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Comprehensive morphodynamical analysis of the Drava River

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***Abstract*— The Drava River is located in southern Central Europe, it is a major tributary of the lower Danube River. It has been the subject for a couple of sediment studies in the recent years, but comprehensive morphodynamical studies have not been done yet. During this study, an extensive field measurement was carried out to survey all the necessary data from river bathymetry to channel morphology. A recreational-grade sonar system was assembled and mounted on a double-hull vessel and connected with a geodetic Global Navigation Satellite System (GNSS) device. Field data were completed with ADCP measurements and suspended sediment sampling with laboratory evaluation. Seven characteristic river bed compositions were separated based on the field data, each representing a different mixture of grains from medium sand to course gravel (d_{50} = 0.125–16 mm). Fine particles were completely absent in the upper layer of the armoured river bed. Previous studies shown that 50% of the annual sediment transport occurs during high flows due to this phenomenon. We analysed the reach from Őrtilos to Drávaszabolcs, the length of approximately 160 km with internally coupled TELEMAC-2D and SISYPHE models using the Wilcock–Crowe formula for bed-load and the Bijker formula for suspended load. Three scenarios of different temporal characteristics and numerical approaches were selected to get an overview of the long- and short-term morphological processes. Short-term bed-load and suspended load transport, long-term bed-load transport and morphology, and finally the cohesive transport (measured concentration, double and half concentrations, equilibrium concentration). Results showed that at the streamflow of 363 m^3/s bed-load is less than 20% of the total sediment transport reaching its highest values at the steepest reaches of the upper part and suspended transport is generally two magnitudes higher. Significant changes in the bed also occur on the steeper upper part, gradually widening narrow sections and moderating steep slopes. Annual bed-load is estimated to be around 40 kt at Barcs and annual suspended load is approximately 2.5 Mt, these are in the range of previous studies of the same flow regime. Modelling only cohesive sediment resulted in erroneous results due to the important role of coarser grains. Finally, higher discharges were simulated on a smaller scale in order to analyse the development of a natural flood plain channel at Heresznye and the possible effects of dredging. Results showed the slow migration of the river bed and the erosion of the artificially modified flood plain channel, returning itself to a naturally stable condition.**

I. Introduction

The major rivers of Central Europe in general have undergone heavy anthropogenic influences since navigational and power driven utilizations become important issues. These influences result in changing hydrological and morphological regimes without exception. The Drava River is located in southern Central Europe, it is a major tributary of the lower Danube River originating from Northeastern Italy. Several dams and reservoirs are located along the river for hydropower generation that led to a heavily modified behavior both in hydrological and morphological manner [1, 4]. It has always been a subject for sediment studies [5, 6] and also for sediment modeling in the recent years [2]. In the current study we analyzed the reach between Őrtilos and Drávaszabolcs (Fig. 1.) the length of approximately 160 km, where the river serves as the basis of the border between Hungary and Croatia. The same reach was studied in [1] and a significant decrement of the water levels was presented based on long-term (1875-2006) water level time-series due to upstream reservoirs. Reference [8] shows about 65% decrement in suspended sediment concertation at Botovo station (beginning of our study area) and 81% at Donji Miholjac station (end of our study area) between the 1960 and 2017 caused by construction and operation of reservoirs. These reservoirs trap the particles approximately above coarse pebbles so only finer sediment arrives to the study area, but the confluence with Mura River at Őrtilos returns coarser sediment. The river is still rich in sediment thus it reacts very dynamically to hydrological circumstances as it is discussed in [4]. The annual average discharge on the studied reach was 521 m^3/s in the past 10 years, while the lowest value was 151 m^3/s and highest was 2305 m^3/s.

Figure 1. The study area.

An extensive field measurement campaign was carried out to survey all the necessary data. These data included detailed river bathymetry, channel morphology, sediment properties and hydrological parameters such as water level and discharge. The used equipment was a recreational-grade sonar system assembled and mounted on a double-hull vessel and connected to a geodetic Global Navigation Satellite System (GNSS) device. Field data were completed with ADCP measurements and suspended sediment sampling at numerous locations for laboratory evaluation. The database of the processed data served as an input for numerical modelling. We used the TELEMAC-2D model for two dimensional hydrodynamic analysis and later coupled it internally with the SYSIPHE morphodynamic model.

