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River-bed degradation and overbank deposition: A human induced geomorphic disequilibrium in the Donau-Auen National Park

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Abstract

The Danube east of Vienna is the 'lifeline' of the Donau-Auen National Park. In the last about 140 years it has been strongly altered by river engineering and, in a second stage, by a bed load deficit due to hydropower plants in the upper reaches of the river and its tributaries. As a consequence the river is degrading, with deepening rates between 2 and 3 cm/a in most parts of the study reach. On the other hand, overbank deposition and natural levee formation lead to an aggradation of the floodplain, the channel and its floodplain are diverging. In natural rivers, overbank deposition usually is balanced and restricted by side erosion and lateral channel migration. However, the banks of the Danube are fixed by riprap, thus the overbank deposits cannot be eroded, and distinct 'natural' levees are formed. Both river-bed degradation and overbank deposition are aspects of a geomorphic disequilibrium, and the system will further depart from the natural state.

Keywords

Danube; fluvial morphology; dynamic equilibrium and disequilibrium.

Introduction

Natural alluvial rivers, similar to other geomorphic systems, are assumed to be in a state of dynamic equilibrium, or, at least, in a quasi-equilibrium (LEOPOLD & MADDOCK 1953; LANGBEIN & LEOPOLD 1964): In case of disturbances opposing tendencies and feedback mechanism secure the system's stability by adjustments to cross-sectional form (WOLMAN 1955), channel pattern (LEOPOLD & WOLMAN 1957) or channel gradient (KNIGHTON 1998); thus the system is in a 'steady state' (LANGBEIN & LEOPOLD 1964).

However, heavy impacts, exceeding critical thresholds, may drive the system to a new equilibrium, and the transition is related to a phase of disequilibrium. Such impacts often and also in case of the Danube River have been caused by river engineering and by bedload deficit due to the construction of hydropower plants (SCHMAUTZ et al. 2002). As a result, such river reaches are subject to bed degradation, and the frequency and duration of floodplain inundation is reduced (TOCKNER et al. 1998), which is a key-problem in the Nationalpark Donau-Auen; these effects are further increased by overbank deposition and the formation of natural levees (KLASZ et al. 2012).

The Danube east of Vienna, pre-regulated state and human impacts

The Danube River, crossing the Vienna basin between Vienna and Hainburg, is a large gravel-bed river and strongly influenced by human impacts since the last about 140 years. However, it still shows major functional attributes of a natural river such as the dynamics of water level fluctuations and bedload transport (TOCKNER et al. 1998) and associated biodiversity. It thus has become part of the National-Park Donau-Auen (established in 1996). In its unregulated state it can be classified (according to the schema of NANSON & KNIGHTON 1996) as a gravel-dominated, laterally active anabranching river with a medium-energy non-cohesive floodplain, i.e. wandering gravel-bed river floodplain (HOHENSINNER et al. 2008).

In it's natural state the river had in some sections one and in other sections two main channels and several side-arms. There were both smaller, unvegetated, more transient bars, and larger, well-vegetated (even forested), more stable islands, which could persist for many years or some decades (MOHILLA & MICHLMAYR 1996; KLASZ et al. 2012). This river-floodplain system was characterized by high morphological dynamics and hydrological connectivity, a highly variable flow regime, high loads of coarse bed material, and effects of ice jams in winter and large woody debris (HOHENSINNER et al. 2008).

Between 1870 and about 1900 the river was straightened, concentrated into one main channel and channelized; the banks of the Danube were armoured and fixed by riprap, thus erosion can only proceed in form of incision;

most side arms were separated from the main channel by artificial levees, and large parts of the floodplain were narrowed by a flood protection dyke (Marchfeldschutzdamm). Beginning from 1955 most upstream stretches of the Austrian Danube were subject to further massive impacts by hydropower plants. The last of it, Vienna-Freudenau (river-km 1921) was put into operation in 1997. The study reach remained a free flowing river, but due to the retention of bedload (bedload deficit) in the upper parts of the river basin and some of its tributaries the present river regime is dominated by degradation. In Table I, hydrological and hydromorphological characteristics of the river reach are listed.

