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The impact of run-of-river hydropower plants on the temporal suspended sediment transport behaviour

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Abstract Within the last 120 years the meandering and wide flowing Austrian Danube (average discharge approximately 2000 $m^3 s^{-1}$) was first narrowed into a single and straight river bed. The recent erection of hydropower plants along the Danube diverted the stream into an almost complete chain of reservoirs. These changes, together with similar impacts on all the major tributaries as well as new agricultural management strategies, had a significant impact on the sediment transport behaviour of the Danube. Firstly, the lack of gravel transport has caused immense river bed degradation within the last undisturbed region, downstream of the last run-of-river station. Secondly, the suspended sediment now occurs in higher concentrations and, thirdly the annual loads are transported in a shorter period of time than before the existence of the hydropower plants.

HUMAN IMPACTS ON THE REACH OF THE AUSTRIAN DANUBE

The original Austrian Danube (Fig. 1) experienced significant changes within the last 120 years. The driving force for these changes can be seen in the development of the stream into an international waterway. Flood protection played another important key role in the morphological alteration of the Danube. Hence, the dynamic forces of the meandering and wide flowing river were first confined into one, and then into two, straight and almost stable channels. The designed compounded cross section ensured navigation as well as flood protection (Fig. 2(a) and (b)).

In recent years, the construction of hydropower plants significantly changed the characteristics of the Austrian Danube. The waterway purposes of the stream, as well as the flood protection of settlements along its course, were again improved (Fig. 3). The original stream has been changed into an almost complete chain of reservoirs, and the more or less original river dynamic has completely disappeared (Fig. 4).

These human impacts first increased the sediment transport capacity because of the narrowing of a diverted river system into a single straight channel (the overall water surface was reduced by 45% as well as the total length of the river), consequently causing increases in the slope from 0.26‰ to 0.45‰, as well as the flow depth and the flow velocity from 1.5 m s^{-1} to 2.0 m s^{-1}. These increased transport capacities were subsequently reduced by river impoundment; the average flow velocity near the reservoir head is approximately 0.35 m s^{-1}. Only during flood periods, is the hydraulic

