ГОДИШНИК НА УНИВЕРСИТЕТА ПО АРХИТЕКТУРА, СТРОИТЕЛСТВО И ГЕОДЕЗИЯ
СОФИЯ

Том Volume 52 | 2019 | Брой Issue S1

ANNUAL OF THE UNIVERSITY OF ARCHITECTURE, CIVIL ENGINEERING AND GEODESY
SOFIA

Получена: 03.06.2019 г.
Приета: 17.06.2019 г.

RIVER BED EROSION AND SUSTAINABLE SOLUTIONS AT THE AUSTRIAN DANUBE RIVER

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Keywords: *river bed erosion, groynes, morphodynamics, the Danube River*

ABSTRACT

The Austrian Danube east of Vienna is characterized by a sediment deficit causing a long-term erosive trend and posing a hazard for a river bed breakthrough of the gravel cover layer into fine marine sediment deposits. As a remedy, various gravel replenishment methods, as well as the modification of groyne structures were tested. Replacing the top layer with a wide-graded sediment mixture resulted in the best stabilization effect. Moreover, modifications of groyne geometries were tested numerically, employing a sediment transport model based on 3D hydrodynamics. It was found that even comparably small changes to the existing groynes yield a strong morphodynamic reaction of the river bed. Morphodynamic equilibrium could be achieved in particular by optimizing the crest levels of the groyne structures. The measures implemented so far resulted in a clear reduction of the erosion trend in the river reach.

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1. Introduction

A long-term trend of 2 – 3 cm average annual river bed erosion in the free-flowing section of the Austrian Danube east of Vienna was documented for the past five decades [11]. River training measures stabilizing banks and the presence of an upstream chain of reservoirs causing retention of gravel sediment were identified as the root causes of the existing sediment deficit in the reach. Even though the hydropower operator strictly follows the legal requirement to add gravel sediment downstream of the power plant, a sediment deficit prevails [21]. On the long term, the erosive trend yields ecological consequences for the adjacent Danube Alluvial Zone National Park region, leading to a disconnection of the surface water bodies and a reduction of groundwater levels. Moreover, a river bed breakthrough [10] of the gravel cover layer into fine marine sediment deposits present in sublayers is a main potential hazard. Such a breakthrough took place at the Salzach River following a single flood event in 2002 [9].

Various measures to counter the erosive trend were implemented in recent years and have led to a trend reduction to 1 – 2 cm per year [17]. This paper summarizes the implemented measures and presents the numerical framework as well as the related results which were used to project the outcome of the measures prior to their implementation.

2. Study Reach

The study reach comprises the entire free-flowing section of the Danube River downstream of the Freudenau hydropower plant in Vienna to the Slovak border near Bratislava, in total 48 river kilometers (Fig. 1). The reach is located almost entirely within the National Park Donauauen (Danube Alluvial Zone National Park). The implementation of measures was first tested in the two pilot reaches of Bad Deutsch-Altenburg (river km 1884 – 1888; Fig. 1) and Witzelsdorf (river km 1891 – 1894), which were subject to detailed measurement campaigns. The Danube River in the pilot reaches is characterized by a mean annual flow (MQ) of 1930 m^3s^{-1}, a regulated low flow (RNQ) of 980 m^3s^{-1} and a highest navigable flow (HSQ) of 5130 m^3s^{-1}. In Witzelsdorf the bed sediment exhibits an arithmetic mean diameter d_m = 25 mm, a median diameter d_{50} = 20 mm and a diameter d_{90} = 52 mm. As the river characteristics are similar between Witzelsdorf and Bad Deutsch-Altenburg, this paper focuses on the findings in the Witzelsdorf pilot reach.

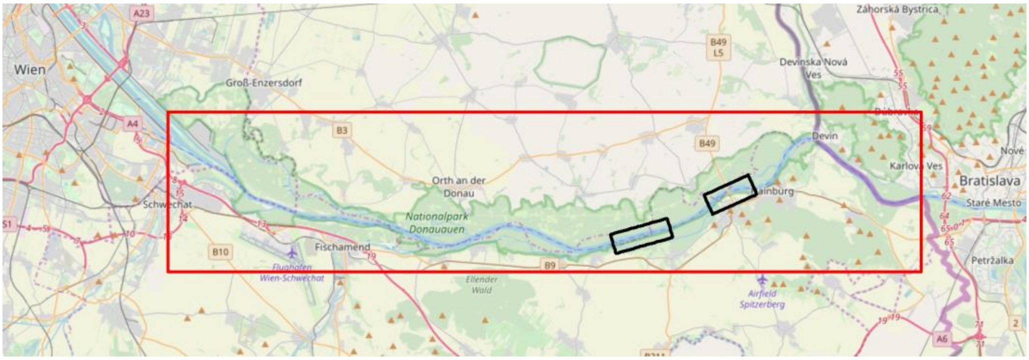

Figure 1. Study reach at the Danube east of Vienna (outer box) including pilot reaches Witzelsdorf (left inner box) and Bad Deutsch-Altenburg (right inner box)