Table 1: Hydrological and hydromorphological characteristics of the Danube River east of Vienna (river-km 1920 – 1880)

A_D	Drainage area (km^2)	≈ 100‘000	([a]
Q_m	Mean annual discharge (m^3s^{-1})	≈ 1‘930	([a]
Q_{maf}	Mean annual flood (m^3s^{-1})	≈ 5‘930	([a]
Q_{bf}	Estimated bankfull discharge (m^3s^{-1})	≈ 4‘800 … 5‘000	([a]
D_{50}	Median surface bed-material size (mm)	20 … 25	([a]
D_{90}	Bed-material size of which 90% is finer (mm)	50 … 70	([a]
B_{bf}	Bankfull top width (m)	≈ 353	([a]
H_{bf}	Bankfull mean depth (m)	≈ 5.75	([a]
S	Channel slope ($m.m^{-1}$)	≈ 0.00041	([a]
G	Mean annual bed-load (m^3a^{-1})	≈ 370‘000	([b]

Data sources: a: Klasz (2010), b: Klasz et al. (2012)

Bed degradation: hydrographic evidence

Changes and trends of characteristic water levels are reliable indicators of bed stability. Characteristic water levels of the Austrian Danube (‘KWD’) have been determined by hydrographic observations and published for certain years (Bundesstrombauamt 1951, 1959, 1970, 1978; Wasserstrassendirektion 1986, 1998; via donau 2012), providing an overview over the last ~60 years. “RNW” (low navigable water level; in German: “Regulierungs-Niederwasser”) is the water level reached or exceeded on 94% of days over a long-time reference period (KWD-2010: 20 years). “MW” (mean water level) is the water level corresponding to the arithmetic mean of the average annual discharges for the reference period. In Figure 1a the temporal trends of the RNW- and MW-data for five gaging stations are plotted. MW-differences to the first reference (MW-1949) are plotted for all gaging-stations, step by step and in the longitudinal section in Figure 1b (including data of the reach upstream, until this reach was impounded by the hydropower plant Greifenstein in 1984).

All data indicate a decrease in the last decades (Fig. 1a/1b). In the period before 1976 the degradations were more significant upstream of Vienna. In the 1980s and 1990s the reaches in Vienna and east of Vienna were affected stronger. Recent deepening rates are ranging between 2 and 3 cm/a.

Downstream of the confluence of the Morava the water levels are influenced by the impoundment of Gabčikovo since 1992. The KWD-2010 indicate a further increase of the MW there (for instance in Wolfsthal), which can be seen as a sign of aggradation in this upper part of the impoundment.

To get a long-term perspective, the lowest water levels (NW) and mean water elevation (MW) of each year were plotted against time for the gaging station Hainburg (river-km 1883.92, data since 1846; Hydrographisches Zentralbüro 1895-2009; Hydrographisches Zentralbüro 1958), see Figure 2. The fluctuations are caused by dry and wet years, but the moving average (n=10) provides information on the stability of the riverbed. Before the regulation the water levels seemed to be stable (however, the period is too short for a certain conclusion); between about 1870 and 1890 (during the upstream regulation works) the water levels were increasing by ~1 m; the first half of the 20th century was nearly a phase of equilibrium, followed by a phase of rising degradation rates after about 1960. Similar results have been found by SCHMAUTZ et al. (2002).

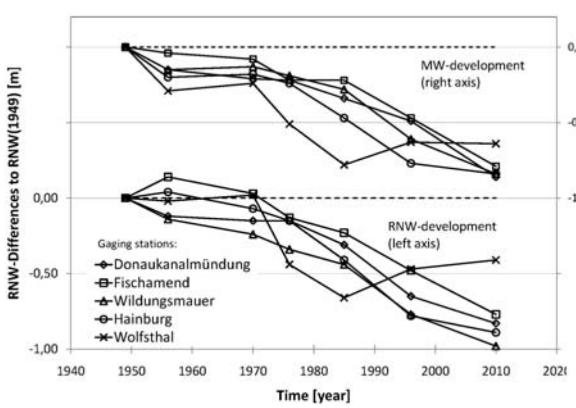

Figure 1a: Differences of MW (mean water level) and RNW (low navigable water level) to reference level (1949) for five gaging stations