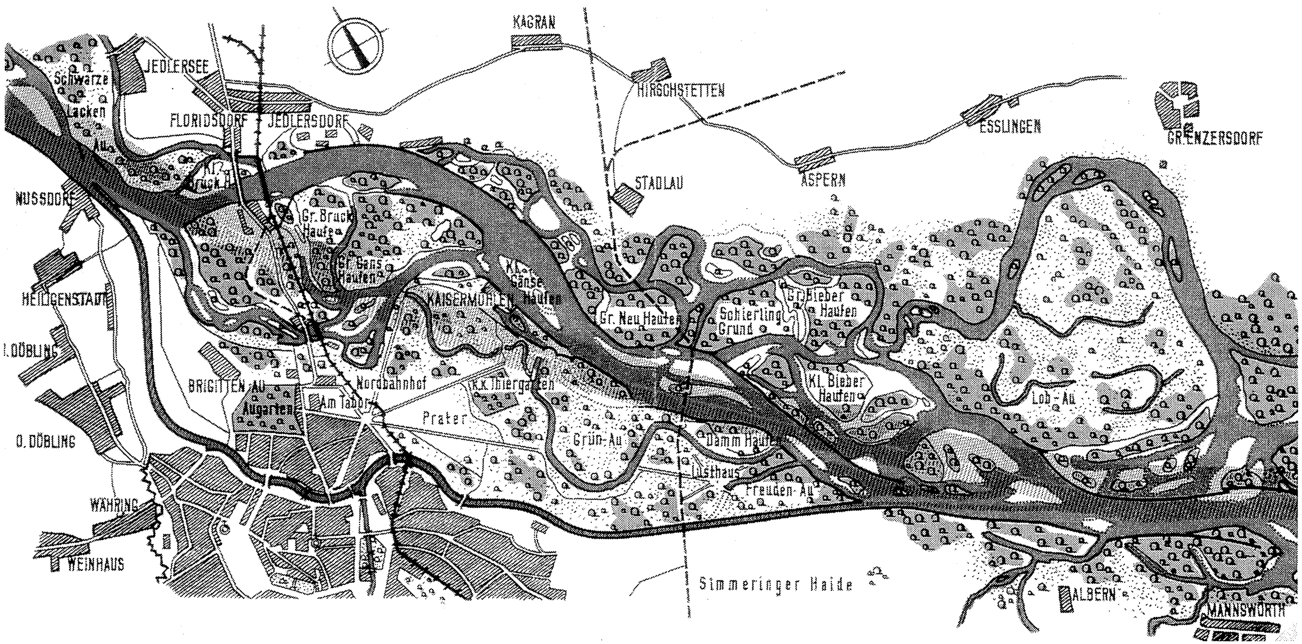

Fig. 1 The Danube near the Austrian capital Vienna showing a dynamic varying river network with large wetlands along its course.