3. Methods

Data from detailed field measurement campaigns were used to calibrate and validate a 3D hydrodynamic model and subsequently a sediment transport model. These models served the purpose to upscale point measurements to the reach scale during the monitoring campaign and moreover comprise tools for the prediction of the functioning of planned river engineering measures.

3.1. Field Measurements

Multi-beam bathymetric measurements were available to represent the river geometry. Several gauging stations in the area provided water levels and river discharges. Bed load was measured using a basket sampler during various discharges within the hydrologic spectrum. Suspended load was monitored by probes located at the gauging stations and by deploying an isokinetic point-integrated sampler. Bed sediment composition was obtained from grab samples and freeze cores. Tracer stones were deployed to derive the transport characteristics of the reach. More information on the monitoring campaign can be found in [14].

3.2. Numerical Modelling

The 3D hydrodynamic model RSim-3D [18] was used in combination with the integrated sediment transport model iSed [20].

3.2.1. Hydrodynamic Model

The three-dimensional hydrodynamic model RSim-3D [18] solves the Reynolds-averaged Navier-Stokes equations on a mesh composed of arbitrary polyhedrons (Fig. 2) using a generalized Finite Volume method [19]. A second order upwind scheme is employed for the interpolation of convective fluxes at cell boundaries. The coupling of pressure and velocity fields is performed by means of the SIMPLE algorithm in a generalized formulation following [1]. Turbulence is modelled using a standard two-equation k-ε closure [12]. The position of the free water surface elevation is derived from the computed pressure field in an iterative process.

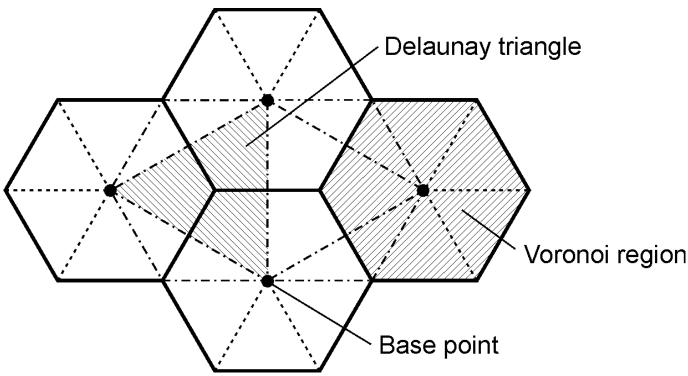

Figure 2. Top view of the mesh layout of the RSim-3D model with polyhedral cells [18]

3.2.2. Sediment Transport Model

The integrated sediment transport model iSed [20] is coupled with external 2D or 3D hydrodynamic codes which in turn provide water depths, flow velocities and bed shear stresses as input for sediment transport and morphodynamics calculations. The model can handle various computation mesh types, ranging from triangular or quadrilateral cells in 2D to hexahedral or polyhedral cells in 3D. According to the physical processes in sediment transport, suspended load and bed load are calculated separately from each other. The underlying layer concept is shown in Fig. 3: suspended load is transported in the water column, while bed load moves at the river bed by various transport modes; an exchange layer is responsible for mixing sediment in transport with the bed material located in the subsurface layers.

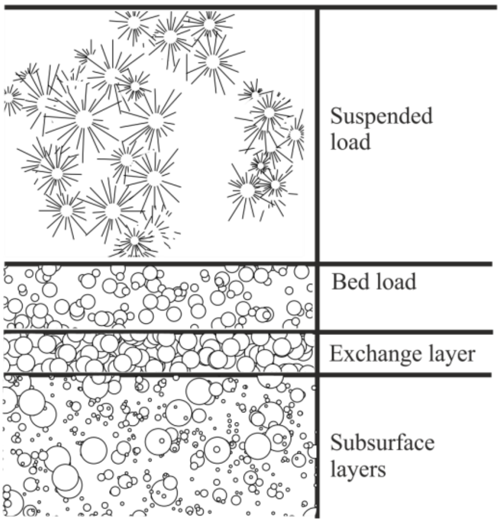

Figure 3. Layer concept of the iSed model (modified after [21])

In order to simulate bed load transport, the iSed model contains both uniform and non-uniform variants of the empirical transport equations by Meyer-Peter and Müller [15], Egiazaroff [3], van Rijn [25] and Wu et al. [27]. The non-uniform transport equations are equipped with hiding-exposure corrections, ranging from the classical correction of Einstein [4] to a concept introduced by Parker [16], which calculates a separate representative diameter for every grain size fraction. In this study, a non-uniform formulation of the transport equation after Meyer-Peter and Müller [15] was used together with the hiding-exposure correction proposed by Einstein [4].

