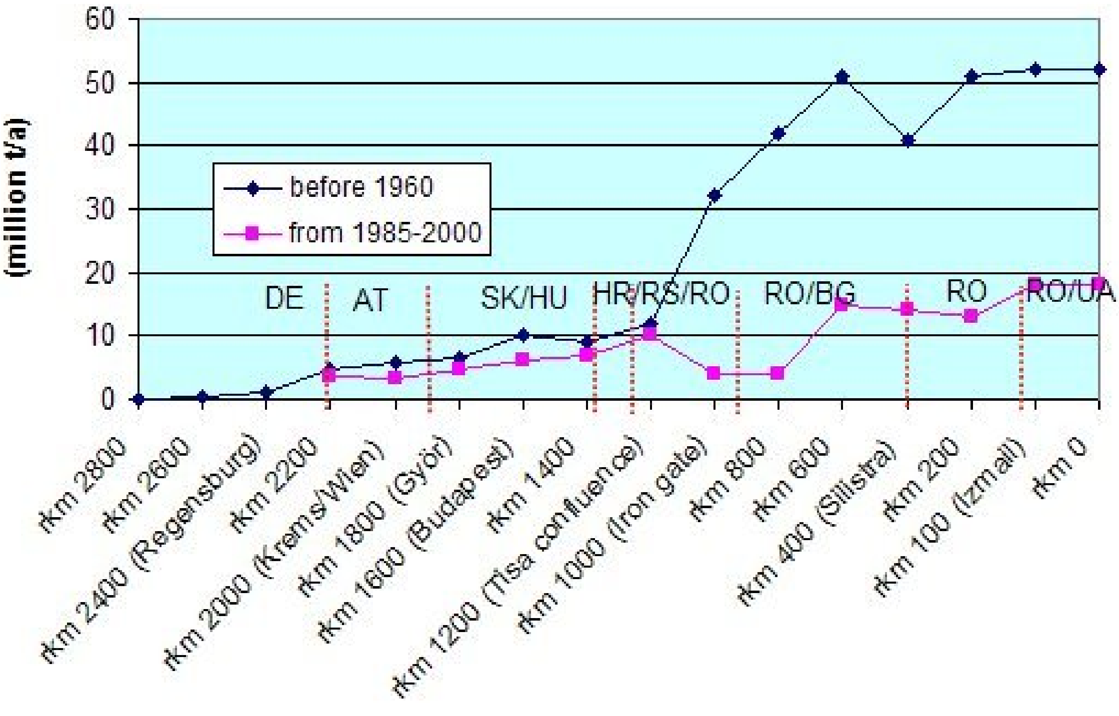


Figure 2: Suspended load transport within the Danube (the data is based on several sources). For the upper Danube, the Danube Monography from 1993 with updates for Serbia (Bruk et al. 2002) was used; for the lower Danube (RO) the data is based on Bondar et al. (2000a).

Table 1: Average trapping efficiency of reservoirs for suspended sediments on the Danube River (information by national consultants).

Location	Trapping efficiency, %
Austrian dams	15%
Gabcikovo	66%*
Iron Gate I	80%

*Between 1958–1960, before the construction of Gabcikovo, the floodplain between Bratislava and Sap also trapped about 30% of suspended sediments

The total suspended load exceeds the bed load amount from the upper Danube and increases continuously downstream to the Danube delta. The construction of the Iron Gate power plants with an impounded backwater stretch of up to 300 km led to a significant reduction of the suspended load along the lower Danube, which then slightly recovers towards the delta. The trapping efficiency of the Iron Gate reservoir is between 66% (year with flooding) and 85% (dry year), and on the average is 80% (see table 1).