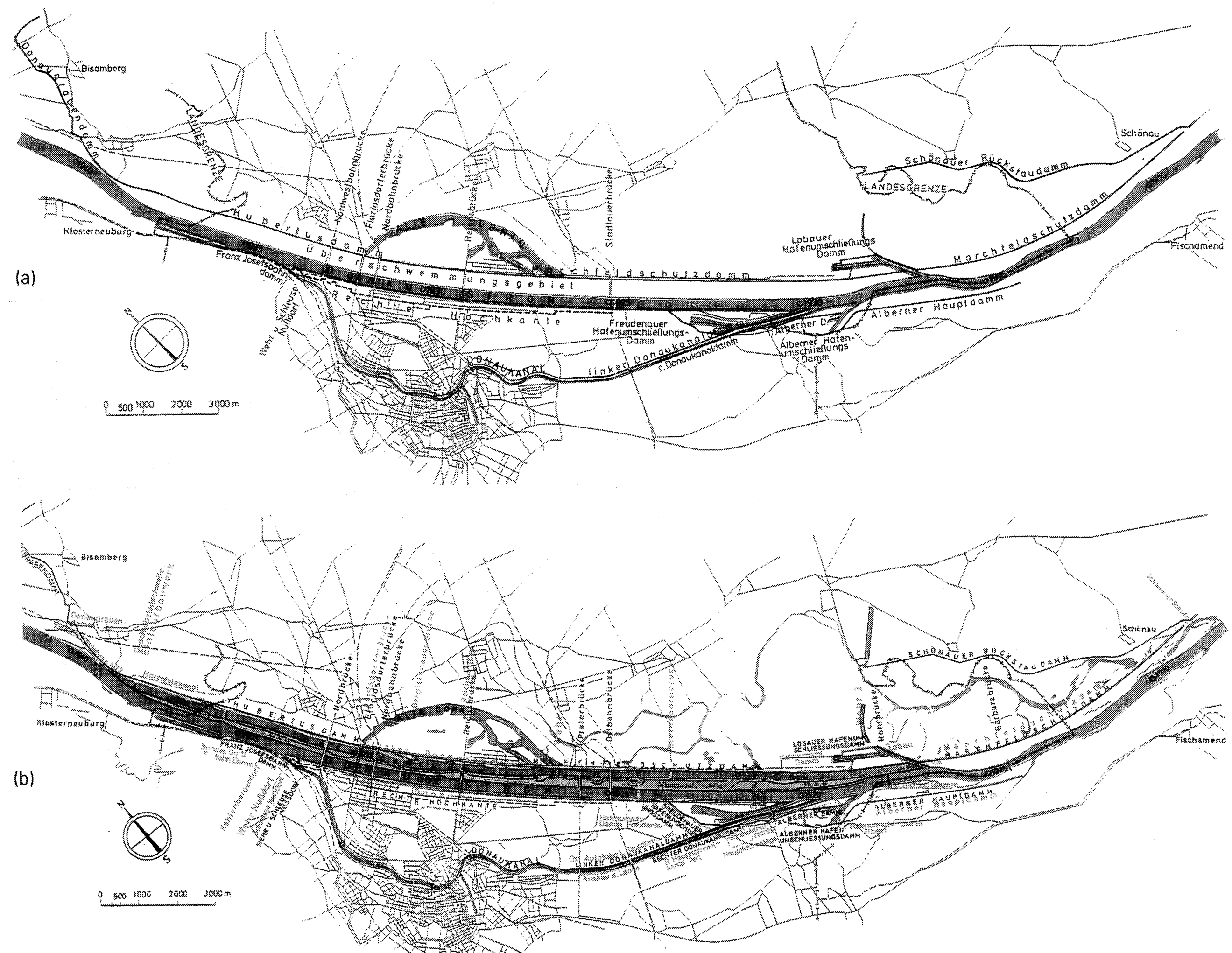

Fig. 2 The flood protection schemes for Vienna. (a) Main channel (Donau Strom) with compounded cross section, designed at the end of the nineteenth century. (b) Main channel (Donau) with compounded cross section, supplemented by a diversion channel (Neue Donau) of similar size – only in operation during flood peaks – built in the seventies. In both cases the wetlands are already reduced.

Fig. 3 The Viennese Danube in the near future – completed by a run-of-river station.

