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Effects of a changing environment on sediment transport in two Austrian river systems

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Abstract This paper analyzes effects of a changing environment on sediment transport in two Austrian gravel-bed rivers, the Danube and Drau, and discusses potential measures to cope with bed degradation. Major impacts on the environmental state of the basins are caused by river engineering, hydropower, and modified land use. Although the results are very similar — degradation of about 2 cm year^{-1} — changes in the environment and especially the alternative measures are different. The River Danube system is impounded by power plants that trap coarse sediment. Large distances to sediment sources, low supply of bed load, and use of the Danube as an international waterway limit engineering measures to stop degradation. The River Drau, with discharge about 3% of the Danube, has great potential for restoration measures mainly because of proximity to Alpine sediment sources and much smaller scale.

INTRODUCTION

All large and most small rivers in western Europe are severely modified (Petts, 1984). Any river reflects activities occurring within its basin by a change in its morphological characteristics. River conservation, therefore, is largely a problem of conservation of catchment areas (Welcomme, 1992). The effects along a river become more severe as the stream order increases and conservation measures become more difficult when larger scales must be faced. It is easy to conserve small, low-order streams as part of a general terrestrial reserve area, but it is more difficult to maintain large rivers in an unaltered state without equivalent conservation policies for the basins upstream.

Sediment transport is a key variable for river morphology and thus for water-related ecology. In the past, many changes in river basins occurred and affected sediment transport. Sediment input to large rivers was decreased by bed load traps at the torrents. Agriculture in valleys was intensified, leading to channelization of the rivers. These impacts have increased flow velocity and thus shear stress in the river bed, whereas sediment delivery was lacking. Therefore, major channel degradation has occurred in recent decades. Two examples of large Austrian gravel-bed rivers, the Danube and the Drau, show these effects. The aim of this paper is to analyze the effects of a changing environment on sediment transport in these two rivers that differ in scale and alternative measures.

DESCRIPTION OF THE STUDY REACHES OF THE DRAU AND DANUBE

In recent studies sediment transport in the Rivers Drau and Danube was analyzed (Habersack & Nachtnebel, 1994a; Rescher *et al.*, 1994; Radler *et al.*, 1993). The River Drau is in southern Austria, entering Austria in eastern Tyrol and flowing to Slovenia. The Central Alps in the north constitute the main sources for sediment, especially bed load. Figure 1 shows the drainage basin of the River Drau and the study reach (about 60 km), between Lienz in eastern Tyrol and Sachsenburg in Carinthia. In the study reach the basin is narrow, surrounded by mountains and with tributaries of steep gradient that transport sediment from source to the main river in a very short distance.

The study reach of the Danube is downstream of Vienna (Fig. 2). It is 49 km in length and is the last free-flowing part of the Austrian section upstream of the Slowakian power plant Gabcikovo. The two study reaches are of comparable length but are significantly different in scale (Table 1). Channel degradation is common to both rivers. Due to distinct hydraulic characteristics (Table 1) in historical developments and to technical and ecological constraints, effects of changing environment on sediment transport are different. In general, major impacts (Fig. 3) on the environment are (a) river engineering measures (for flood protection, navigation) (b) hydropower plants, (c) land use in the drainage basin, and (d) measures influencing sediment transport at tributaries.

River Drau

The River Drau prior to 1890 was a braided, aggrading channel system (Schmidt, 1880). From 1890 to 1930 the river was uniformly channelized, resulting in a 34% reduction of river bed (Habersack & Nachtnebel, 1994a). A decrease of width to about 40 m, reduction of bank erosion, and gravel mining were the major changes. A simple mass

