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Structural Measures to Optimize Sediment Management Downstream a Chain of Reservoirs at the Danube River

Michael Tritthart, Martin Glas, Marcel Liedermann, Helmut Habersack
Christian Doppler Laboratory for Advanced Methods in River Monitoring
Modelling and Engineering Institute of Water Management
Hydrology and Hydraulic Engineering, University of Natural Resources and Life Sciences
Vienna, Austria

ABSTRACT

A lack of available sediments due to retention in an upstream chain of reservoirs as well as generally prohibited bank erosion following river regulation by rip-rap protected banks led to a long-term degradation rate of 2-3 cm per year of the bed of the Danube River between Vienna and Bratislava. Recently, various engineering structures, such as groynes, were modified to stabilize the river bed. It was found that the river bed shows a high sensitivity to comparably small changes to these structures, in particular concerning groyne lengths and crest heights. Moreover, the initial condition of the river bed prior to implementation of measures yields a substantial influence on their efficacy.

KEY WORDS: river engineering; groynes; bed degradation; 3D hydrodynamic model; sediment transport model; morphodynamics

INTRODUCTION

Retention of sediments in upstream hydropower reservoirs is often the cause for bed incision in rivers worldwide. One such example is the bed of the Danube River between the capital cities Vienna (Austria) and Bratislava (Slovakia), which is characterized by a long-term degradation rate of 2-3 cm per year (Habersack et al., 2007). The main reasons for this ongoing incision process are a lack of available sediments due to retention in an upstream chain of reservoirs as well as generally prohibited bank erosion following river regulation in the 19th century (Hohensinner et al., 2004) by rip-rap protected banks. In recent years, various structural measures were initiated to stabilize the river bed and improve the navigation conditions as well as the overall ecological situation, such as increasing the mean diameter of gravels at the river bed - termed granulometric bed improvement - or reducing shear stresses acting on the bed by modifications to existing groyne structures and guiding walls (Tritthart et al., 2014). This paper focuses on these lateral river training structures.

While groynes have been documented since the 16th century (Uijttewaal, 2005), systematic studies on their influence on hydrodynamics and morphodynamics of a river bed were conducted only in the last two decades, both experimentally (e.g. Biron et al., 2005; Uijttewaal, 2005; Kang et al., 2011; Yossef and de Vriend, 2011) and numerically (Ouillon and Dartus, 1997; Alauddin and Tsujimoto, 2012). Innovative groyne types and the difference to orthogonal groynes in terms of hydrodynamics and morphodynamics were studied recently in the field at the river Elbe (Henning and Hentschel, 2013).

Studies of modified groynes at the Danube River were conducted in situ in two river reaches, located near the municipalities of Witzelsdorf and Bad Deutsch-Altenburg, respectively. A systematic study of the influence of groyne parameters on morphodynamics using 3D numerical modelling was presented by Tritthart et al. (2014) for the Witzelsdorf study site. Here we focus on the second study site, a river reach of three kilometers in length, located near the municipality of Bad Deutsch-Altenburg (Fig. 1). In particular, compared to the conditions before implementation of the measures, groynes were rebuilt with a reduced length, a lower crest height, with a larger spacing and in an attracting and curved layout instead of the original orthogonal and straight groynes.

After completion of the engineering measures it was found that erosion processes in the study reach were substantially reduced – thereby indicating a general success of the project. However, it was noted that under these modified conditions now frequent sedimentation processes were taking place in some areas, requiring recurring sediment management activities by dredging operation. In order to understand the causes for the persistent sedimentation processes and to devise a strategy towards sustainable sediment management, a numerical study of the river reach was conducted. Alternatives to the current structures were tested using a 3D hydrodynamic model in combination with a sediment transport model. The aim of the present study was to (i) predict the reaction of the river in terms of hydro- and morphodynamics following modifications of lengths and heights of the groynes, and (ii) investigate the influence of the natural variability of the river bed elevation on the efficacy of the lateral structures.