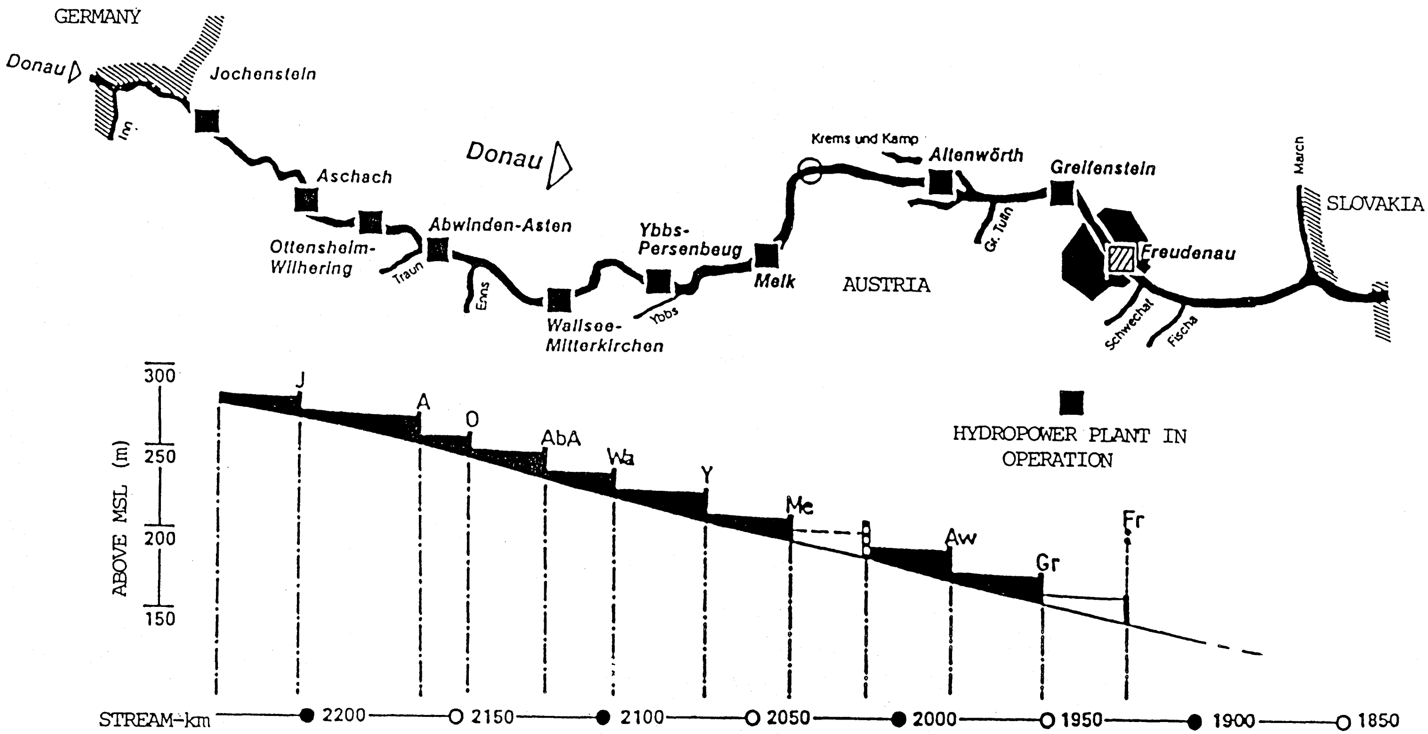

Fig. 4 Hydropower plants along the Austrian Danube.

condition within certain reservoir sections, as well as on a several kilometre long non-impounded natural reach, similar to the condition of the stream without hydropower plants. In the impounded and undisturbed sections, either massive erosion or displacement reservoir sediments during peak flows and/or rapid river bed degradation occurs. This leads to a decrease in the surrounding groundwater tables, causing the drainage of the ecological valuable wetlands on both sides of the Danube.

Impacts on the transport of coarse bed load material

Graf (1971) compared different bed load equations under given hydraulic conditions for the Danube near Vienna in 1950s when no hydropower station yet existed. The results varied between 8.6 kg s^{-1} (by the Schoklitsch equation), 288 kg s^{-1} (by Meyer-Peter *et al.* equation), 290 kg s^{-1} (by the Kalinske equation) and 380 kg s^{-1} (by Einstein's equation). These equations are derived to predict the maximum bed load that a stream in equilibrium can possibly carry at the given hydraulic and sedimentary conditions, however, the so called transport capacity was either overestimated or underestimated by a power of 1 (Fig. 5) . Applying these equations to the known hydraulic conditions of the original Danube of the nineteenth century, almost no transport of bed load is indicated. In the 1970s after several hydropower plants had already been erected, an annual bed load that was only approximately 10% of Ehrenberger's measurements (Ehrenberger, 1931) was estimated from available data by Gruber (1973). Hence, the channelling of Danube increased the transport of bed load drastically, and was supplied by the alpine tributaries. Run-of-river stations now interrupt this transport, causing heavy river bed erosion-impounded river bed downstream of the last reservoir.