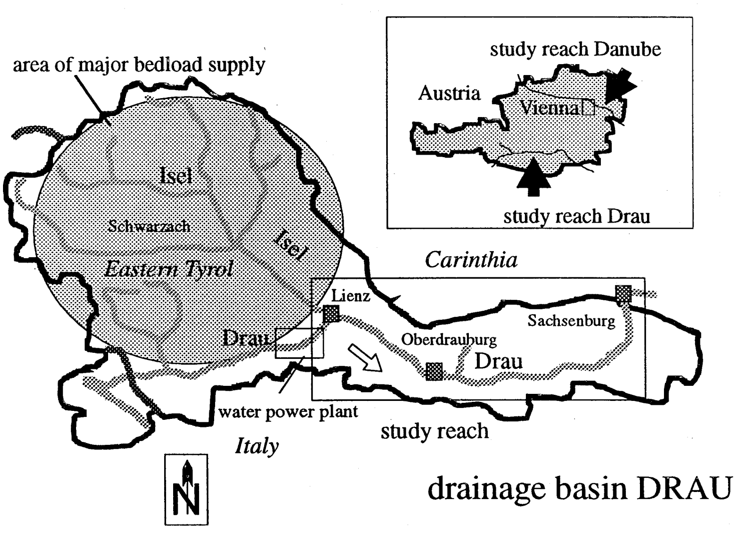

Fig. 1 Map showing drainage basin of the River Drau and study reaches in Austria.

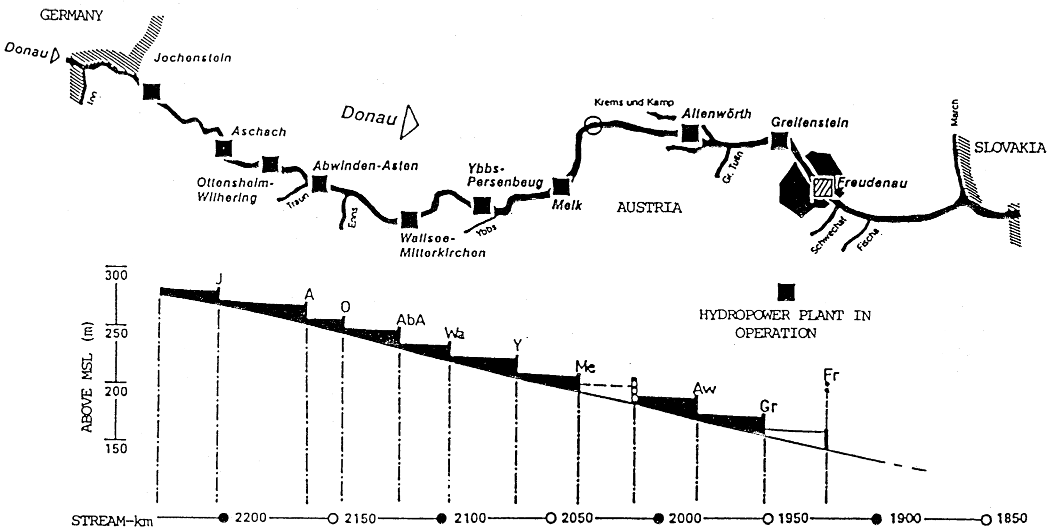

Fig. 2 Diagrams showing chain of water power plants upstream of the study reach.

balance indicates that 60% of the degradation volume was gravel abstraction. The effects of hydropower plants on sediment transport in the main river depend on the type of water intake or reservoir. Compared to the River Danube, these influences are small. Concerning land use, there is a major difference between the Danube and the Drau basins. Surrounding mountains of the River Drau have steep slopes and settlements and agriculture are limited to the main valley; tributaries are mostly of low stream order, reflecting short distances to the sediment sources.

Table 1 Hydrological data for the Drau and the Danube.

Gaging station	Drau Sachsenburg	Danube Vienna Reichsbruecke	Ratio between Drau and Danube
Stream order	6	9	
Catchment (km^2)	2561	101 731	1:40
River bed width (m)	40	360	1:9
Channel slope ($m\ m^{-1}$)	0.0015	0.000 45	1:0.3
Average discharge ($m^3\ s^{-1}$)	76	1700	1:22
HQ_{100} ($m^3\ s^{-1}$)	1029	10 400	1:10.1
Est. annual bed load ($m^3\ year^{-1}$)	40 000	<400 000	1:10
d_m of bedload (mm)	20^1	11^2	1:0.5
Degradation ($cm\ year^{-1}$)	0.2-2.5	0.5-2.5	1:1
Distance to sediment source (km)	1-100	150-5000	1:100 (5000)
Length of study reach (km)	60	49	1:0.8

1: recent measurements of bedload (unpublished); 2: according to measurements by Schmutterer (1961).