The transport of suspended load is simulated by solving the governing advection-diffusion equation numerically. Depending on the dimensionality of the underlying flow physics, the equation can either be formulated in 2D [21] or in 3D [24]. An exchange term accounting for deposition [26] and erosion fluxes [5] provides the cumulative sediment flux between the river bed and the water column. A total of 21 grain size fractions were used, 9 in the suspended load range and 12 in the range of material transported as bed load.

The morphodynamic evolution of the river bed is obtained from the evaluation of the sediment continuity equation (Exner equation), yielding the vertical elevation change per grain size fraction for every computational node. By balancing the corresponding mass fluxes, a new grain size distribution is derived for every calculation time step.

4. Sustainable Solutions

Various measures were implemented in a 1:1 test in the field; many of them were also subject to a numerical study prior to their implementation. This section details the measures and their functionality.

4.1. Granulometric Bed Improvement

The core idea behind the granulometric bed improvement [2] is that larger gravels yield a higher resistance against being set in motion than smaller gravels due to the resulting inertial forces. Therefore, depending on morphological conditions, a layer of 25 cm right below the river bed is either replaced by larger grain sizes (Fig. 4) or this layer is added upon the river bed. Over time, this material mixes with both transported and subsurface gravels, yielding a sediment mixture which is coarser than the original but still within the natural grain size spectrum.

The allowance/replacement gravel mixture projected during the planning stage ranged between 40 and 70 mm. Numerical modelling as well as physical model tests indicated a stable behavior of these grain sizes. However, field tests showed a higher mobility of this grain size fraction than expected. Finally, a larger grain size range of 32 mm to 120 mm yielded the best stabilization effect [14]. The increased mobility of the gravel layer in the field test compared to numerical and physical model tests was credited to the presence of transport phenomena in the field such as gravel sheets and increased turbulent kinetic energy or small-scale turbulent structures.

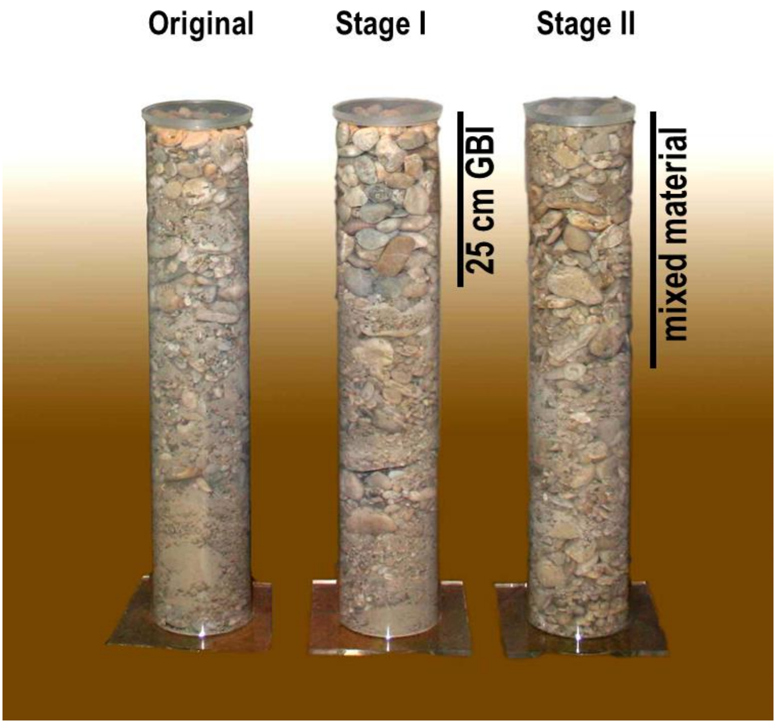

Figure 4. Concept of the granulometric bed improvement

4.2. Groyne Modifications

Intensive river regulation by guiding walls and groynes was present in the pilot reaches at water levels up to mean flow and still exists in many other locations of the study reach. These structures channelize the flow and particularly during low-flow situations lead to increased bed shear stresses, which in turn facilitate river bed erosion. There are several possibilities to modify groyne structures in order to reduce their erosive effect:

1. Reduce the number of groynes, thereby lowering the channelization effect;
2. Reduce the crest elevation of groynes, hence minimizing the discharge spectrum during which the groynes affect the flow;
3. Reduce the length of groynes, thus effectively reducing the river width affected by channelization;
4. Change the inclination angle with respect to the river banks, with the effect of directing the flow towards the banks during groyne submergence (so-called attracting groynes), which leads to bank erosion and additional sediment availability to counter a sediment deficit.