Due to the very detailed mapping of the navigable Danube since 1909 along the lower Danube, a lot of data concerning bathymetry, width of the channels and islands is available to compare morphological changes. The river bed undergoes a permanent erosion process downstream of the Iron Gate dams along the entire RO-BG transboundary river stretch, which means more erosion, unstable banks, more shallows (navigable water depth < 25 dm) and more islands. The number of islands increased from 93 with a total length of 283 km in 1934 to 135 with a length of 353 km in 1992 (Bondar 2000b).
Together with the reduced sediment load of the Danube, most of the RO and BG tributaries lost most of their sediment load due to the construction of chains of dams (e.g. Jiu, Olt, Arges, Ogosta, Iskar), aggravating the erosion processes. The reasons for these more unstable conditions lie not only in the reduced sediment transport, but are also closely related to the 90% reduction of the floodplain areas and to the various river engineering measures.
The delta has different characteristics and it is not easy to determine the annual changes because the water level in the Black Sea is rising by about 3 mm each year. Generally, the discharge has decreased in the Chillia branch and now the strongest erosion can be observed in the Sulina branch, which is continuously being straightened and protected by rip-rap for sea-to-river navigation purposes. Also, the Sfantu George branch shows a slight deepening tendency due to meander cuts in the past 15 years. All banks of Danube delta river branches are subject to erosion because of unwise dredging and is accelerated by waves (caused mainly by ship traffic). Therefore, the Chilia branch has a tendency to widen by about 2 m per year.

2.2 Water level lowering and erosion on selected river stretches

The lowering of the water level can be observed along nearly the entire free-flowing Danube, particularly for low water stages. In impounded stretches, no incision occurs, only the aggradation of sediments*.* Figure 3 shows the general impacts of channel degradation such as instability of infrastructure and lowering of ground water levels. Secondary impacts are the disconnection of side channels and floodplains and often the aggradation of fine sediments in the floodplain as well as increasing floodwater peaks as result of reduced flood cross sections.

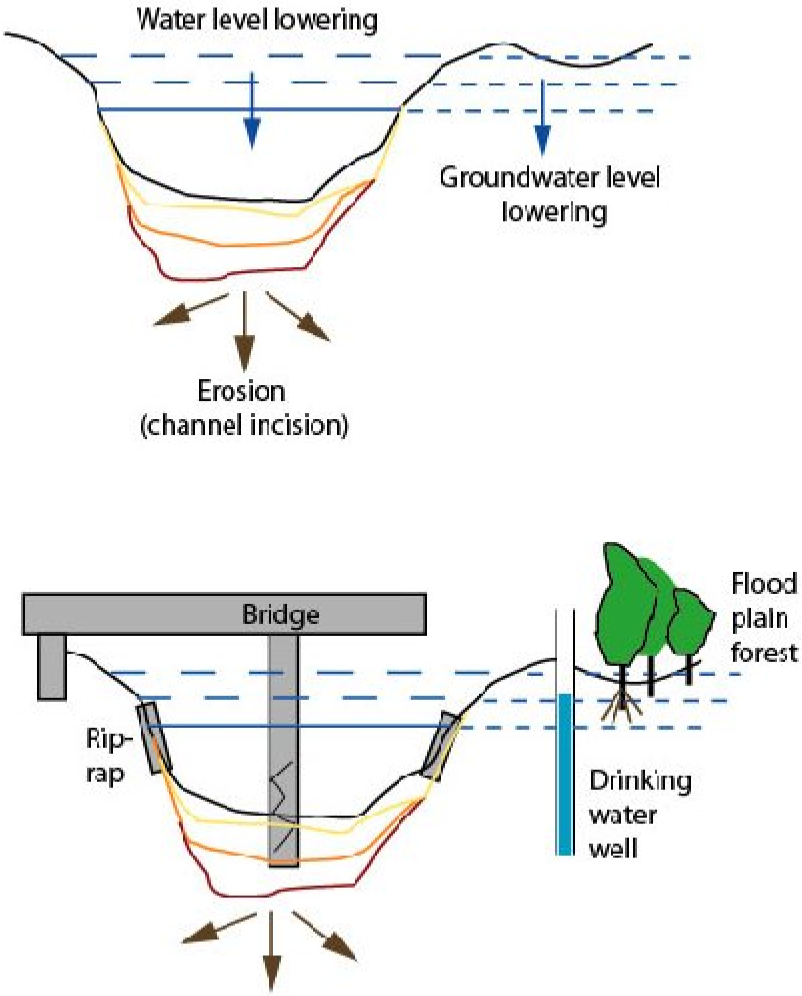


Figure 3: Channel incision and its impacts on the stability of infrastructure, groundwater and the floodplain.