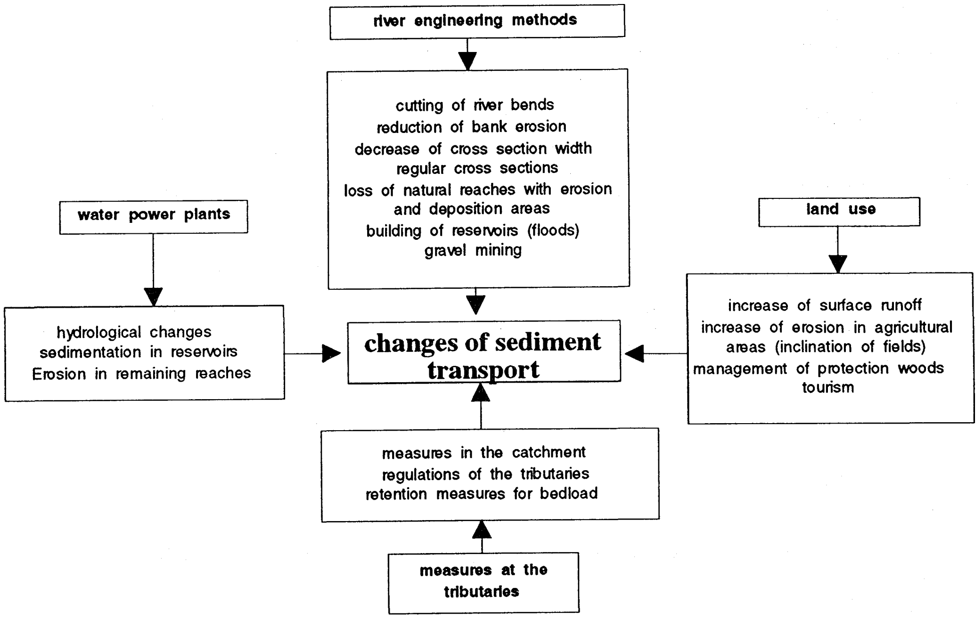

Fig. 3 Chart showing changes of the environment in relation to sediment transport.

River Danube

Regulation measures of the last 120 years led to about a 45% reduction of the River Danube bed (Radler *et al.*, 1993). Cutting of river bends increased the gradient from 0.26% to 0.45%. Generation of electricity on the River Danube and its use as an international waterway have a great influence on the potential measures. Preservation of a free-flowing reach with riverine forest and wetland is also a major objective for the section downstream of Vienna. Due to outstanding biological diversity, this area is to be designated a National Park. The waterway is maintained by dredging, accounting for about 2/3 of the volumetric changes in the channel. Dredging in the fords is necessary to maintain a minimum 2.5-m water depth for navigation. Figure 2 shows that hydropower plants transformed the Danube into a chain of reservoirs.

At the gaging station Reichsbruecke and the beginning of the study reach, the basin area of the River Danube is 40 times larger than that of the River Drau (Table 1). Due to intense agriculture, increased soil erosion, sediment transport and surface runoff are apparent (Radler *et al.*, 1993). Effects of a changing environment on sediment transport by the River Danube, a 9th-order stream (Table 1), are results of impacts of several rivers like the Drau (e.g. Inn, Salzach, Enns, Ybbs). Sources of change, therefore, must be analyzed for the entire drainage basin.

IMPACTS ON SEDIMENT TRANSPORT REGARDING TEMPORAL AND SPATIAL SCALE

As a result of the anthropogenic influences, effects on sediment transport are analyzed.

Change in sediment transport affects economic and ecologic objectives (Fig. 4). River bed degradation increases costs of bank protection and preservation of bridges and concrete works along the river, and economic benefit from gravel mining is reduced. Within ecology, reduction of dynamic river reaches occurs, decreasing species richness (Petts, 1984). Lowering of the river bed decreases groundwater levels in the valley and reduces frequency of flooding of riparian forests.