At the Danube River east of Vienna all of the above variants were tested in the field (Fig. 5) simultaneously. In turn, strong sedimentation processes resulted. Thus, model simulations were performed to understand how sensitive river bed morphodynamics are with respect to the various modifications. The numerical study considered the following variants: (i) orthogonal groyne layout, (ii) attracting groyne layout, (iii) groyne spacing of 1x the average groyne length, (iv) groyne spacing of 3x the average groyne length, (v) length increase of groynes by 20%, (vi) length decrease of groynes by 20%, (vii) increase of crest elevation by 0.4 m. The findings of the study are summarized in section 5.

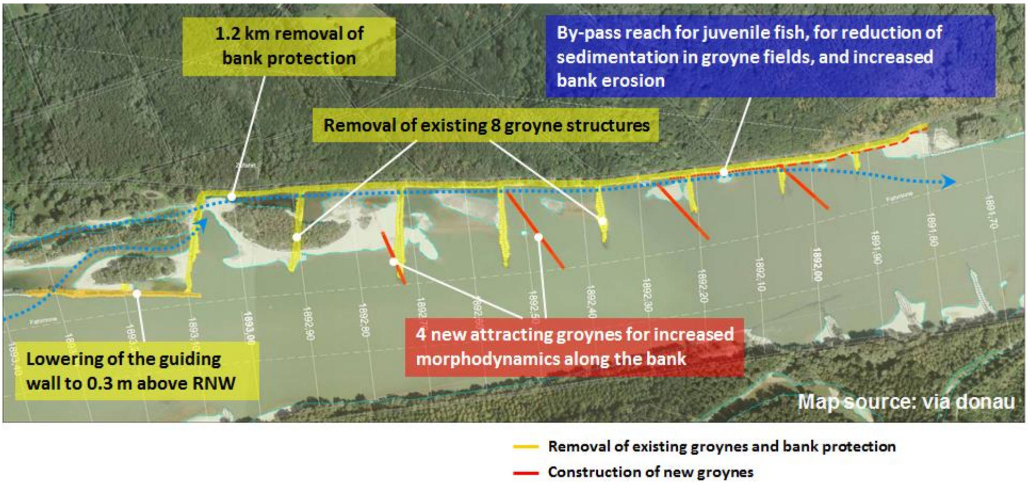

Figure 5. River engineering measures (example Witzelsdorf pilot reach); modified after [23]

4.3. Artificial Island Building

The concept underlying the construction of artificial islands is to create a flexible sediment buffer at the side of the navigation fairway. The island serves the purpose to achieve channelization and therefore increase the water depth during low-flow periods, but on the other hand it is erodible during higher river discharges and allows the river to carry sediment for gravel replenishment. The structures are unstable by design on the long term and thus need to be subject to maintenance operations. At the pilot reach of Bad Deutsch-Altenburg one such island was implemented successfully and further ones in other reaches of the Austrian Danube are in the planning stage. A scientific analysis of their functionality is currently ongoing.

4.4. Other Ecologically Oriented Methods

Further methods were implemented in the field to improve the ecological situation, in particular the connection between the main river and its floodplains in the National Park area. The first notable modification was the reconnection of several side arms in the study reach. The side arms were connected at discharges well below mean flow, thereby achieving flow passage during most of the year and thus restoring the original character of an anabranching river system [13]. Also the lowering of groyne root elevations (Fig. 5) to create an in-stream by-pass for juvenile fish with small flow velocities was tested in the scope of the project [5, 13]. Finally, the removal of rip-rap protection at all banks not directly exposed to the flow was aimed towards increasing the amount of sediment in the river by allowing lateral erosion processes.

5. Results

This section focuses on the results of the numerical groyne modification study. For each of the structural variants detailed in section 4.2, the hydrodynamic and morphological conditions were assessed after 30 days of model simulation time. The result of an increased groyne crest elevation by 0.4 m compared to the reference conditions after measure implementation (cf. Fig. 5) is exemplarily shown in Fig. 6. The elevated groynes lead to bed shear stress increases by 2 – 5 Nm^{-2} in the fairway, which in turn correspond to a river bed erosion of 10 – 15 cm in the same area. While in principle undesired, this amount of erosion was found to counter the sedimentation processes initiated by the project implementation, and thus resulting in the desired dynamic equilibrium. Comparable results were found in [6].