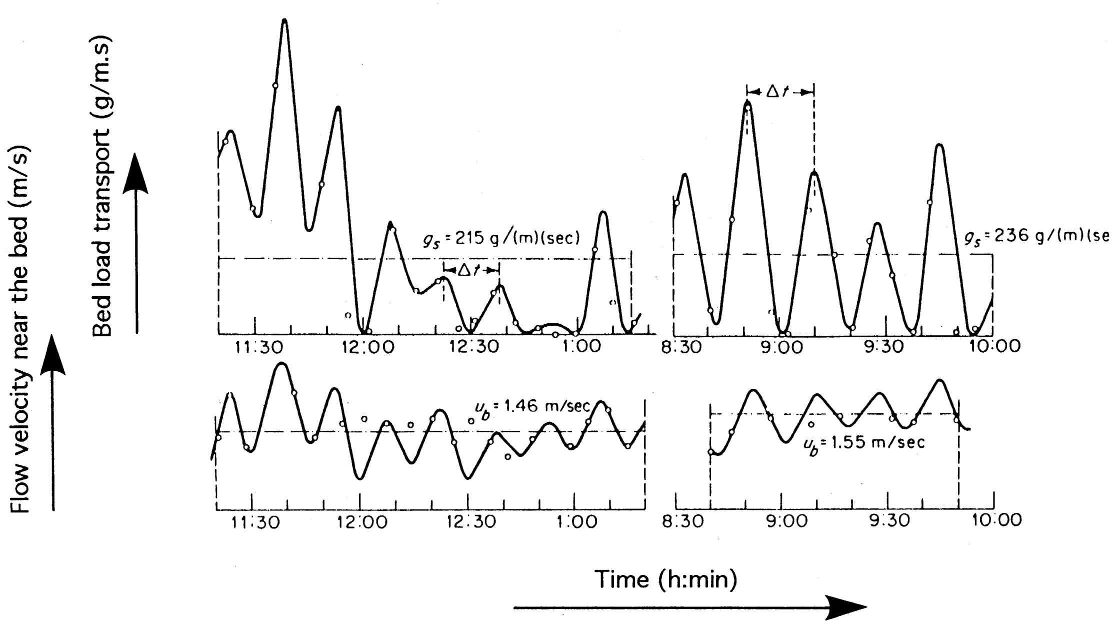

Fig. 5 Unsteady bed load transport in the Danube (Ehrenberger, 1931).

Impacts on the suspended sediment transport

It can be stated that the major effects of the sediment transport processes take place within a short period of time. Already published data by Meade & Parker (1984) indicate for rivers in the USA that 50% of the annual sediment load is discharged in only 1% of the time, and 90% load is transported in only 10% (= 36.5 days) of a year. A very similar behaviour can also be observed at the Yellow River, where 50 to 90% of the annual suspended sediment load is carried only within 5 to 10 days of the year (Deyi, 1984).

In comparison to Meade & Parker (1984), Fig. 6 (Radler *et al.*, 1993) shows very similar behaviour for the Danube within its Austrian alpine upstream region. The stream has an average discharge of 1900 m^3 s^{-1} with floods up to 14 000 m^3 s^{-1}. Figure 6 indicates that 50% of the sediment load occurs in only 5% of a 4-year period of daily observations, whereas 90% is discharged in 37% of the time after installation of hydropower plant in 1964. After the erection of the hydropower plants (Fig. 4 and Fig. 6) a decrease in the length of the sediment discharge period was experienced. Now 50% of the load is moved in only 2% of an observed 10-year period and the 90% load is discharged in only 25% of the time. In the same period the sediment concentration monitored during flood peaks has also risen by a factor ranging between >1 and 2.

Hydraulic as well as sedimentological explanation The erection of hydropower plants has caused impoundment with almost permanent water depths of >10 m (depending on the size/head of the power station), in comparison to an original depth of approximately 3 to 5 m during floods. Flow velocities and the energy slopes have been reduced. Only during floods are movable sluice gates opened once the discharge reaches a certain level. This immediately causes hydraulic conditions similar to the ones of the