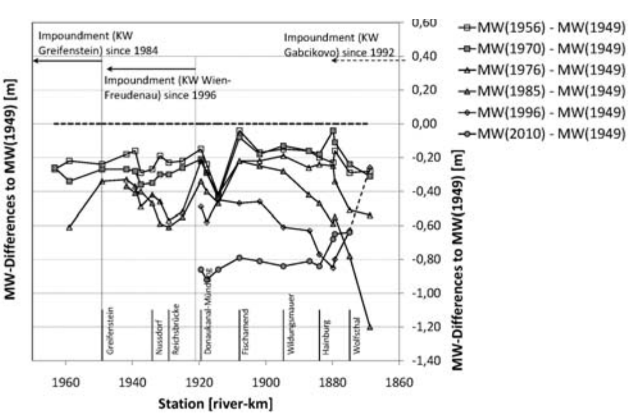

Figure 1b: Differences of MW (mean water level) to reference level (1949) in the longitudinal section

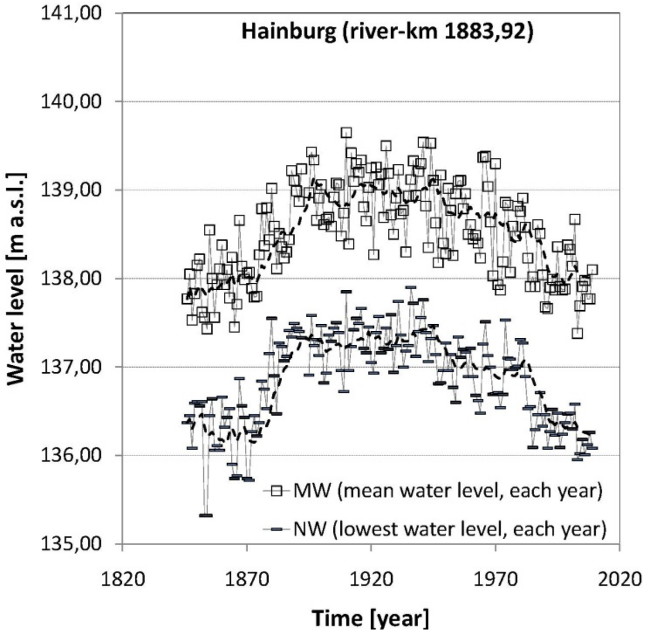

Figure 2: Mean water level (MW) and lowest water level (NW) of each year; time period: 1846-2009; gaging station: Hainburg

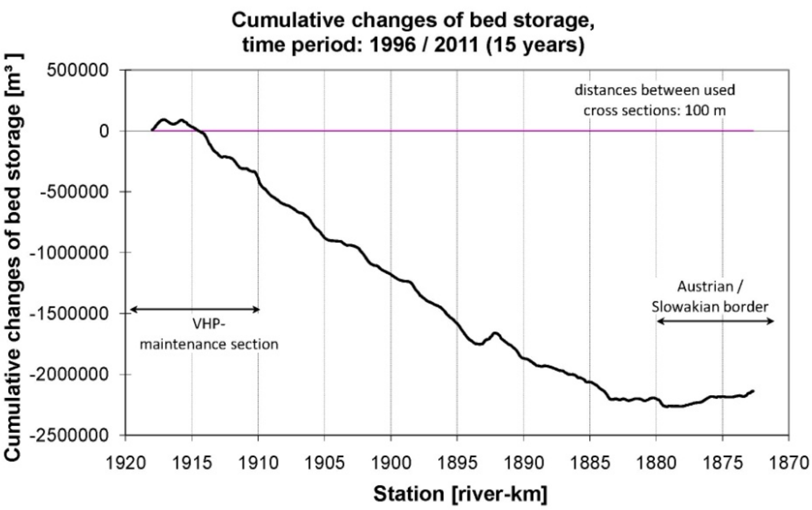

Figure 3: Cumulative changes of bed storage (=bedload output); time period: 1996-2011

