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Numerical Analysis of the Effects of Engineering Measures on the Sediment Transport and Morphodynamics on the Lower Danube

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ABSTRACT

Over decades morphodynamic developments in a bifurcation zone in the Lower Danube led to an unequal discharge distribution towards the northern arm resulting in decreased water depths in the southern arm and a detour for navigation (~110 km). This study focuses on the expected morphological developments caused by hydraulic engineering measures. The objectives were thus given by determining sediment transport characteristics and associated alterations of hydromorphology. The processes were computed employing non-uniform transport equations embedded in the sediment transport model iSed. The results show improved navigation conditions for two scenarios. However, also scouring processes downstream transverse structures are expected.

KEY WORDS: Danube River; numerical model; bifurcation, sediment transport; morphodynamics.

INTRODUCTION

The present study focuses on the impacts of different conceptual hydraulic engineering measures on morphodynamics of a widely intact bifurcation zone in the Lower Danube. A modification of the bifurcation zone has become necessary due to the fact that at low to medium discharges the water depths in the southern branch downstream the bifurcation are insufficient for navigation, leading to a required detour for vessels of about 110 km. The shallow water depths result from an unequal discharge distribution between the northern and southern branch.

According to Tubino et al. (2007) the parameters responsible for water and sediment partition at bifurcations are morphological asymmetry (e.g. topographical effects, transverse bottom inclination, inlet step, etc.) of the morphological configuration at the node. Additionally they found that the discharge increases with the width and depth of the branch. Kleinhans et al. (2008) confirm that the slope and width of the branches influences the water and sediment distribution. Miori et al. (2012) support the statement that an inlet step influences the discharge distribution at the bifurcation. According to Miori et al. (2012) bedforms and flow structures exert only a secondary influence, while bed discordance between the distributaries is responsible for discharge partition. Federici et al. (2003) noted that if the incoming flow concentrates on one side of the channel, the branch of the bifurcation on the opposite side loses discharge and may close.

These findings are based on results of either observations in nature, physical model tests or numerical models. Kleinhans et al. (2008) applied a one-dimensional model for simulating the long-term evolution and an idealized quasi-three-dimensional model for predicting the propagation of sediment and morphodynamics at bifurcations on a timescale of decades to centuries. The quasi-three-dimensional model was based on the nonlinear shallow-water equations simplified by a hydrostatic pressure assumption. Dargahi (2004) and Hardy et al. (2011) applied a three-dimensional flow model based on the RANS-equations using the RNG k-ε turbulence model and a non-equilibrium wall function for simulating bifurcations. Hardy et al. (2011) focused on the simulation of different artificial bifurcations, while Dargahi (2004) modelled a natural bifurcation in Sweden. Dargahi (2004) analysed the sediment transport employing a model based on a 2-D sediment transport continuity equation in combination with the flow model.

A modelling approach similar to Dargahi (2004) and Hardy et al. (2011) was adopted in this study. Based on hydrodynamic results (Glock et al., 2015; Habersack et al., 2015), sediment transport and morphodynamics are predicted using the model iSed (Tritthart et al., 2011a). Successful applications of the model iSed are reported in Tritthart et al. (2011b) and Tritthart et al. (2012). In contrast to Dargahi (2004) and Hardy et al. (2011) this study focuses on impacts of conceptual engineering measures implemented in an existing natural bifurcation.

The objectives of the sediment modelling task were thus given by the determination of sediment transport characteristics (i.e., suspended sediment concentrations) and the associated alteration of hydromorphology due to the construction works planned.

INVESTIGATION AREA

Reference Conditions

The investigation area of this study represents a widely intact bifurcation zone of the Lower Danube (Fig. 1, encircled area) in Romania. The modelling domain comprised a length of 3.5 km upstream the bifurcation and downstream lengths of 3.5 km (northern arm) and 7 km (southern arm). The average width of the river is around 600 m and it is delimited by levees in the north-east and north-west, while in the south it is bounded by natural hillsides. The bathymetry of the bifurcation at reference conditions represents the year 2012 and is shown in Fig. 1. A defining characteristic at the bifurcation are the large bed level differences between the northern and southern arm. In the first two kilometres downstream of the bifurcation the bed levels of the southern arm are in the range of 1.5 to 3.5 m above mean sea level, while the bed levels of the northern arm are only -3.0 to -1.0 m above the sea level in a comparable section. Moreover, remains of old constructions characterize the inlet into the northern arm. These dilapidated structures were built in the second half of the 20th century and include a transverse structure around 700 m downstream the bifurcation node and a guiding wall at the river bank of this branch. Sediments in the river are mostly sandy, characterized by an arithmetic mean diameter (d_m) of 0.29 mm, a median diameter (d_{50}) of 0.20 mm, a diameter d_{90} of 0.78 mm and a standard deviation of the grading curve (U) of 2.75. The hydrology of the Danube at the investigation area is characterized by a regulated low flow (RNQ; 94% probability of exceedance) with a discharge of 2745 m^3s^{-1}, by a mean flow (MQ) with a discharge of 5048 m^3s^{-1} and a highest navigable flow (HSQ; 1% probability of exceedance) with a discharge of 11164 m^3s^{-1}.