II. METHODS

A. Analysis of the measured data

The output of the river bed scanning was a digital terrain model of 1x1 m resolution with the error less than 0.1 m in altitude. This DTM served as the geometric input for the numerical modelling. The detailed process of assembling the equipment, the collection of data and the post-processing of the surveyed information is described in [3].

The sampling of the river bed material on the studied reach resulted in 40 particle distribution curves shown on Fig 2. The curves represent approximately seven characteristic river bed compositions that are well separated in the range of medium sand to course pebble (d_{50} = 0.125–16 mm). Fine particles were completely absent in the upper layer due to armouring of the river bed. The armoured bed surface consist of coarser particles trapping fine particles and is unlikely to present significant sediment transport during lower flow conditions. Previous studies shown that 50% of the annual sediment transport occurs during high flows due to this phenomenon. The seven characteristic curves were used as initial bed compositions in the morphodynamical modelling. Nine sediment fractions were introduced in these compositions with the diameters of 0.125, 0.375, 0.75, 1.5, 2.4, 3.4, 6, 12 and 16 mm.

Samples of water containing suspended sediment particles with the diameter of less than 63 microns were analysed in laboratory by laser scanning. Concentration distributions were obtained for 10 diameters from 1.5 to 60 microns.

B. The hydrodynamic model: TELEMAC-2D

The TELEMAC-2D model was selected to perform the modelling tasks due to its stable, reliable and fast solution algorithm and its capability of modelling sediment processes through SYSIPHE. A fully dynamic simulation was required on a relatively fine TIN of 10 meters. This resolution allowed the model to represent a realistic cross-section shape even in narrow sections, the fine shape of islands and the rough outline of bridge piers yet allowed manageable simulation time and size of result files. The TIN (as shown on Fig. 3.) consisted of 563755 calculation points and 1091411 triangles.

Steady-state simulations were carried out with the inflow discharge of 363 m^3/s at Őrtilos. The lower boundary condition was 87 m a.s.l. at Drávaszabolcs. The uniform roughness of 0.028 $s/m^{1/3}$ was defined based on previous studies and current validation runs. This value represented an average roughness of the river bed giving satisfactory results in previous hydrodynamic studies and flood plain inundation modelling, thus this value is assumed to represent an average bed material of the study area.

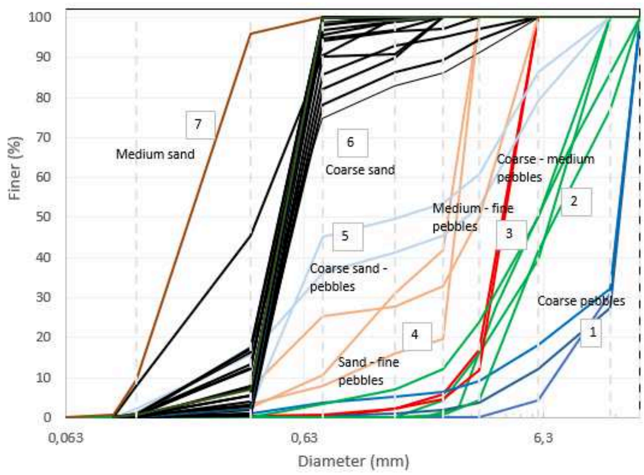

Figure 2. River bed composition (0.125, 0.375, 0.75, 1.5, 2.4, 3.4, 6, 12 and 16 mm diameters as dashed lines)

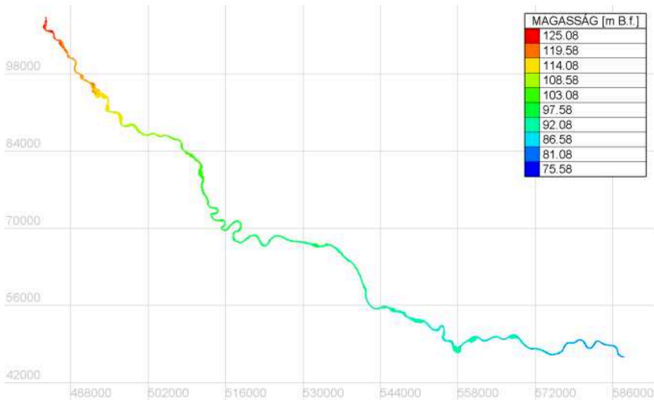

Figure 3. TIN model for TELEMAC-2D

C. *The morphodynamic model: SYSIPHE*

We coupled the validated hydrodynamic model internally with SYSIPHE. Three versions of the model were created to estimate short-term and long-term non-cohesive, and cohesive sediment processes. All morphodynamic simulations used a heterogeneous fraction distribution as initial condition, so the measured sediment mixtures were loaded into each calculation points at the beginning by an external FORTRAN subroutine. The hydrodynamic initial conditions were derived from previous hydrodynamic simulations to have a hot start and avoid extreme initial results.