In Bavaria, the reach from Straubing to Vilshofen has an overall lowering tendency of 1.5 cm/yr (overall tendency means and includes the existence of short stretches with accumulation tendencies near tributary confluences or river engineering measures). Along the Austrian Danube, in the free-flowing stretch within the Wachau a slight deepening of 0-1 cm/yr is observed, and the stretch downstream from Vienna has a lowering of 2-4 cm/yr. Along the Hungarian-Slovakian border the channel incision downstream of the power plant Gabcikovo is 2-3 cm/yr and then reduces downstream of Komárno, where it reaches 1-2 cm/yr (but also as a consequence of the Danube bend gorge, which is a regional erosion base). The overall incision for Hungary is estimated to be at about 1-3 cm/yr. For the Serbian reach further downstream to the Iron Gate backwater (near the Tisza confluence) there is no clear evidence of channel incision. Downstream from the Iron Gate dams, the incision along the Romanian-Bulgarian Danube reaches an average of 2-3 cm/yr.

Table 2: Incision rates for the upper and middle Danube

River	Stretch rkm	Incision at LW level	Total incision during a given time period	
Danube	Straubing-Vilshofen (rkm2,320-2,250)	1-1.5 cm/yr	In short term 20-30 cm	
	Wachau	0.5 cm/yr	1.5 m between 1956-1991	
	Tullnerfeld		1.4 m between 1895-1950, due to river regulation (later “stopped“ by hydropower plants)	
	Wien-state border to SK	3 cm/yr	2.2 m between 1960-2001	
Danube	Sap - Komarno	2.2 cm/yr	1.0 m between 1957-2003	
	Danube Bend	0.5 cm/yr	1.5 m between 1956-1991	
	Budapest-Mohacs	1.5 cm/yr	2.1 m between 1950-1999, at Gemenc	Average deepening of the reach between Dunaremete (rkm 1,826) and Mohács (rkm 1,447) between 1901 and 2006 is 1.38 meters, the minimum incision (0.80m) being observed at Esztergom (rkm 1,719) and the maximum (2.16m) at Dunaföldvár (rkm 1,560).

Due to the permanent sediment deficit on the one hand and the river regulation with resulting increased erosion capacity (shear stress) at the bottom on the other hand, all remaining free flowing stretches of the German and Austrian Danube already had the tendency for incision, even before the chain of power plants were completed. In some Danube tributaries, the incision amounted to several meters, including the adjacent groundwater bodies – even more than in the Danube.

For the Austrian stretch, the incision before the construction of the chain of hydropower plants between 1893-1952 was considerably high near Mauthausen (rkm 2,112), with up to 1.2 m deepening since about 1850, and nearly the same value near Zwentendorf (close to Tulln, 30 km upstream of Vienna). The river stretches in between are characterised mostly by permanent incision values of 25-40 cm within this period.

This clearly indicates how much the river regulation is responsible for the channel incision since about the middle of the 19th century. On the other hand, hydropower plants also influence long stretches, causing very strong erosion downstream of the dam and often accumulation tendencies further downstream. Excessive gravel exploitation also leads to regressive bed erosion. For example, intensive dredging in the 1970s and 1980s in the Slovakian reach of the Danube increased the incision between Hainburg and Bratislava from some 10-15 cm during 1960-1970 to up to 1.2 m in Bratislava from 1970-1986.

The Danube in the vicinity of Bratislava is subject to different influences and tendencies. Due to the increased gravel feeding and also due to the ending of backwater of the Gabcikovo dam, the stretch in Bratislava can be seen as an accumulation stretch. Downstream from the Cunovo weir (barrage on the old Danube river channel) the erosion is stronger, particularly downstream from the main dam (power house, sluices) when the bypass joins the former Danube again. Changes in low flow water level indicate that there is a permanent incision of up to 1.8 m in Sap (rkm 1811), and 1 m on average over the past 50 years in the section between Sap and Komarno. Another reason for the incision is the erection of groynes and partial dredging for waterway transport during low water periods. The amplification of adverse effect on low water level is significant.

