Lack and surplus of sediments being transported by river systems

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Abstract The aim of this paper is to analyse the situation related to the lack and surplus of sediment transport in river systems. Major environmental changes, trapping of material in reservoirs and lack of sediments in free flowing sections of rivers are discussed for the Alpine region and the large rivers in Austria. Reservoir sedimentation attains values between 100 and 2000 $m^3\ km^{-2}$. In the case of large rivers (mean annual discharge > 30 $m^3\ s^{-1}$), about 36% of the total length of 1884 km is impounded and only 35% remains as free flowing sections. The percentage with a lack of sediment reaches 66% in maximum compared to 70% in maximum with a surplus. The lack of sediment leads to bed degradation and reduction of dynamic gravel bars, whereas the surplus of material is associated with reservoir sedimentation, which causes security problems in reservoirs and ecological deficits in rivers. A study of the River Drau in Austria shows one way to reduce these deleterious effects could be to increase river bed width in the remaining free flowing sections.

INTRODUCTION

Although erosion and sedimentation have always been active throughout geological time and have shaped the present landscape of our world, erosion, transport and sedimentation can cause severe engineering and environmental problems (Julien, 1995). These problems mostly result from river training works, construction of water power plants, changes in land use, deforestation, and construction of roads and other elements of the infrastructure.

The aim of this paper is to focus on the interaction between the lack and surplus of sediments being transported by river systems, with reference to the large reservoirs and rivers of Austria. Recent modifications of river engineering methods to reduce the gap between the lack and surplus of sediment are presented for the River Drau.

SEDIMENT PRODUCTION AND LARGE RESERVOIRS

Large catchments in Alpine regions deliver on average an input of about 4 to 100 $m^3\ km^{-2}$ of sediments which are often trapped in large reservoirs. The largest reservoir and highest dam in Austria is the Kölnbrein Dam with a storage capacity of 190 hm^3 and a height of 200 m. Other annual storage reservoirs have capacities between

Table 1 Sedimentation data for reservoirs in Austria (after Arbeitsausschuß Wasserkraftnutzung im Gebirge, 1991).

Reservoir	Start of operation	Storage capacity	Catchment area (total)	Sedimentation ($10^3 m^3$):		Denudation	Duration of sedimentation
		(hm^3)	(km^2)	total	$year^{-1}$	($mm\ km^{-2}$)	(years)
Wasserfallboden*	1961	86	142	996	29.3	0.38	3000
Schlegeis*	1971	129	131	158	14.4	0.16	9000
Tauernmoos*	1929	67	50	1700	30.8	0.86	1800
Durlaboden*	1967	63.5	76	918	54.0	0.90	1000
Mooserboden*	1955	87	99	234	8.7	0.14	10 000
Gepatsch*	1964	140	279	390	20.0	0.11	7000
Silvretta*	1960	38.6	46	-	70.0	1.75	5500
Raggal**	1968	2.4	160	700	41.0	-	(60)
Margaritze**	1963	4.16	64	429	15.4	-	(280)
Stillup**	1969	8.2	269	412	41.2	0.25	(200)
Bürg-Kaprun**	1649	0.24	28	291	7.8	0.28	-
Bächental**	1961	0.69	60	687	22.0	0.37	-
Wiederschwing**	1962	1.16	153	200	6.3	0.04	180
Gerlos after 1987	1945	0.88/	188/	470	(60)/	0.40/	-/-
before 1987**		0.93	157		(15)	0.1	

*Annual storage
**Daily, weekly storage

40 and 150 hm^3 (Table 1). According to measurements, the reservoir sedimentation in Austria ranges between 100 and 2000 $m^3\ km^{-2}$ (Schöberl, 1992). Large reservoirs trap about 100% of the incoming sediments because they act like lakes, where flow velocities can be neglected.

In the Alpine region, the reduction of storage capacity is of no major concern, and the theoretical time period to complete sedimentation is somewhere between 1000 and 10 000 years. Nevertheless flushing of fine sediments out of reservoirs increasingly becomes a critical task in Austria. On the one hand, sedimentation of reservoirs causes problems with functionality of bottom outlets of reservoirs, which leads to risks concerning the stability of dams. On the other hand, spilling of fine sediments out of large reservoirs may cause problems in the rivers, where ecological and economical influences due to a surplus of sediment might occur.

RIVERS

In Austria about 36% of the length of the large rivers (average discharge greater than 30 $m^3\ s^{-1}$) are impounded, and only 35% remain as free flowing sections (Fig. 1). The rest are heavily influenced by surge effects and diversions (Fig. 2). A very high percentage of the free flowing sections is affected by regulation, bank protection measures, flood protection measures and also by water quality problems (Muhar, 1992). Sediment transport varies in several respects between the major rivers in Austria.