STUDY SITE

The study site is a three-kilometer reach of the Danube River east of Vienna, ranging from river km 1884.5 to 1887.5, located in a National Park zone (Fig. 1). For the purpose of numerical modelling an additional upstream and downstream section of 500 m each was

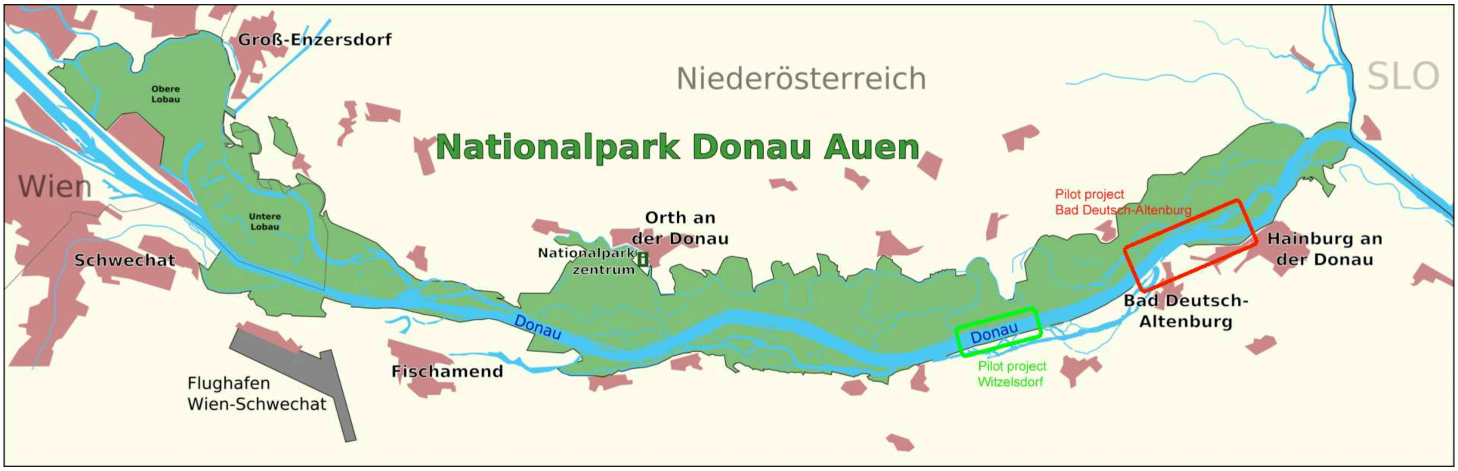

Fig. 1 Location of the pilot projects Bad Deutsch-Altenburg and Witzelsdorf within the Danube River reach east of Vienna, Austria.

considered. A comprehensive field monitoring campaign has been conducted in this reach since the year 2005, which forms the data base for the numerical study presented in this paper.

Three characteristic discharges were studied: regulated low flow (RNQ; 94% probability of exceedance) with a discharge of 980 m^3s^{-1}, mean flow (MQ) with a discharge of 1930 m^3s^{-1} and highest navigable flow (HSQ; 1% probability of exceedance) with a discharge of 5130 m^3s^{-1}. The results presented in this paper are related to MQ. The average river width at the study site amounts to 280 m. Grain sizes in the bed of this section of the Danube River are characterized by an arithmetic mean diameter of d_m = 27.5 mm, a median diameter of d_{50} = 21.5 mm and a diameter d_{90} = 59.9 mm (Tritthart et al., 2011b). Sediment samples in groyne fields and near the river banks, which were taken during the course of the measurement campaign, in part exhibit substantially finer grain size characteristics (Tritthart et al., 2014).