In the 1980s a drying process of the floodplains on the lower Hungarian Danube reach became evident. The analysis of the water levels showed that the riverbed of the Danube was lowering. River regulations (mean water regulation and shortening of nearly 50% of the meander reach) in the 19th century and regional dredging are responsible for the lowering. According to Kalocsa et al. (1997), the maximum deepening of river bed until 1990 was 180 cm at the Paks gauging station.

Extending the data series in the analysis to 2005, the highest decrease is 216 cm at the Dunaföldvár station. Here the former investigations showed only 140 cm lowering, but the incision process now at this station seems to be faster compared to other stations or to previous periods. Taking the dredging activities in the reach into account it seems that dredging played an important role in this fast deepening reach (Tamas, 2006).

For the lower Danube the channel incision is very differentiated and not the result of only one factor. Downstream from the Iron Gate dams, the erosion (in depth and width) is reasonable, but not physically measured and published. Only an estimate of an incision of 80 cm since the construction of Iron Gate dams based on suspended sediment loads according to Bondar et al. (2000b) was published.

Concerning the sediment deficit, all tributaries from Romania and Bulgaria are characterised by decreased transport due to numerous dams built since around 1960. In addition to the reduced sediment transport due to dams, the moderate river engineering measures, and in particular the loss of nearly 90% of active floodplains, raised the pressure and instability of the main channel. Bondar provided data for this study showing increasing number of islands and partly increased lateral erosion. Erosion stretches are followed by accumulation stretches, regularly causing navigation problems during low water stages.

Based on (a) the sparsely published long-term incision data, such as the data from Batuca 2005, which gives a value of 1.5 m incision for the Romanian town Giurgiu between 1977-2003, (b) the considerable transport reduction (and incision rates calculated by Bondar based on suspended load), as well as (c) the large amount of dredged material, it can be estimated that large parts of the lower Danube are subject of an, at least, moderate channel incision of 1-2 cm/year.

2.3 Current situation of dredging and extraction

The extraction of sediment is mostly related to the clearance of cross sections of flood ways and the retention in the upper catchments for hydropower and flood protection purposes. In the middle and lower river courses, commercial extraction becomes more important. In Germany and Austria, commercial extraction is carried out almost completely outside of the active channels, mostly within the morphological floodplain and lower terraces. However, along many other sections of the Danube and its tributaries, the regular extraction from rivers is common.

Where the rivers are used and maintained as waterways, the extraction of sediments plays an important role. For example along the Danube east of Vienna most of the bed incision is related to dredging for the waterway (about 900,000 m³ were dredged during 1994-2003, or 100,000 m³/yr). In Germany and Austria, most of the material extracted for the maintenance purposes will be returned back to the river in other stretches. For the project Straubing-Vilshofen, e.g. in the planning alternative without dams, 135,000 t will have to be extracted, but about 140,000 t will be added to the pools. In the 1970s, 150-250,000 t/yr were extracted from the German Danube. Today, the overall amount is about 45,000 t/yr (mostly from the backwaters of the Kachlet power plant).

Sand and gravel are the most important raw materials for construction and aggregates for concrete and other construction elements. Gravel is used, in particular, for foundations, line construction (mostly for roads) and other infrastructure.
Sand and gravel mining is dependent on postglacial terraces, particularly when the larger rivers leave the mountain foothills. After the instances of excessive gravel mining from rivers, the extraction sites move into the active floodplain. Along some stretches, such as parts of the Bavarian Danube, the deposits within the recent floodplain are already mostly exploited. Because of this, the mining areas move further into the morphological floodplain or even into terraces far from the river. In intensely used landscapes such as the Upper Rhine valley, abandoned gravel pits can be valuable secondary biotopes in the cultural landscape. In such cases the mostly open connections to groundwater bodies have to be protected from water pollution.
The demand for gravel in the region of Regensburg (pop. ca. 250,000) is estimated to be about 2.2 million m³ per year. In Switzerland, the demand is estimated at about 25 million m³ per year. The demand per capita in Germany is about 2-5 m³ per year , and in Switzerland – about 4 to 5 m³. If a similar level of demand – 1-2 m³ per year per capita – is assumed in the Central Europe, taking into account their growing economies, for the Danube region this would mean a demand of 120 million m³ per year (Germany with comparable pop. of 80 million needs about 400,000 million m³).
In some decades, particularly between 1960-1990, about 100 million m³ of sediment were extracted from the Danube. In many countries it can be estimated (Bauer 1965) that the gravel tributaries were used even more extensively. Currently, the sediment

extraction is mostly focused on the tributaries in the lower catchment (e.g. Mures in Romania).
As an example, 10 million m³ of extracted material within 200 rkm with an average river width of 0.5 km causes 10 cm lowering of the river bed, or an incision rate of 1 cm/yr.