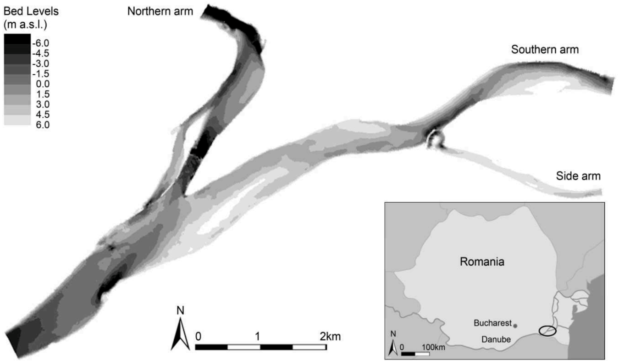

Fig. 1 Bed levels of the bifurcation area at reference conditions (m a.s.l. = m above sea level) and overview of the investigation area.

Overview of Different Conceptual Measures

In the course of various feasibility studies different conceptual measures at the bifurcation were planned by Administratia Fluviala a Dunarii de Jos R.A. Galati (AFDJ, personal communication, 2013), Pessenlehner (2014) and Glock et al. (2015). Based on these considerations five different scenarios (Fig. 2) were exemplarily selected to estimate their effects on the alteration of morphology. The reference situation without any structures is depicted in light grey in all variants. In variant "a" (Glock et al. 2015) a modification of the river course (M) by linking a former waterbody to the western arm, a guiding wall (G) and a dam cutting off (C) the original course of the northern branch were planned. Variant "b" (Pessenlehner, 2014) includes a spur (S) at the node of the bifurcation, a lowering of the bed elevation (L) in the southern arm and the filling of the scour hole (F) in the northern arm. In addition a renaturation (R) of longitudinal structures built several decades ago was planned. In variants "c", "d" and "e" (AFDJ, 2013) various transverse structures (T1, T2, T3) in the northern arm and a guiding wall (G) cutting off the western side arm of the river were tested. Compared to variant "c" the crest of the transverse structure in variant "d" was reduced by around 1 m and in variant "e" by around 2.6 m. Only in variant "d" an additional bed elevation lowering due to dredging operation (D) was planned in the southern arm. The implementation of bed protection measures up- and downstream of the transverse structure are shown in detail "f".

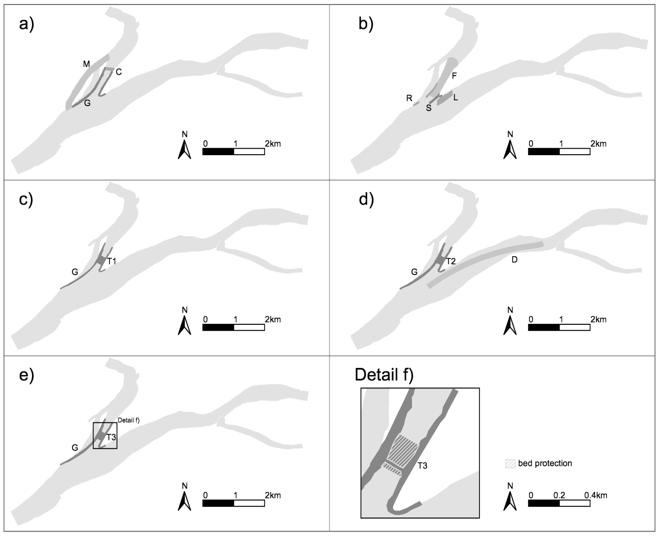

Fig. 2 Overview of the investigation area (light grey) including five different conceptual measures and detail of bed protection measures up- and downstream of the transverse structure.

FIELD MEASUREMENTS

Bathymetry

The underlying digital elevation model was compiled in a 2 x 2 m raster grid based on terrain elevation data originating from airborne Light Detection and Ranging (LIDAR), multi-beam river bed bathymetry (06/2011) and single-beam measurements (03-09/2012).