A digital elevation model (DEM) of the original regulated river bed prior to the implementation of engineering measures is depicted in Fig. 2a. The DEM after completion of measures - with lower groyne crests, substantially reduced number of groynes and in curved, attracting shape - is shown in Fig. 2b. Further elements of the river engineering measures are also visible, such as an artificial longitudinal gravel bar in the encircled area near the orographic left bank and a reconnected side arm at the right bank in the downstream half of the study reach. Fig. 2c depicts one of the variants proposed and investigated in this study, which is characterized by an increase in groyne length by 25 m (within the encircled area), as compared to the state after completion of measures. As a second variant an increase of groyne elevation by 0.60 m was investigated in combination with the length increase by 25 m (Fig. 2d).

NUMERICAL MODELS

Hydrodynamics were calculated using the three-dimensional numerical model RSim-3D (Tritthart, 2005) which solves the Reynolds-averaged Navier-Stokes equations on a mesh composed of arbitrary polyhedrons by means of the Finite Volume method. Details of the model are given in Tritthart and Gutknecht (2007). Sediment transport and morphodynamics were simulated using the integrated sediment transport model iSed (Tritthart et al., 2011a) with both bedload and suspended load transport enabled. Bedload was calculated using a modified version of the equation by Meyer-Peter & Müller (1948), accounting for non-uniform transport by means of a hiding-exposure correction. Details of the model setup and calibration for the study reach are presented in Tritthart et al. (2011b).

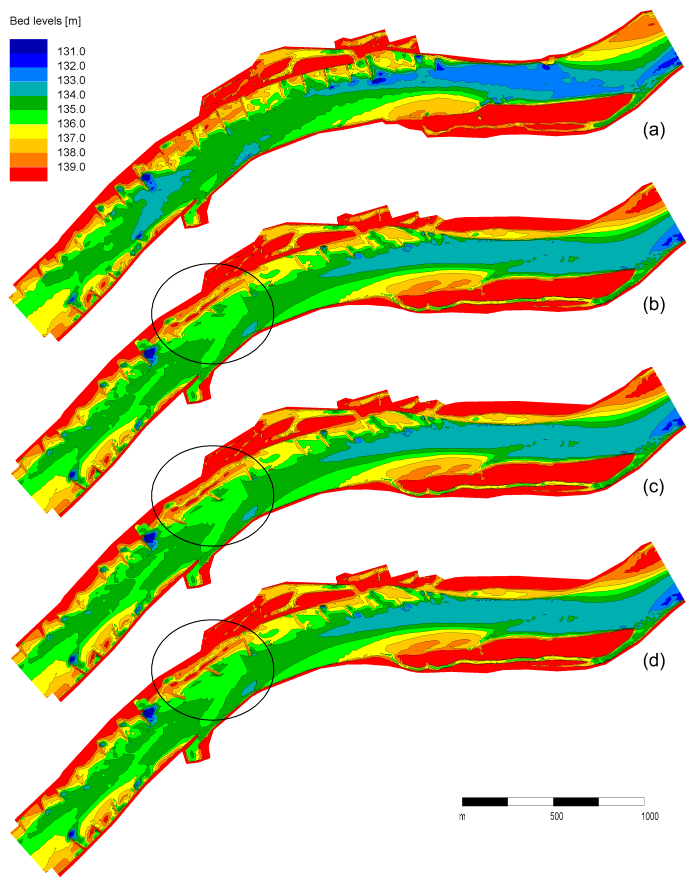

Fig. 2 Digital Elevation Models (a) of the original regulated state; (b) after implementation of measures; (c) variant with increased groyne lengths; (d) variant with increased lengths and heightened groynes. Area with investigated modifications is encircled. Flow direction is from left to right.

RESULTS AND DISCUSSION

Morphodynamics of Implementation Stage and Variants

From the comparison of Fig. 2a with Fig. 2b it is immediately obvious that the implementation of the engineering measures – in particular the lowered groynes in reduced number and with modified shapes – were a success of the project insofar that the river bed incision was stopped within the study area. The additional sediment input from the riparian zones due to removed bank protection structures, together with enhanced sedimentation processes following the new and modified groynes, led to higher bed levels both in the critical zone (encircled in Fig. 2) as well as in the downstream half of the project reach. However, the higher river bed posed challenges to the navigability of the river during low-flow periods and therefore led to the requirement of recurring sediment management activities by dredging operation. Therefore the modified variants with an elongation by 25 m, respectively heightening of three groynes by 0.60 m, were studied numerically.