The Wilcock-Crowe formula [7] was used for bed-load due to the promising results in other studies while dealing with armoured bed and wide range of sediment sizes. The suspended load was modelled in the short-term simulation by the Bijker formula. SYSIPHE assumes an exponential distribution of suspended sediment in the water column. This assumption is valid in our case as the lowest Rouse number is app. unity for the smallest particles and higher values for coarser particles. Equilibrium initial and boundary condition were used everywhere. A temporal ratio of 120 was used to stretch the 5 second hydrodynamic time step to 10 minutes and the entire simulation period to 70 and later to 365 days for long-term morphodynamic evaluations.

Cohesive sediment was modelled with two different set of boundary and initial conditions. First based on the measured concentrations and then using the Van Rijn equilibrium concertation. Both of the simulations resulted in very high concentrations on the steep sections and heavy deposition elsewhere. We assume that the bed armouring and the interaction of cohesive and non-cohesive sediments have a significant role on the concentration of particles below 63 microns. These particles might get trapped by coarse particles thus not causing significant erosion and deposition. A severe concentration deficit is assumed during the simulated flow conditions originating from upstream parts of the Drava River. Setting the Krone-Partheniades constant to zero would lead to zero erosion in the Exner equation. This approach gives relatively constant simulated concentration profile along the model domain in the range of measured values, however is a theoretic setup with unacceptably strong simplifications. Therefore the results of these simulations are not discussed in the Results section. The proper approach in case of Drava River would be the modelling of mixed sediment with several classes in both the non-cohesive and the cohesive size range.

Local simulations were also carried out based on the results of the comprehensive simulations. One of the studies was the analysis of a flood plain channel at Heresznye at higher discharges and on a finer TIN. Hydrodynamic simulation were done with HEC-RAS 2D at 1 meter resolution based on diffusive wave approximation to select the necessary model variants. Finally morphodynamic simulation were done on 5 meters with 800 and 1500 m^3/s main channel discharges. These long-term steady-state simulations are hypothetical because such discharge values do not have the assumed duration, but they allowed us to analyse the flood plain and the stability of artificial canals in the natural environment under inundation.

III. RESULTS

A. *Short-term simulations*

Short-term analysis of bed-load and suspended load transport showed that bed-load is less than 20% of overall sediment transport on the steeper upper parts. On the lower parts of the river bed-load is less than suspended load with two magnitudes (Fig. 4.). Regarding the size of particles smaller diameters are present in higher quantity, such as 0.125 mm and 0.375 mm. The bed evaluation shows an intensive trend from the interpolated geometry to a smoother and more natural bed shape in the first half of the simulation mostly on the steeper parts, and after these major changes are done the slower and more expected changes remain in operation. For example the narrow sections are getting deeper and the washed-out sediment is deposing in the downstream wide section as it is shown at Vízvár on Fig. 5.

A frequently referred section of the Drava River is the upstream cross-section of the bridge at Barcs (154.1 river km). Annual bed-load is estimated to be around 40 kt at his cross-section and annual suspended load is approximately 2.5 Mt. These values are in the range of previous studies of the same flow regime.

The traveling speed of major bed formations was also estimated based on the results. It ranges from 1 m/day on the steeper upper part to 5 m/s at the lower part. A short section of the river bed in the initial and the simulated state is presented on Fig. 6.