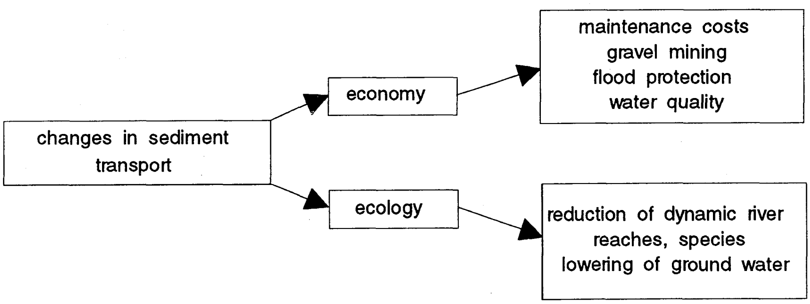

Fig. 4 Chart showing effects of changes in sediment transport on economy and ecology.

River Drau

Comparison of environmental changes shows little difference between the rivers Danube and Drau. The River Drau exhibits high temporal and spatial variability of sediment transport (Habersack & Nachtnebel, 1994b). The average annual degradation rate over 60 years was 1-2 cm, but mean bed level of the River Drau changed rapidly between aggradation and degradation. Aggradation was typical prior to the twentieth century. Later, degradation was dominant. A key event was the flood of 1965-1966, when large quantities of sediment were deposited and led to retention measures at most tributaries. At the River Drau, degradation accelerated when gravel mining began. The main reason for temporal and spatial variability at the River Drau is tributary inflow to the river within the study area that still has potential to supply large quantities of sediment. At one tributary, the Gragraben, a photogrammetric survey of the alluvial fan allowed an analysis of sediment input. One local event deposited about 1500 m^3 of coarse gravel, and during a minor flood of the River Drau, 300 m^3 of sediment were eroded in 12 days. This spatial variability of sediment input is reflected by the longitudinal profile of the river in which five sub-reaches with higher or lower degradation rates can be defined.

River Danube

Figure 5 shows degradation (Eintiefung) at the River Danube downstream of Vienna. Within the average degradation, high temporal and spatial variability of sediment transport occurs (Bors, 1992). In the study reach there are no major tributaries that supply large amounts of sediment to compensate for a lack of bed load from hundreds of km distance to principal sources (Table 1).

The degradation rate was about 1 cm $year^{-1}$ 30 years ago (Rescher *et al.*, 1994), but

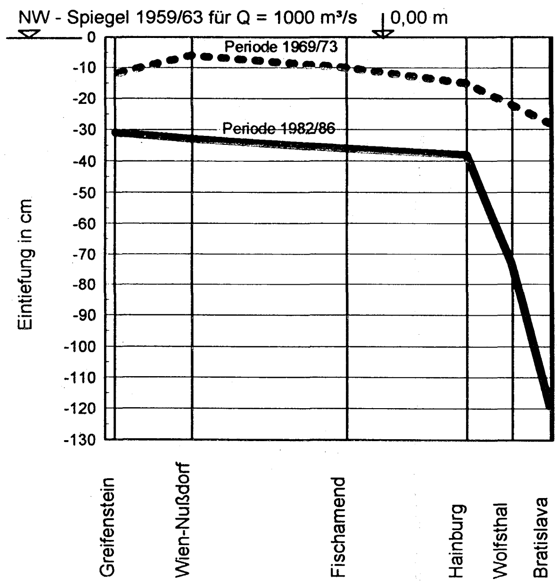

Fig. 5 Graph showing river bed degradation at the River Danube between Greifenstein and Bratislava, related to a discharge of 1000 m^3 s^{-1} (after Kresser, 1984).

recently this value has increased to 2-3 cm $year^{-1}$. Channel degradation of the River Danube is not a short-term effect of environmental change, but a long-term process initiated by changed hydraulic conditions.

ROLE OF SCALE IN THE DESIGN OF MEASURES TO STOP DEGRADATION

River Drau

Because of a lack of bed load, the major aim is to increase sediment input. The small basin size allows assessment of the sediment delivery by tributaries and identification of measures to increase sediment input. For river engineering, the intent is again to increase the channel width and to reduce shear stresses and transport capacities to stop degradation at a specific reach. For the 60-km study reach, it is important that the river bed acts as a buffer for sediment (Jäggi, 1992). One scenario is that an increase of river bed width in the upper project area causes temporary storage of sediment, thereby increasing the rate of degradation downstream. Low-water measurements show that river bed change is a long-term process. Future measures, like increase of river bed width and sediment input, therefore, must be planned for a period of several decades.