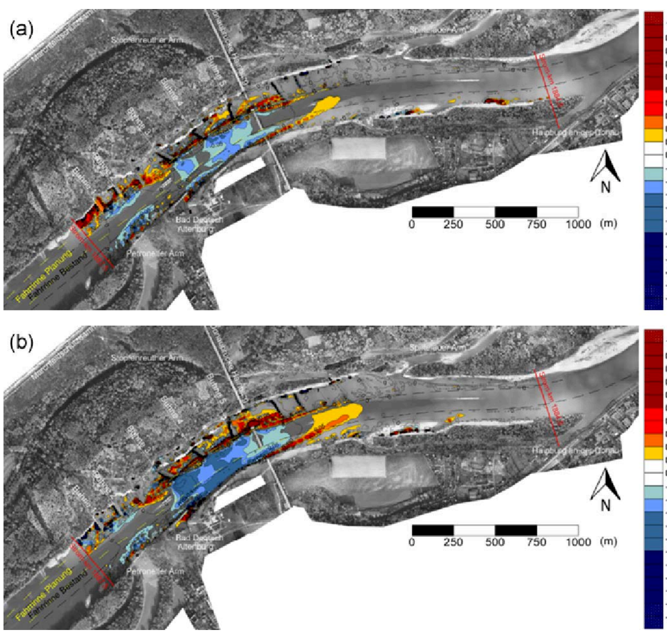

Fig. 3 Simulated differences in bed elevation (in meters) after 3 months simulation time (discharge: MQ); between implementation stage and (a) variant with increased groyne length, (b) variant with increased length and heightened crest elevation.

Fig. 3 shows the predicted differences in bed elevation between implementation stage and the two investigated variants, respectively, after three months of simulation time, applying a constant discharge of MQ. The increase in groyne length (Fig. 3a) is expected to lead to relative erosion (i.e. a decrease of sedimentation) in the area where navigation was affected by sedimentation processes. An even stronger influence is expected from a combined increase in length and height of the groyne structure (Fig. 3b), for which the model predicts a river bed evolution up to 0.15 m lower than for implementation stage. A horseshoe-shaped relative deposition zone is expected downstream the area of modified groynes, which is in line with the fundamental morphodynamics processes taking place in the widening zone downstream of a river width constriction (Tritthart et al., 2011a). However, the bed elevation increase in this deposition zone is expected to be relatively small; moreover, this zone does not pose a challenge to navigation.

In addition it was found that the erosion relative to the sedimentation process in the implementation stage tends asymptotically towards a limit, which is reached after approximately 3-5 months of the same investigated discharge. Hence the river bed can be expected to reach a dynamic equilibrium once this time has passed after a variant will have been implemented. However, this can only be expected for a relatively constant river discharge between regulated low flow and mean flow, as flood events are known to change the river bed morphology considerably. Therefore the sensitivity of the initial river bed morphology on the occurring morphodynamics processes was investigated further.

Sensitivity of Initial River Bed Morphology

The sensitivity was analyzed by repeating the simulations for the two groyne modifications (length, elevation) on the basis of a different bathymetric river bed survey. While the river bed for the DEMs used throughout this study (reference DEM) was measured at a point in time preceded by dredging activities and several months of low to mean discharges, the alternative survey was conducted during elevated discharge (4000 m^3s^{-1}) and less than a month after a 1-year flood event had occurred. Due to sedimentation processes in the wake of the flood event, the overall bed elevation was substantially higher, with local differences of up to 1 m, as compared to the reference DEM.