Bed Layer Material and Suspended Sediment

Sediment samples of the bed layer material were taken in 7 cross sections on the left and right river bank by grab samplers. All samples were sieved in 7 classes, ranging from 0.09 to 2 mm. The suspended sediment concentration was sampled in 7 cross sections. In each cross section 4 values (left bank 0.5 m below water level (b.w.l.); centre 0.5 m, 1.5 m and 3.0 m b.w.l.; and right bank 0.5 m b.w.l.) were taken.

METHODS

Sediment Transport Model

Based on the hydrodynamic results (Glock et al., 2015; Habersack et al., 2015) sediment transport and morphodynamics were predicted using the model iSed (Tritthart et al., 2011a). This model is capable of calculating suspended load and bed-load separate from each other. Due to the fact that sediments in the river are mostly sandy (d_m = 0.29 mm), bed-load was disregarded. The suspended load was determined by solving an advection-diffusion equation. Calculations of bed evolution were performed using the Exner equation (Tritthart et al., 2011a).

Coupling with the 3D-hydrodynamic simulations

The computation mesh of the 3D hydrodynamic model was also used in the sediment transport model iSed. The results of each steady-state hydrodynamic simulation were used as initial conditions for the sediment transport simulation at the corresponding discharge.

Boundary conditions

Suspended sediment concentrations were prescribed at the inflow boundary depending on the corresponding discharge. The correlation between the suspended sediment concentrations and the discharges is based on measurements and calculated rating curves (Habersack et al., 2015). The calibration was done based on hydrodynamic simulation results at a discharge of 3840 m^3s^{-1} and a suspended sediment concentration of 10 mgl^{-1} was assigned at the inflow boundary. In the validation stage, which was defined as scenario for comparing the reference conditions with all variants, an independent case (5530 m^3s^{-1} with an inflow sediment concentration of 33 mgl^{-1}) was simulated using the calibrated sediment transport model.

Bed layer material

The initial bed layer material in the river was assigned to the computation mesh according to the available sediment samples using the Kriging interpolation method. In the floodplains an artificial sediment material was assigned, characterized by grain sizes much larger than the limit of suspended sediment, i. e. 1 mm. The use of this material led to a significant decrease of morphological changes at these areas, which corresponds to the natural processes occurring there. Moreover, the remains of old constructions at reference conditions as well as the newly designed constructions implemented in the variants were defined as inerodible structures. In these areas morphological changes were prohibited in the model to protect the designed constructions from morphological changes.

RESULTS

Calibration and Validation of the Sediment Transport Model

The aim of the calibration was to find a dynamic equilibrium of the sediment transport in the entire investigation area by adjusting scaling parameters of the empirical bed exchange flux terms (erosion and deposition) embedded in the advection-diffusion equation of the model. The steady-state simulation result of the calibration shows a homogeneous distribution of the suspended sediment concentration of around 10 mgl^{-1} in the whole investigation area (Fig. 3).

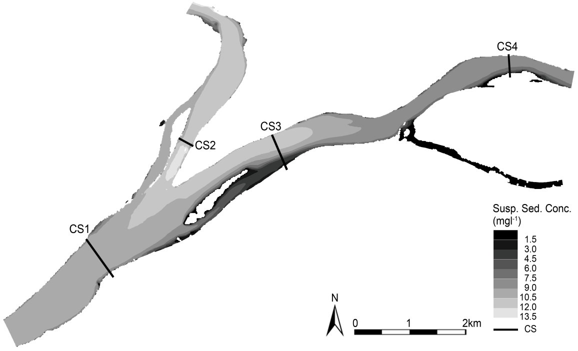

Fig. 3 Suspended sediment concentrations at reference conditions for the steady-state simulation of the calibration discharge of 3840 m^3s^{-1} and position of the measurement cross sections (CS).

In the calibration and validation stage the modelled suspended sediment concentrations were compared with measurements in 4 cross sections. A good agreement was found for all cross sections over the whole investigation area. The comparisons between the modelling results and the observations are exemplarily shown for two cross sections in Fig. 4.

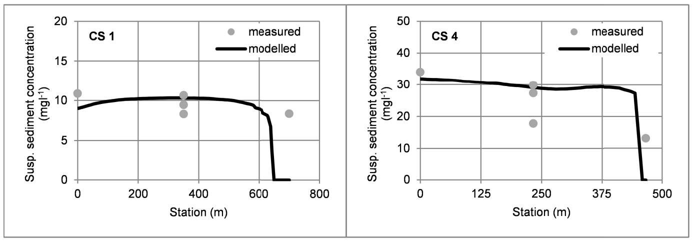

Fig. 4 Calibration and Validation: Comparison between measured and modelled suspended sediment concentrations in the cross sections (CS) 2 and 4.