Direct evidence on degradation is given by comparisons of cross sections from different dates, obtained by riverbed surveying. The difference of cross sectional areas between two points of time multiplied by the "thickness" of the cross section (that is, the half distance to the next upstream cross section plus half distance to the next downstream cross section) provides $\Delta V(i,j)$, the change of the bedload storage of the particular cross section i and time interval j; finally the cumulative bedload output (over the time interval j) is derived by integration of these partial volumes in the flow direction. In Figure 3 this is shown for the time period between 1996 and 2011 for the reach between river-km 1918 and river-km 1873 (Wolfsthal). Time-averaged annual degradation rates per unit length are almost constant between river-km 1915 and 1890, with a value of ~5'400 $m^3 km^{-1} a^{-1}$); in the section between river-km 1884 and 1880 a saturated state is reached, followed by an aggrading reach, influenced by the impoundment of the hydropower plant Gabčikovo.

To avoid additional degradation by the hydropower plant Vienna-Freudenau and based on the licensing requirements the operating company (Verbund Hydro Power) has dumped an average of ~190'000 m^3 gravel per year (artificial bedload supply) downstream of the hydropower plant (SCHIMPF et al. 2009). Thus it was possible to maintain a stable riverbed in the upper part of the reach, but the degradation process war not stopped on the whole.

From the bedload output of the entire reach (~2.3 million m^3 in this time period, see Fig. 3; that is, ~150'000 $m^3 a^{-1}$ and the averaged artificial supply of ~190'000 $m^3 a^{-1}$ the transport capacity and entire bedload deficit of this reach can be calculated to lie between 340'000 and 350'000 $m^3 a^{-1}$. These values are in good agreement with previous estimations (GRUBER 1969; ZOTTL & ERBER Zivilingenieurbüro 1987; KRESSER 1988; KLASZ 2002), but they are supported by more and higher quality data than they had in the past.

Some effects of degradation on side-arms and gravel bars

By degradation the main channel and the floodplain are gradually disconnected, duration and frequency of the inflows into the side-arms are decreasing, and their morphological dynamic is reduced. If the connectivity falls below a critical value, bushes and trees are growing quickly, and in interaction with siltation these side-arms are transformed into riparian forest.

Degradation may also undermine the success of restoration projects. For example, the large-scale 'Regelsbrunn / Haslau-'project, realized between 1996 and 1998, should reestablish hydrological connectivity and dynamics of an 8 km long side-arm by lowering parts of the riverside embankments (TOCKNER et al 1998); the deepest inlets were set at an elevation of MW-0,5 m. However, the mean water MW was derived by the KWD-1985, and in the meanwhile (over the last about 25 years) this water level has declined by ~60 cm there, see Figure 4. Thus, the duration of inflowing was reduced from 216 $d.a^{-1}$ to ~143 $d.a^{-1}$; if this tendency will go on, the hydrological effects of this restoration project would be transient.

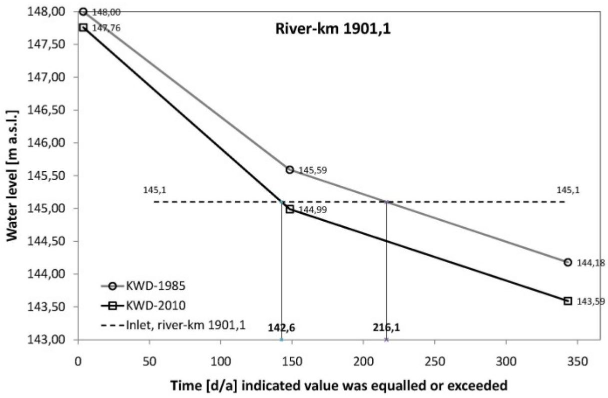

Figure 4: Duration curve, water level (for river-km 1901.1) versus time [d/a], the indicated value was equalled or exceeded; situation in 1985 (KWD-1985) and 2010 (KWD-2010)

The interaction between incision and vegetation can also concern gravel bars within the main channel. Contrary to the deeper parts of the river, most alternate and point bars are not eroding, thus they are gradually growing up relative to the declining mean water level. Similar to the side-arms, dense vegetation (bushes and trees) is developing as soon as the frequency of inundation falls below a critical value. In the last years this process can be observed on a large point bar between river-km 1884.5 and 1883 (left side of the river, opposite of Hainburg). Thus, there is a shift from gravel-bed areas to forested areas even within the channel. Dense vegetation can stabilize and protect such gravelly areas against the tractive forces of floods, and siltation is supported there; as a result, the active width of the channel is gradually reduced: The bankfull channel becomes deeper and somewhat narrower.