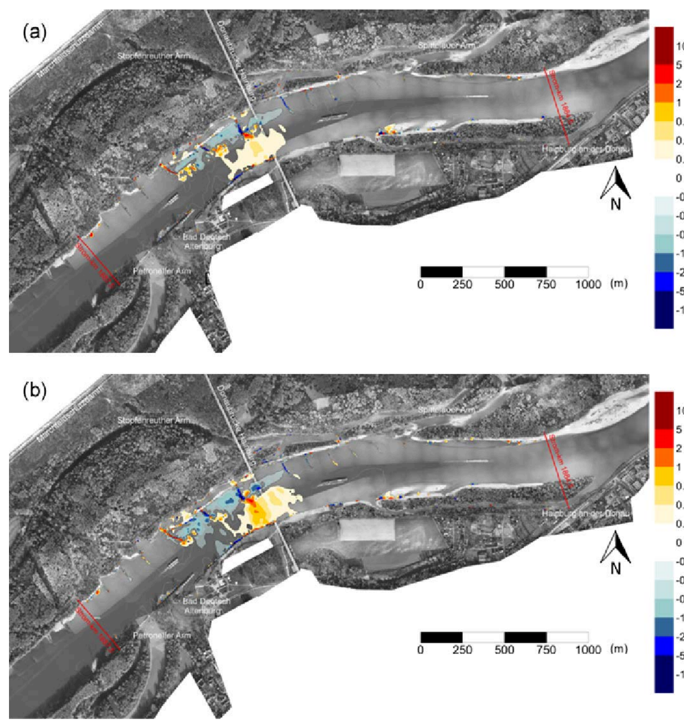

Fig 4 Simulated differences in bed shear stresses (in Nm^{-2}) for a steady discharge (MQ); between a flood-influenced initial morphology and (a) variant with increased groyne length, (b) variant with increased length and heightened crest elevation.

In Fig. 4 the simulated differences in bed shear stress between the two groyne variants investigated on the basis of the reference DEM and the same variants using a flood-influenced initial morphology are shown. The bed shear stress serves as a proxy for morphodynamic evolution since it is the driving force in the underlying sediment transport equation. It was found that the bed shear stress is up to 2 Nm^{-2} higher for the flood-influenced initial morphology for the variant of the groyne elongation (Fig. 4a) and up to 3-4 Nm^{-2} in case of the variant considering an additional crest elevation increase (Fig. 4b). These values are relatively high when seen in context with the bed sediment sizes at the Danube River reach and can be expected to lead to a much stronger impact of the groyne modifications right after floods, as compared to low- to mean-flow periods. Higher relative erosion (reduction of sedimentation) can therefore be expected during the passage of flood waves and in the falling limb of the hydrograph. Hence this influence – implicating additional uncertainty in river engineering projects – needs to be taken into account when making predictions of bed morphodynamic evolution on the basis of a given river morphology.

CONCLUSIONS

The Danube River east of Vienna is characterized by a long-term bed degradation rate of 2-3 cm per year. Therefore river engineering measures were implemented in order to stop the incision and achieve a dynamic equilibrium of the river bed. After the implementation of modifications to existing groyne structures, reducing their number, lengths and crest elevations, it was discovered that the overall erosive trend was stopped in the study reach. However, local sedimentation tendencies challenged the navigability of the river. In order to understand the causes for the persistent sedimentation processes and to devise a strategy towards sustainable sediment management, a numerical study of the river reach was conducted. Alternatives to the current structures were tested using a 3D hydrodynamic model in combination with a sediment transport model. The expected reaction of the river in terms of hydro- and morphodynamics was studied numerically. It was found that the river bed shows a high sensitivity to comparably small changes to the structures, in particular concerning groyne lengths and crest heights. Moreover, the study revealed that the initial condition of the river bed prior to implementation of measures – e.g. a level change due to a preceding flood event – yields a substantial influence on their efficacy and ultimately their success in reaching a sustainable dynamic equilibrium of the river bed.

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