Impact Analysis of Different Measures on Morphodynamics

In Fig. 5 the morphological developments after 3 months of steady-state simulations are depicted for the reference conditions and all variants for a mean discharge of 5530 m^3s^{-1}.

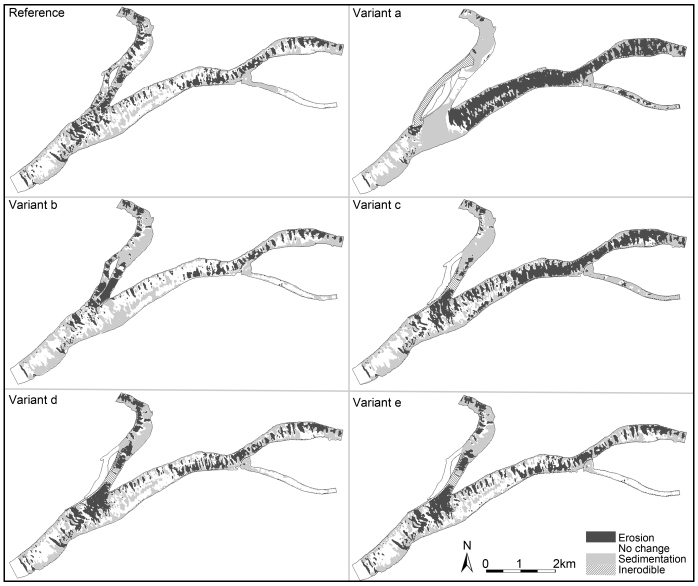

Fig. 5 Morphological developments after 3 months of steady-state simulations for reference conditions and all variants, for a mean discharge of 5530 m^3s^{-1}; "no change" indicates morphological changes in the range of ± 1 cm.

The results for the reference conditions show a quite homogeneous evolution of the morphology over the whole investigation area. However, at the bifurcation entrance in the northern arm and around two kilometres downstream of the bifurcation in the southern arm the model predicts notable erosions. In contrast to the reference conditions, the simulations of variant "a" show intensified erosions in the southern arm. Moreover, an aggradation is predicted downstream the mouth of the new side arm. Slight erosions at the entrance and mouth of the new side arm indicate local scouring processes in these areas. Compared to the reference conditions, the simulations of variant "b" depict substantial erosions downstream of the spur in the northern arm. The implemented guiding wall in variants "c", "d" and "e" leads to similar intensified erosions at the bifurcation entrance in the northern arm. Moreover, the different heights of the transverse structure in the northern arm affect the morphological developments in the whole investigation area. The higher the transverse structure, the lower are the erosions in the northern arm downstream of the construction and the higher are the erosions in the southern arm.

Detailed Analysis of Bed Protection Measures

The morphological developments in the longitudinal section LS1 after 3 months of steady-state simulations are depicted in Fig. 6 for variant "e" with planned bed protection in place and without bed protection measures up- and downstream of the transverse structure at the bifurcation entrance in the northern arm. Compared to the simulation with bed protection erosions downstream of the transverse structure are expected for the simulation without bed protection, leading to a scour whole with a length of around 100 m and a mean depth of 0.8 m.

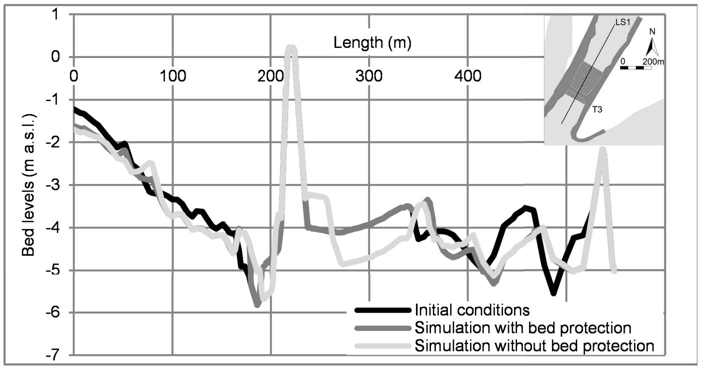

Fig. 6 Morphological developments in the long section (LS) 1 after 3 months of steady-state simulations for variant "e" with and without bed protection measures up- and downstream of the transverse structure, for a discharge of 5530 m^3s^{-1}; inset: position of the longitudinal section.