In the German reach of the Danube, since 1896 excavations usually extracted much higher bed load amounts than the river transported. Until 1960 the dredged amount was still about 250,000 m³/yr, whilst the average transport at Straubing was about 80,000 t/yr (Bauer,1965).
For the still free-flowing reach from Straubing to Vilshofen, different project alternatives for improving navigation conditions were evaluated – status without improvements and different alternatives, including dams and low water regulation works. Estimations for the needed dredging, according the Bavarian Ministry for Economy, Transportation and Technology (2001), reach up to 140,000 m³/yr for the alternative with the deepest navigation channel.
Until the construction of the Wien Freudenau dam, the extraction of sediments in Austria was mostly carried out for navigation improvements (similar to other Danubian countries). Due to the situation in the National Park downstream from Freudenau after the dam construction, several fords and shallows established farther downstream. These have to be dredged regularly (some 100,000 m³/yr).
The impoundments of Altenwörth near Krems, where the Danube leaves the Wachau, are regularly dredged for some 180,000 m³/yr, and 15,000 m³/yr are dredged in Abwinden-Asten, where the tributary Traun still feeds gravel into the Danube. The clearance of the dammed sections along the Austrian stretch can reach in total about 190,000 m³/yr.

In Slovakia near Bratislava, the sediment extraction for flood protection and navigation reasons increased during the 1990s. One reason was the above-mentioned sediment management in the Austrian reach, and the second one – that backwater of the Gabcikovo dam begins in the city area of Bratislava and increases sedimentation processes there. A total volume of 2.6 million m³ was extracted during 1999-2003, approximately the same amount as the river transported into this reach during that time.
Downstream from the Gabcikovo dam, dredging for navigation purposes increases the instability of the river.
Between 1972–1982, an amount of 8,165,743 m^3 was dredged between rkm 1857-1869, mostly for commercial reasons. The amount extracted between Szap and Szob (Slovak-Hungarian Border) between 19970-1992 is estimated at 60-65 million m^3, whilst today's regular maintenance dredging on the whole Hungarian Danube reach amounts to only ca. 100,000 m³/yr.
Rákóczi (2000) documented the dramatic incision of up to 9 cm/yr, which occurred between 1973-1985 near Bratislava, and 8.5 cm/yr during 1966-1985 in a 30 km long stretch near Rajka (where today the tailrace canal of Gabcikovo starts). Further downstream the incision rates are much smaller depending on local dredging activities. The sum of the total incision during the period 1960-1987 can be estimated at about 1 m for Szigetköz and about 70 cm near Nagymaros, which can be directly related to the huge dredging amounts.

Rákóczi (2000) compared the phase of intensive construction of housing in Hungary (1970-1985) with the sand and gravel exploitation from the Danube, and found a clear correlation.
On the lower Hungarian reach downstream from Budapest, the amount of extracted bed material in the last ten years (1997-2006) is close to 12 million m^3.
In Serbia, dredging licences are valid for one year. In 2004, permits for the dredging of 24 million m^3 from the Danube were issued. There is no capacity for such a huge dredging, as most of dredging companies are not operable. Some 20 or 30 years ago, when large dredgers were operating, the total amount of dredging in Serbia did not exceed 10 million t/yr. During the period 1978-1988, for the Serbian part of the Danube from rkm 1,333 to rkm 1,382 (mouth of the Drava river), permits were given for dredging of about 5 million m^3 but it is not clear whether this material was really dredged.

Table 3 shows a very similar picture for the Romanian-Bulgarian border reach like for many other Danube countries, with extraordinary high dredging volumes for commercial reasons in the period from 1970 to 1990 and a strong decrease up to today. However, the average total annual dredging amount for the period from 1991-2005 still was about 2.5 million m³/yr and is further slightly decreasing.