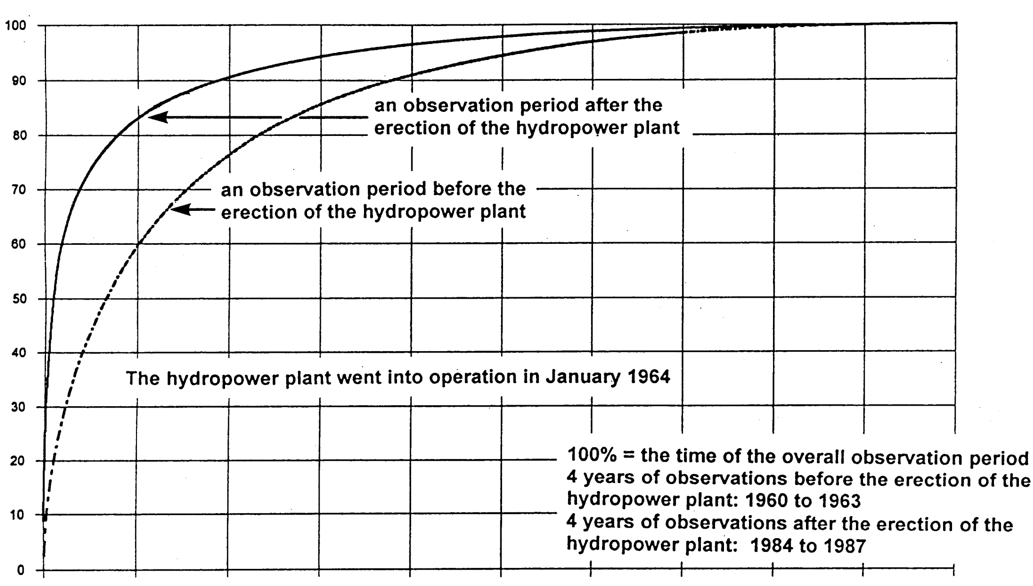

Fig. 6 Relative values indicating the discharged sediment load on the Austrian Danube before and after the erection of the hydropower plants (Radler *et al.*, 1993).

natural stream. Although the duration of floods is reduced, almost the same annual suspended sediment load for before and after the erection of hydropower stations is observed. Flood waves travel faster in deep impoundment than in shallow rivers if the Froude-number $Fr < 0.5$ then $dc/dh > 0 \Rightarrow$ with increasing water depth h the wave velocity c also increases. This leads to the faster transport of sediment down the Austrian Danube. At the same time concentration of sediment peaks increased by a factor of >2. Reasons for this are:

(a) there is practically no limit on the availability of erodible river bed sediments in the upstream vicinity of the run-of-river stations, and
(b) there is an increase in the sediment yield in the basins of the major tributaries to the Austrian Danube.

Agricultural changes in the watershed An increase in the annual sediment yield within the last 30 years of between 30 and 50% has been caused by a change in agricultural management, the development of flood protection schemes and the erection of hydropower plants on the Austrian Danube. The extension of the cultivated area of maize with no soil coverage in spring and possibly early summer, the season of intensive rainfall, by a factor of more than 4 (Hintersteiner & Klaghofer, 1993) can be seen as a major factor for this development (Table 1).

Table 1 Comparison of the crop distribution in the Austrian catchment of the Danube in the fifties and the eighties (Hintersteiner & Klaghofer, 1993).

Crop	Portion (%) 50-59/80-89
Maize	4%/16%
Potato	11%/3%
Beet	7%/5%
Summer corn	22%/22%
Winter corn	27%/36%
Vegetable	7%/2%
Others	22%/16%

SUMMARY AND CONCLUSIONS

Two major morphological changes diverted the Austrian Danube from a meandering river into an almost complete chain of reservoirs:

(a) Flood protection schemes were based on the concept of concentrating the flow into one single and straight river bed, with an approximately rectangular channel cross section. Forty-five percent of the total water surface was lost, the slope increased from 0.26‰ to 0.45‰ and the flow velocity increased from 1.5 m s^{-1} to 2.0 m s^{-1}. Consequently, more of the available gravel supplied by the tributaries was transported downstream without difficulty and created structured river banks, now the environment for fish, birds and other wildlife.

(b) Run-of-river stations reduced the dynamic of the stream (flow velocities were reduced from 1.85 m s^{-1} to 0.35 m s^{-1}) causing the aggradation of suspended sediments as well as gravel in the backwaters. In the downstream reach of the reservoir chain, heavy river bed erosion now occurs due to a significant lack of sediments.

As is generally known, impoundment increases the velocity of flood waves. This phenomenon is the reason for the faster transport of the annual load of suspended sediments downstream in the Danube. This means that in about half the time that was required before the erection of the run-of-river stations, almost the same amount of sediment is moved. Hence, it is understandable that an increase in the sediment concentration during flood peaks was observed. In addition, the sediment yield in the tributary watersheds also increased by a factor ranging between 1.3 and 1.5. The above mentioned increase in the peak concentration of suspended sediments during floods cannot yet be quantitatively be apportioned between a higher availability of river bed sediments and an increase in the sediment yield from the watersheds.

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