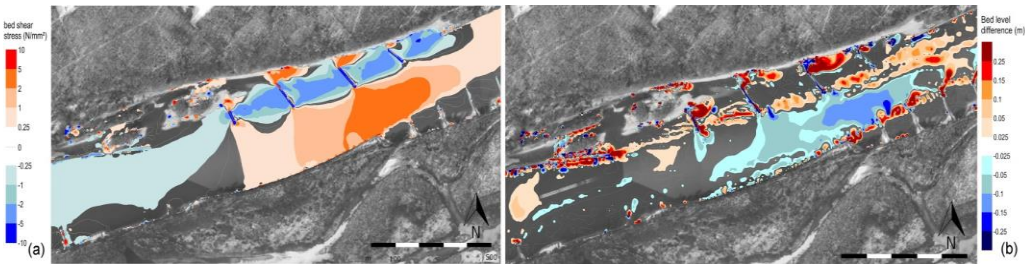

Figure 6. (a) Bed shear stress differences, (b) difference of differences of bed level changes, between increased crest elevation and reference condition for MQ [23]

Tab. 1 summarizes all groyne variants investigated. The number of arrows indicates the strength of the resulting effect while the direction shows whether the structural modification is positively or negatively correlated with the process. The results clearly show that the strongest morphodynamic effects can be achieved by changing the groyne spacing or the crest elevation. However, while a modification of the groyne spacing is a costly process requiring substantial mass movements on the construction site, a change in crest elevation is comparably cheap.

Therefore, this variant is recommended for achieving a dynamic equilibrium in similar situations. The numerical projection of the river bed evolution was validated successfully against measurements and models applied after the on-site implementation of a variant including increased crest elevations [7]. Further comparable numerical results for various groyne variants and their effect on the river bed in the main channel were also found in [6], including other simulated discharges and a flood wave scenario.

Table 1. Summary of the influence of the groyne variants on hydrodynamics and morphodynamics; for three characteristic discharges RNQ, MQ and HSQ

	Flow velocity			Bed shear stress			Water surf. elev.			Bed level change		
Groyne variants	RNQ	MQ	HSQ	RNQ	MQ	HSQ	RNQ	MQ	HSQ	RNQ	MQ	HSQ
Orthogonal groynes	≈	↑	≈	↑	↑	↑	≈	↑↑	↓	≈	≈	≈
Attracting groynes	≈	↑	≈	≈	↑	↑	≈	↑	↓↓	≈	≈	↕
Spacing 1x length	↑↑↑	↑↑↑	↑↑	↑↑↑	↑↑↑	↑↑	↑↑	↑↑↑	↑	↓↓	↓↓↓	↓↓↓↓
Spacing 3x length	↕	↑	≈	↕	↑	↕	↕	↑	↓↓	↑↑	↓↓	↕
Increased length	↑↑	↑↑	≈	↑↑	↑↑	↑	↕	↑↑	≈	↓↓	↓	↓↓
Decreased length	↓	↓	≈	↓↓	↕	↓	↓	≈	↓↓	↑	↑	↑↑
Increased elevation	-	↑↑↑↑	↑	-	↑↑↑↑	↑	-	↑↑↑↑	≈	-	↓↓↓	↓↓

6. Conclusions

Various gravel replenishment methods and structural modifications were tested numerically and in the field in order to counter the erosive trend present in the free-flowing section of the Austrian Danube east of Vienna. The allowance of larger gravels within the natural grain size spectrum, the so-called granulometric bed improvement, showed that a wide-graded mixture, ranging from 32 mm to 120 mm, resulted in the best stabilization effect. Moreover, gravel replenishment techniques by artificial islands are currently under evaluation. In addition, modifications of groyne geometries (length, crest elevation, inclination with respect to the banks) were found to be highly effective as even comparably small changes to the existing groynes yield a strong morphodynamic reaction of the river bed. Morphodynamic equilibrium could be achieved in particular by optimizing the crest levels of the groyne structures. The measures implemented so far resulted in a clear reduction of the erosive trend in the river reach and can serve as examples for other river reaches facing similar erosion issues.

Acknowledgements

The financial support by the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation of Research, Technology and Development is gratefully acknowledged. Moreover, we thank viadonau for their logistic support and contribution of data to this study.

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