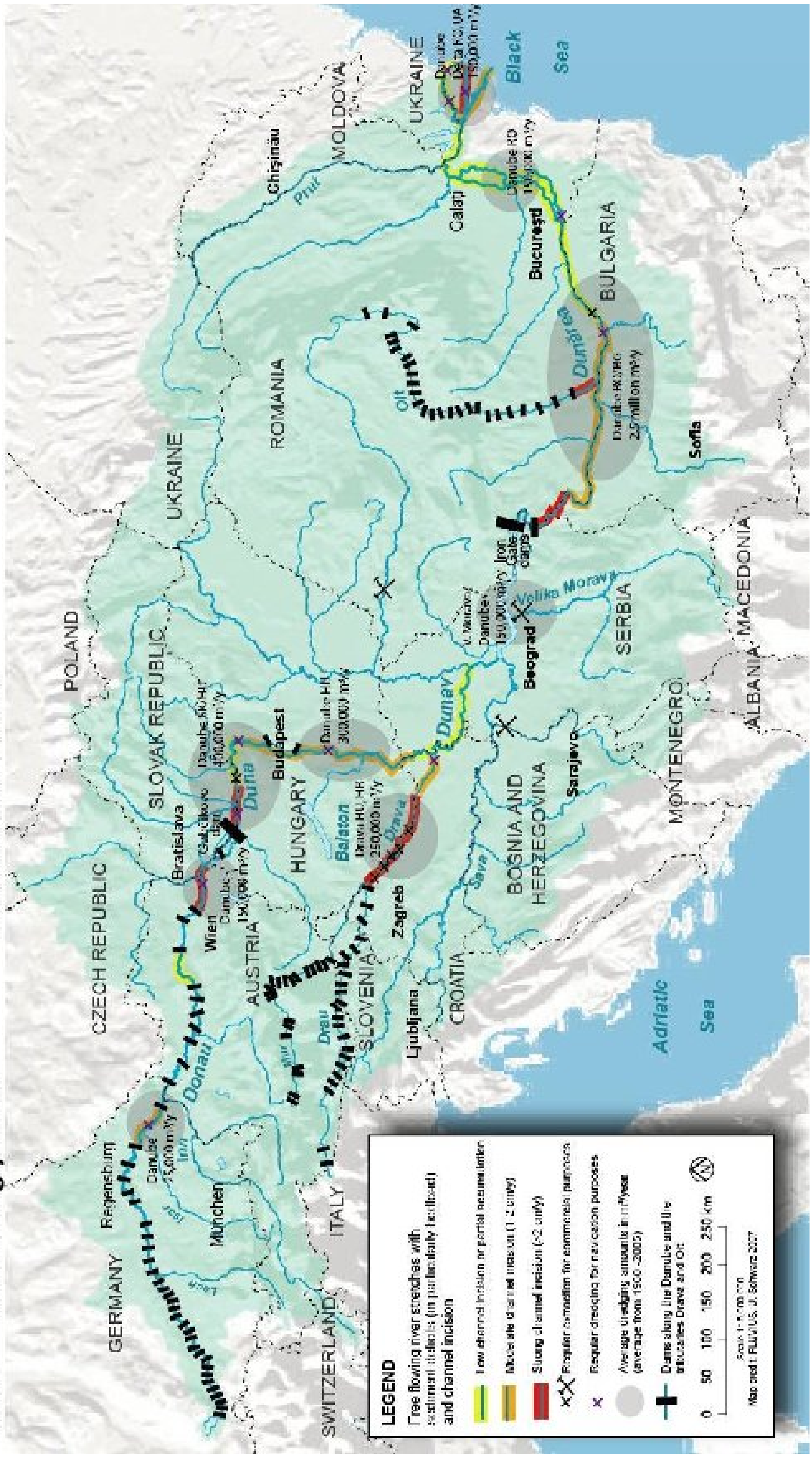
Table 3: Dredging amounts at the common Bulgarian-Romanian Danube stretch (470 km), in $m^3 * 10^3$ (data from national consultant Modev). 1* - dredging for commercial purposes, 2** - dredging for navigation maintenance