DISCUSSION

Glock et al. (2015) and Habersack et al. (2015) showed that the implementation of variants "a" and "c", which are reducing the bed level differences between the northern and southern arm, leads to a harmonisation of the discharge distributions at the bifurcation. Tubino et al. (2007) and Miori et al. (2012) also found that bed level differences influence the discharge distribution at the bifurcation. The resulting discharge distributions, inducing higher bed shear stresses in the southern arm, lead to substantial erosions in this branch in the morphodynamic simulations. Initially these erosions are expected to improve the navigation requirements regarding the water depths. However, over a longer period of time these morphological changes might cause a new unequal discharge distribution in favour of the southern arm. Moreover, the concentrated discharge into the new side arm of variant "a" leads to erosion processes at the entrance and mouth of this branch. An extension of the protected areas by artificial constructions has the potential to reduce these scouring processes.

Due to the fine sediments in the investigation area any attempt not to implement bed protection measures downstream of the transverse structure leads to serious erosion processes downstream of this construction. Therefore appropriate measures are essential to ensure sustainable functionality of the transverse structure independent of the crest height.

CONCLUSIONS

In this study the evolution of hydromorphology was simulated for different conceptual hydraulic engineering measures. It was found that the morphological developments are directly linked to the resulting discharge distributions due to the construction works planned. Therefore a discharge increase in the southern arm of the bifurcation leads to higher bed shear stresses followed by substantial erosions in this branch. An improvement of the navigation requirements regarding water depths is expected in this branch, however due to the fine river bed sediments in this investigation area, over time morphological changes might reverse the discharge distribution towards the southern arm. Further additional investigations using quasi-steady or fully unsteady sediment transport simulations over longer time spans in the range of several decades are recommended to yield a sound basis for an assessment of the long-term stability of river morphology. For such modelling approaches a monitoring program resulting in a more detailed data set is an indispensable prerequisite.

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REFERENCES

Dargahi, B. (2004). Three-dimensional flow modelling and sediment transport in the river Klarälven. Earth Surface Processes and Landforms. 29:821-852.

Federici, B., Paola, C. (2003). Dynamics of channel bifurcations in noncohesive sediments. Water Resources Research. 39(6):1162.

Glock, K., Tritthart, M., Gmeiner, P., Pessenlehner, S., Hauer, C., Habersack, H. (2015). Numerical analysis of the effects of engineering measures on the Lower Danube. In: E-Proceedings of the 36. IAHR Congress, 2014, Den Haag.

Habersack, H., Tritthart, M., Gmeiner, P., Glock, K. (2015). Scientific Report - 3D numerical modelling and ADV measurements, Romanian Danube between Calarasi and Braila (River-km 375-175), Period February 01 – October 31, 2015. Vienna (Austria): University of Natural Resources and Life Sciences.

Hardy, R.J., Lane, S.N., Yu, D. (2011). Flow structures at an idealized bifurcation: a numerical experiment. Earth Surface Processes and Landforms. 36(15):2083-2096.

Kleinhans, M.G., Jagers, H.R.A., Mosselman, E., Sloff, C.J. (2008). Bifurcation dynamics and avulsion duration in meandering rivers by one-dimensional and three-dimensional models. Water Resources Research. 44(8):1-31.

Miori, S., Hardy, R.J., Lane, S.N. (2012). Topographic forcing of flow partition and flow structures at river bifurcations. Earth Surface Processes and Landforms. 38(1):47-61.

Pessenlehner, S. (2014). Prognose der Auswirkungen von flussbaulichen Maßnahmen auf Hydrodynamik und Sedimenttransport an der Donau in Rumänien. [Master thesis]. Vienna (Austria): University of Natural Resources and Life Sciences.

Tritthart, M., Schober, B., Habersack, H. (2011a). Non-uniformity and layering in sediment transport modelling 1: flume simulations. Journal of Hydraulic Research. 49(3):325-334.

Tritthart, M., Liedermann, M., Schober, B., Habersack, H. (2011b). Non-uniformity and layering in sediment transport modelling 2: river application. Journal of Hydraulic Research. 49(3):335-344.

Tritthart, M., Liedermann, M., Klösch, M., Habersack, H. (2012). Innovationen in der Modellierung von Sedimenttransport und Morphodynamik basierend auf dem Simulationsmodell iSed. Österreichische Wasser- und Abfallwirtschaft. 64:544-552.

Tubino, M., Bertoldi, W. (2007). Bifurcations in gravel bed streams. Developments in Earth Surface Processes. 11:133-159.