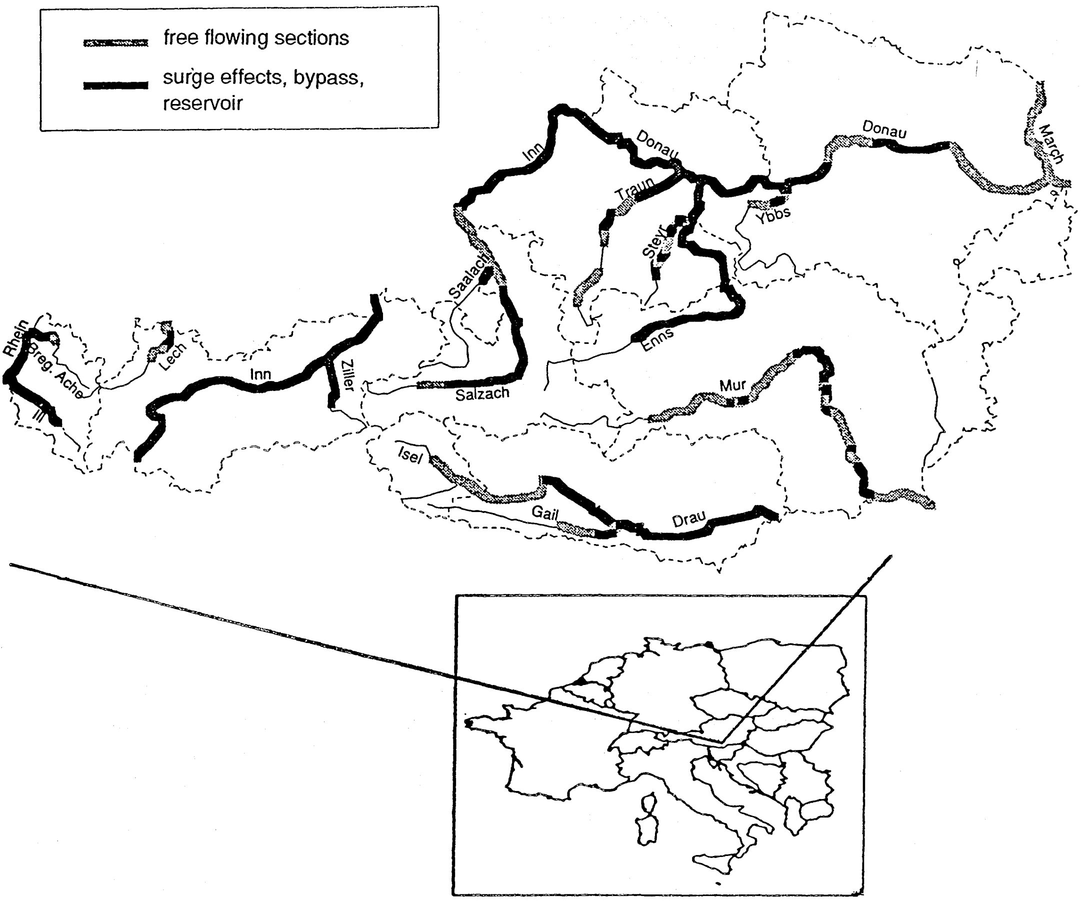

Fig. 1 The distribution of free flowing sections and reaches with surge effects, bypasses and reservoirs in the large rivers in Austria (MQ > 30 m^3 s^{-1}), after Muhar (1992).

Danube

The Danube, which was the largest river studied and had the greatest length investigated, has about 30% of its course as free flowing sections. The major concern from an engineering point of view is the section downstream of Vienna, where degradation rates of up to 2 cm $year^{-1}$ occur (Habersack & Nachtnebel, 1995). This degradation is mainly caused by a lack of sediment and an increase of shear stresses, and over the last 120 years regulation measures have lead to a lowering of the river bed by about 45% (Radler *et al.*, 1993). If the distribution of reservoirs and free flowing sections are considered, it is obvious that especially bed load transport has been interrupted by a chain of water power plants upstream of Vienna (with the exception of the Wachau reach, Fig. 1).