		Romania			**Bulgaria**			**Total**		
Period		1*	2**	sum	1*	2**	sum	1*	2**	sum
1961-1990		35131	28056	63187	12739	11169	23908	47870	39225	87095 **2903/y**
1991-2005		2017	17043	19061	427	6785	7212	2444	23828	42889 **2859/y**

An EC-Phare project identified bottlenecks close to Belene Island, between Svistov and Russe, and a huge sand bar close to the bifurcation near Silistra (Harris 1999). In those stretches, the minimum water depth decreases below 1.5 m for at least 2 months. The estimated annual dredging amount needed to fulfil the international navigation agreements (25 dm for RLW) is estimated at 4 million m³ for the entire Romanian-Bulgarian Danube stretch (huge dredging ships with capacities of about 50,000 m³/week would be necessary to carry out the works). The costs for maintenance dredging are estimated at about 3 €/ m³ (Harris 1999). Nowadays a new project downstream from Calarasi foresees comparable amounts. Further improvement works with low water regulations, closure of side channels and bottom sills are planned.

Finally the figure 4 (map on next page) try to integrate most of the results for channel incision and dredging and shows the most important dams along the Danube.

Figure 4: Danube Map: Sediment extraction and channel incision along the Danube and selected tributaries



3 CONCLUSIONS

The channel and bed incision has been caused firstly by the intensive river regulation since about 1850, which caused increased erosion and sediment transport, secondly by the sediment deficits resulting from the sediment retention in hydropower dams and reservoirs, and thirdly by dredging.
The sediment balance must be seen as closely related to any further river regulation works, in particular the narrowing of river channels by low water regulation schemes on the one hand, and hydromorphological restoration activities increasing the resilience of the systems on the other hand.

- In many stretches of the river, the extracted amounts of gravel and sand exceeded or still exceed the amount that can be naturally transported from upstream. The effects of local dredging are apparent far up and downstream, and it often takes years or even decades to fill dredging holes and to re-establish a new balance of the riverbed; sometimes alterations are irreversible. The continuation of unregulated or commercial extraction from riverbeds should be stopped in general. Dredging for maintenance purposes (navigation, flood protection) should be minimised and carefully prepared in consideration of overall environmental objectives (e.g. WFD), and its implementation should be monitored.
- The main consequences of dredging and river regulation include hydromorphological degradation and channel incision followed by lowered water tables and reduced flood frequency in the floodplain. The massive reduction of morphological dynamics (i.e. fixation of river banks) can also increase the fine-sediment aggradation on banks and floodplains during floods. Furthermore, erosion downstream from hydropower dams leads to sediment accumulation further downstream and associated reduction in the average water depth, which hampers navigation and therefore necessitates additional dredging.
- The construction of chains of hydropower plants reduces the amount of bed load considerably (coarse sediment in the upper course, up to 90% reduction, and sand in the lowland river stretches, over 30% reduction). The Iron Gate dams with their 300 km backwaters severely reduce the suspended load: their retention efficiency is on average 80%, and suspended load is reduced in total over the whole lower Romanian-Bulgarian Danube (600 rkm) by about 36%. In addition to the Iron Gate dams, the chains of dams along the lower Danube tributaries are also responsible for the sediment deficit. Therefore, the sediment continuum should be re-established as much as possible.
- There are only a few clear legislative regulations concerning the extraction of gravel and sand from the rivers (different from contaminated fine sediments, which are more regulated), and only in Germany and Austria do regulations assure that the amount of sediment dredged in the river bed for maintenance work is returned to the river (in a different location, i.e. no net loss). Sediment management must be more transparent and a regular surveillance of dredging activities by independent authorities should be established.
- The sediment balance should be integral part of planning assessments concerning waterway transport, EC flood directive as well as EC Water framework and groundwater directives.

- Independent from the proposed recommendations, which are based on data that is sporadic and difficult to compare, it is absolutely necessary to undertake joint efforts to increase data reliability and to further harmonise the quantitative sediment assessment through international programmes, such as the UNESCO/IHP ISI (International Sediment Initiative) and by the Danube Commission (ICPDR 2006).

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