River Danube

The recent degradation rate of 2-3 cm $year^{-1}$ (Kresser, 1984; 1988) implies that there is ample time to identify appropriate measures. In principle this is true, but because the gravel layer is thin, erosion may soon expose the fine sandy sub-layers and cause accelerated degradation. Urgent measures, therefore, are required. The influence of spatial scale on selected measures may be seen from two points of view. First, the large scale of the drainage basin (Table 1) and existing hydropower plants upstream show that measures related to the entire basin may be unrealistic. Secondly, variability in sediment transport and river use for navigation, requiring a minimum water depth, prohibit most alternatives like increase of cross-section width in the study reach. Presently, possibilities to stop the bed degradation include (a) artificial input of bed load, (b) low-water regulation combined with installation of an artificial armoring layer, (c) erection of additional water power plants, and (d) erection of a bypass channel, serving as a waterway. Concerning temporal scale, measures for the River Danube must be functional immediately (no time to wait for natural changes of river morphology).

ROLE OF SCALE IN MONITORING PROGRAMS

River Drau

Analysis of the River Drau led to the requirement that monitoring programs including geodetic surveys, particle size analyses of surface and subsurface sediment, and measurements of sediment transport are necessary (Habersack & Nachtnebel, 1994b). After realization of measures, only detailed monitoring allows one to compare of results with the original aims and, if necessary, to react promptly to negative developments. For the temporal scale, annual low water level measurements of the River Drau, which show river bed change at 200-m intervals, seem to be sufficient. Sites where prototype measures have been started (e.g. increase of channel width) must be monitored more frequently.

Short-term results demonstrate the usefulness of monitoring. Our experience suggests it is necessary to monitor two to three times a year, more often if significant floods occur. For the first time on the River Drau, bed load data since 1994 using a large Helley Smith sampler and a recently developed bed load trap have been collected.

River Danube

All calculations for the River Danube, from modelling to engineering (Bernhart, 1987), are based on data from Schmutterer (1961), who measured the River Danube 1956-1957, using an Ehrenberger basket sampler. A main problem is that since then the hydropower plants were completed upstream of the study reach, causing much lower transport rates and especially particle size distributions. At the River Danube, therefore, both geodetic surveys and measurement of bed load transport are necessary in the future. To obtain representative estimates of the temporal and spatial variations of bed load transport, several years of bed load and discharge measurements are necessary.

CONCLUSIONS

Two alluvial rivers, the Drau and Danube, were selected to investigate impacts of environmental change on river regime. Due to reservoirs that trap sediment along Alpine tributaries, the bed load transport has been reduced. Simultaneously, river training works and channelization of the major rivers increased flow velocity and shear stress, and enhanced degradation of the river bed. The two rivers differ remarkably in hydrologic and hydraulic characteristics, providing a basis to investigate alternative measures to cope with degradation processes.

The measures include (a) increase of coarse sediment input via tributaries, (b) artificial sediment input, (c) enhancement of bank erosion to increase bed load, (d) modification of cross sections to reduce shear stress, (e) engineering to protect the river bed by artificial armoring, and (f) protection of the river bed by the erection of hydraulic structures.

Due to the various functions of the two rivers, different actions are recommended. For the River Drau, the close link to sediment-delivering torrents suggests enhancement of sediment input. Channel widening may result also in reduced shear stress, advantageously affecting sediment transport. These measures would contribute to environmental preservation because the river geometry would approximate natural characteristics.

The River Danube serves navigation and the depth and width must be maintained. Measures that seem useful for the River Danube are (a) artificial input of bed load, (b) low water regulation combined with installation of an artificial armoring layer, (c) erection of additional hydropower plants, and (d) construction of a bypass channel, serving as a waterway.

Due to lack of sediment transport data, monitoring programmes are requested to indicate the efficiency of the measures. Because of the different characteristics of the two rivers, a monitoring programme based on a medium- to long-term scale (over one decade) of the entire Drau basin is recommended, whereas geodetic surveys and measurements of bed load transport based on a short to medium temporal scale are necessary in the River Danube study reach.

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