Sedimentation in reservoirs of the Danube is monitored and management strategies have been developed. Of course it is mainly suspended load that may be flushed out, and a large quantity of bed load still remains in the reservoirs. Figure 3 shows longitudinal

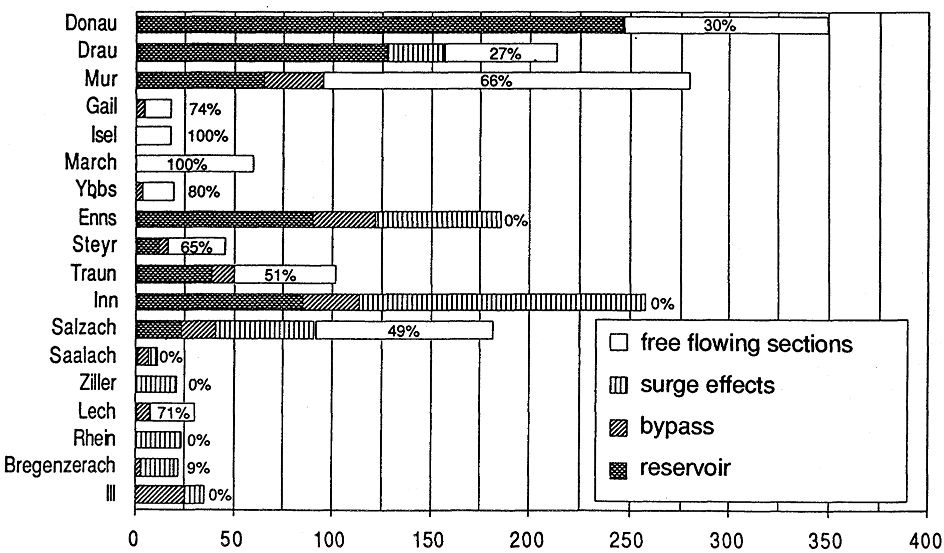

Fig. 2 The percentage of free flowing sections, reaches with surge effects, bypasses and reservoirs in 18 rivers of Austria (river length im km), after Muhar (1992).

sections of the reservoirs and the distribution of bed elevation changes. The letter S marks the point in each reservoir where the uppermost sedimentation of suspended load takes place. The effective head at the weir is marked with the letter H. It is interesting to note that sedimentation of suspended load takes place in all reservoirs, whereas in areas with mostly bed load degradation also occurs. This is mainly caused by gravel mining in order to maintain flood protection. One of the differences between the reservoirs is related to the fact that those with low heads and those which are located below large reservoirs have less sedimentation (Prazan, 1990).

Drau

About 27% of the length of the River Drau in Austria comprises a free flowing section (Fig. 2). The major difference with other rivers is related to the fact that the chain of water power plants is located downstream of the free flowing section, so that bed load transport still occurs from the sources of the Drau. Just in the Eastern Tyrol section of the river, a water power plant influences the sediment transport, but as the Isel is the major source of bed load (Habersack & Nachtnebel, 1995), this power plant has not very much effect on the free flowing section.

Mur

The River Mur shows bed degradation tendencies especially in the border section (between Austria and Slovenia) downstream of Mureck to Radkersburg. In this reach, the degradation rates over a period of about 20 years are about 2-5 cm year^{-1} (Plattner,