Overbank deposition and natural levee formation

In the study reach distinct natural levees have been formed. Based on airborne laserscanning data a sequence of n=111 cross sections perpendicular to the flood protection dyke was derived, an example is given in Figure 5a, and by that method a mean levee height of ~1.31 m can be determined. In Figure 5b the characteristic elevations (H_1: highest elevation near the river bank, that is, the crest of the natural levee; H_2: elevation of floodplain near the dyke / inside the inundation area; H_3: elevation near the dyke / outside the inundation area) are plotted along a longitudinal profile; the differences H_1-H_3 are strongly varying, which can be partly explained by the floodplain flow situation (inflow / outflow sections) (KLASZ et al. in prep.).

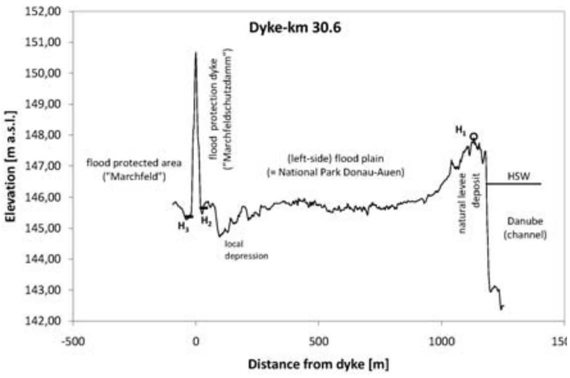

Figure 5a: Characteristic transect, definition of the characteristic elevations H1, H2, H3

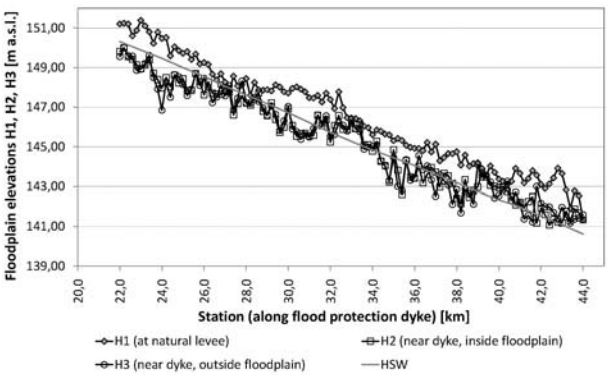

Figure 5b: Longitudinal profile of the left-side floodplain of the Danube; the characteristic elevations H_1, H_2 and H_3 for all transects are projected on the dyke-section; in addition, the characteristic water level 'HSW', which is nearly the bankfull stage, is plotted

The magnitude of these natural levees can be understood as a further symptom of disequilibrium. In natural and laterally active rivers overbank deposition is usually balanced and restricted by side erosion and natural channel migration. However, if the banks are fixed (by riprap), which has been the case for more than a century along the Danube east of Vienna, the overbank deposits cannot be eroded, and distinct 'natural' levees are formed. These levees will develop and grow further and affect both flood protection and floodplain ecology (KLASZ et al., in prep.).

Conclusions

The development and biodiversity of riverine ecosystems is controlled by hydrological and morphological dynamics and the connectivity between river and floodplain (WARD et al. 2002). A key factor in natural systems is also a dynamic stability. However, in the National-Park Donau-Auen the ability for self-regulation has been reduced by human impacts such as the stabilization and fixation of the banks (by riprap) with consequences such as bed degradation, natural levee formation, and siltation of side-arms. From a geomorphic point of view, the present system is far away from a dynamic equilibrium.

Taking this into account, the conception of restoration projects should include effective measures to reduce bed degradation and to improve the dynamic stability of the system; artificial bedload supply and the removal of bank stabilization (riprap) wherever possible must be key elements of such projects. Otherwise many parts of the National park will steadily lose its alluvial and riverine character.

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