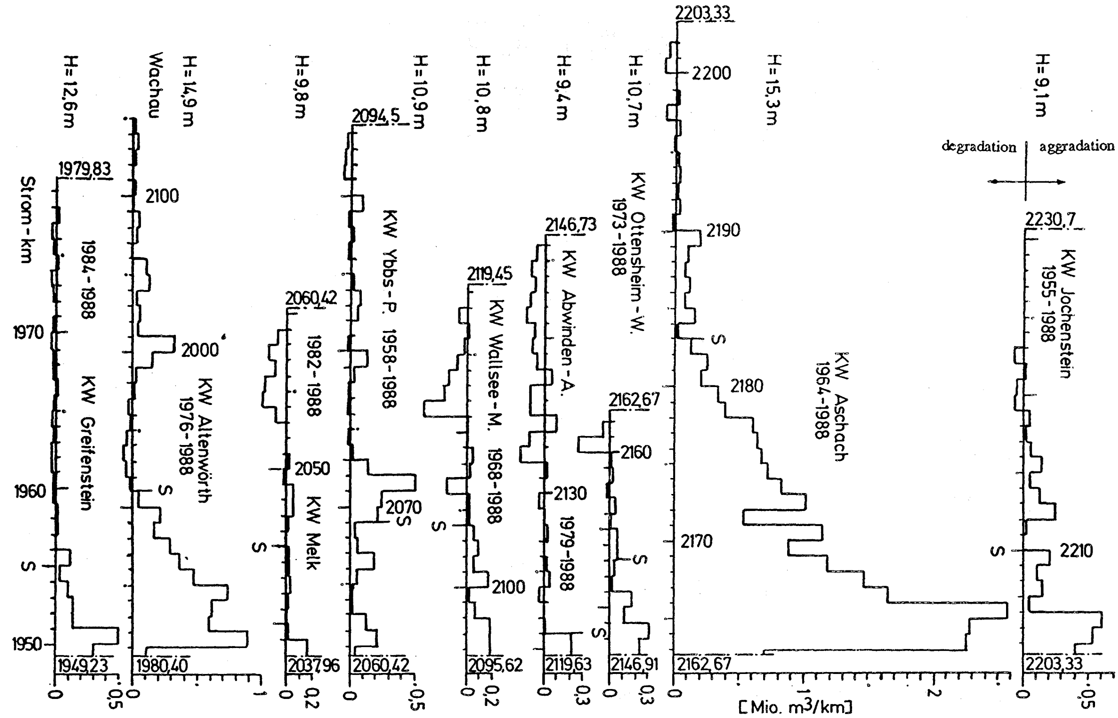

Fig. 3 Sedimentation in reservoirs of the River Danube, after Prazan (1990).

1993). As there are still major free flowing sections with tributaries transporting bed load, management strategies are being developed to flush material out of reservoirs during floods in an attempt to release material to the downstream section. The River Mur has the longest free flowing section of all large Austrian rivers (about 66%).

Enns

About 33% of the length of the River Enns is influenced by a lack of sediments whereas about 47% has a surplus (Table 2).

Inn

Within Austria, the River Inn is influenced by bypasses, surge effects or reservoirs, and no free flowing sections remain. The calculated length of the river (44%) with a lack of sediment is a theoretical value, which is based on the fact that a lack of sediments can occur in bypass-systems during floods. The value of 29% for the length of the river in surplus is well documented through an analysis of sedimentation in reservoirs. According to Mühlhofer (1933), the suspended and bed load transport rates at Kirchbichl are 7.5 and 3.44 Mt year^{-1}, respectively. Hofer (1990) calculated, on the basis of data for sediments flushed out of reservoirs, that the total load would be on average about 227 000 m^3 year^{-1}, of which about 140 000 m^3 year^{-1} comprised bed load transport.

Table 2 Lack and surplus of sediments in selected rivers in Austria.

River	Gauging station	Average discharge ($m^3 s^{-1}$)	Analysed length (km)	Lack of sediments (% length)	Surplus of sediments (% length)
Danube	Vienna	1931	350	30	70
Drau	Drauhofen	112	214	27	59
Mur	Bruck/Mur	105	280	66	24
Enns	Steyr	202	186	33*	47
Inn	Kirchbichl	289	258	44*	29
Salzach	Golling	142	182	49	13

*Situation depends on hydrological situation (wet or dry seasons).

Salzach

About 49% of the length of the River Salzach experiences a lack of sediment, whereas about 13% has a tendency to exhibit a surplus of sediment. Bed load and suspended sediment transport are high. The annual volume of bed load is estimated at 150 000 m^3 while the suspended load transported in free flowing sections has been estimated to be as high as 1.5 Mm^3 (Schöberl, 1992).

IMPLICATION FOR MANAGEMENT STRATEGIES

The major concerns for managing such river systems, which are strongly influenced by human activity, are on the one hand to stop degradation tendencies in free flowing sections and on the other hand to reduce sedimentation processes in reservoirs.

Although the scope for altering the current pattern of degradation and sedimentation is very limited because of existing power plants and river training works, a new engineering concept has been employed in the River Drau to overcome this situation for bed load transport and partially for suspended load transport. A variety of studies have shown that major bed degradation problems exist in the River Drau because of a lack of sediment input and also a very high potential transport capacity caused by regulation and narrowing of river bed width (Habersack & Nachtnebel 1994).

Echo-sounding in the uppermost reservoir of a chain of water power plants downstream from the study reach reveals that actual transport rates of bed load are around 30 000 m^3 $year^{-1}$ on the average. The maximum measured value was *c.* 50 000 m^3 $year^{-1}$. One major aim of future engineering measures is to increase the sediment input from tributaries, but this would also increase sedimentation in the uppermost reservoir. In order to reduce this effect, it is calculated that an increase of river bed width would be effective at least for the near future and would also reduce bed degradation. Figure 4 shows the calculated reduction of potential transport capacity for one cross section using numerical simulations based on the Meyer-Peter-Mueller equation (Exenberger *et al.*, 1995). An increase of river bed width from about 50 to 90 m would reduce transport capacity to a very low value. This means that if the river bed

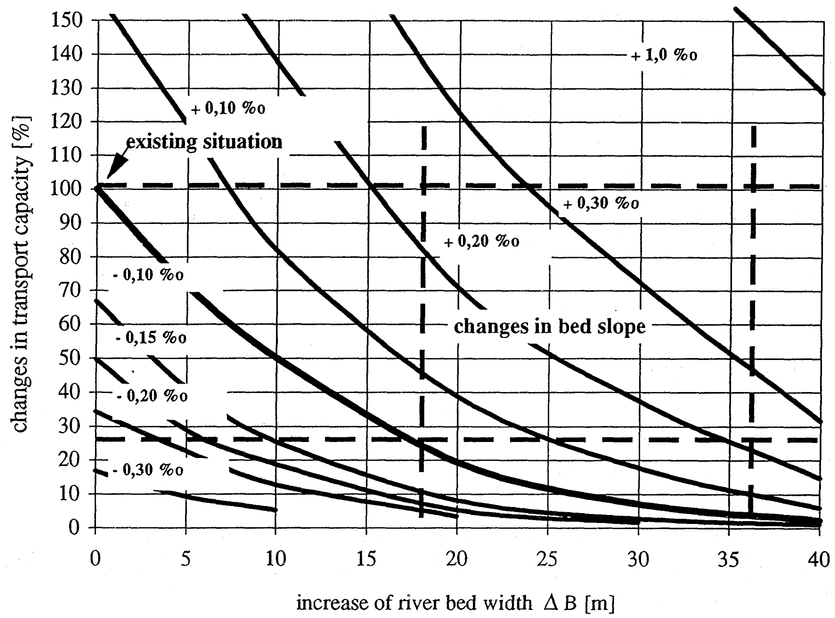

Fig. 4 The effect of an increase in river bed width on transport capacity.

width is increased by about 40 m, sediments will be deposited in this section immediately after the completion of the measure. However, after some floods which caused sedimentation, the energy gradient in this section would increase. This higher slope would again cause higher transport capacities (Fig. 4) so that an equilibrium state would be reached after some years. The lower horizontal dotted line in Fig. 4 marks the actual rate of transported sediments (as documented in reservoirs), and shows that an increase of *c.* 18 m in width would be necessary to reduce the transport capacity to the point where degradation ceases. After reaching the equilibrium stage the slope in the section with the increased width would become higher, in this case by about plus 0.24% (shown by the vertical dotted line in Fig. 4). The second vertical dotted line to the right (Fig.4) marks the maximum increase of width which could occur without reducing flood protection through aggradation.

In order to minimize the dilemma of having to increase the input of sediments into a river system but at the same time not wishing to increase the rate of sedimentation, several arguments have to be regarded:

- increase of sediment input decreases bed degradation (depending on grain sizes);
- reduction of erosion in degrading reaches reduces output;
- increases of river bed width cause aggradation, which compensates to a certain extent the sedimentation in reservoirs in the downstream section.

Ecological aspects of increased river bed width

A prototype measure at one site in the River Drau, which included an increase in the river bed width, was implemented, and the short term effects on morphology, substrate, flow field and ecology were documented (Habersack & Nachtnebel, 1995). The morphological analysis showed that after one year with no major floods, aggradation had occurred and that it was possible to change river morphology significantly. Biological investigations demonstrated the value of these changes for natural reproduction of fish species (including rare ones), in higher population densities of macroinvertebrate fauna (compared to uniform channel reaches), through providing brooding areas for many kinds of birds and in creating dynamic locations with pioneer vegetation, which does not exist in a typical form anywhere else, because of the absence of bars and islands or braided sections.

CONCLUSIONS

A lack or a surplus of sediments being transported in river systems causes major concerns for the large rivers in Austria. Management alternatives have to be found in order to stop both ecological and economical damage.

In general the following conclusions may describe the situation in Austria:

(a) The influence of human activity on river systems has caused dramatic impacts on sediment transport.

(b) The lack of sediments in free flowing sections is responsible for severe bed degradation problems.

(c) The surplus of sediments in reservoirs causes loss of storage capacity, problems with flood protection (reduction of cross section areas) and security of dams.

(d) Monitoring programs are necessary to provide data for adequate management of sediments.

(e) Management strategies have to take into account effects on upstream and especially downstream sections of reaches, where compensation measures are planned.

(f) To a certain extent, the lack and surplus of sediments in regulated rivers cannot be changed completely.

(g) The increase of river bed width in free flowing sections might be a possible way to reduce the discrepancy between the lack and surplus of sediments.

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