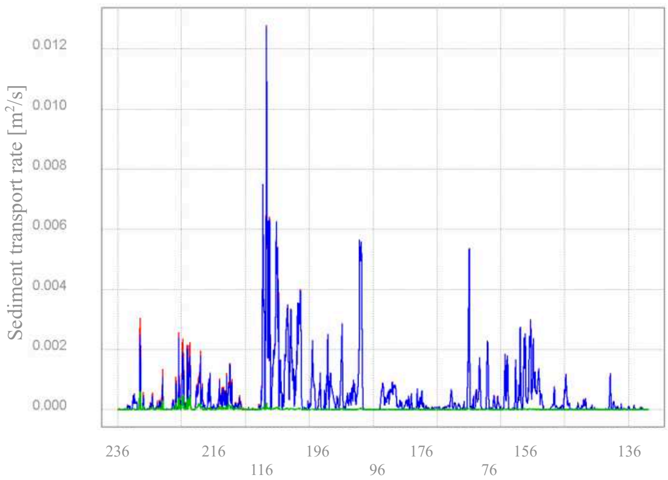

Figure 4. Total sediment transport (red), suspended load transport rate (blue), bed-load transport rate (green) [m^2/s]

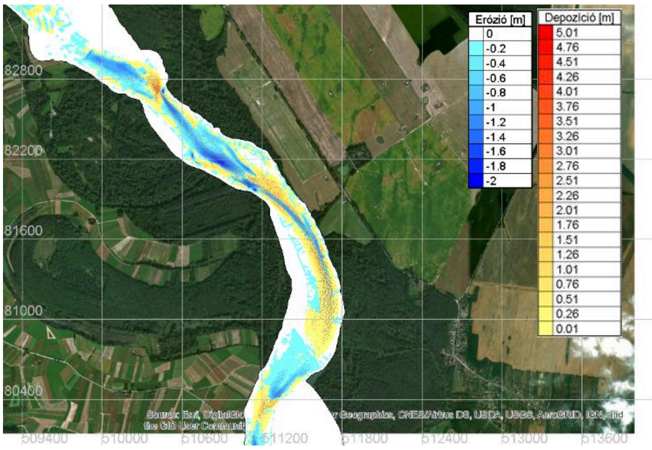

Figure 5. Erosion and deposition at Vízvár after 12 hours of simulation start.

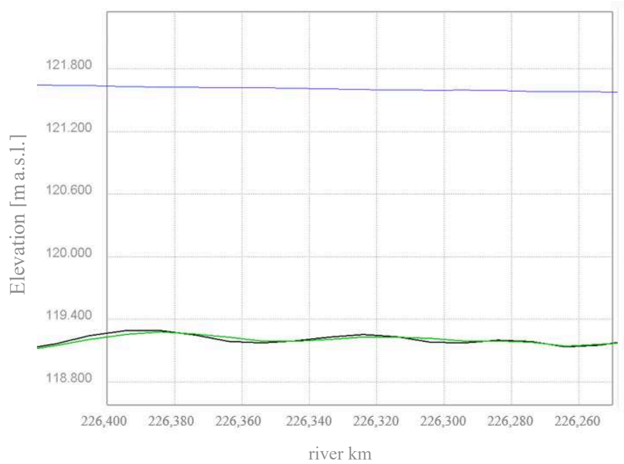

Figure 6. Moving bed formations before (black) and after (green) 12 hours of simulation.

B. *Long-term simulations*

Long-term simulations based only on bed-load showed the same trends and magnitudes as the short-term ones. High bed-shear stresses occurred in the first few days of the simulation leading to significant bed changes. The longitudinal profile of bed-shear stress is shown on Fig. 7. The steeper upper part (app. the first 50 km) is represented with higher initial and also final values, while the lower part is relatively constant. Fig 8. and 9. also show the significant drop of bed-shear stress to 0 to 70 days.

The travelling of major bed formations also showed the same magnitude as the previous simulations. Highest speeds occurred on the upper part up to 5 m/day. A section of the longitudinal bed profile is shown on Fig. 10. The initial bed level is compared to the changed bed after 70 days of simulation. However the river bed undergone significant changes some characteristic points are easily recognisable and their travelling speed can be assessed.

Bridge piers were represented in the model with minor simplifications so their impact on the river bed is visible in the results. The bridge at Barcs is shown on Fig. 11. with a lesser and a greater scour hole downstream of the piers. Velocity and bed-load transport vectors show a bit of divergence close to these bed formations due to the major changes in the bed slopes. Fig. 12. shows the evolution of the river bed around the bridge piers. Downstream scour holes are slowly filled while upstream scours are deepened.

Long-term analysis generally showed the tendencies of river bed evolution. Major changes are experienced on the steeper upper part (Fig. 13.) and generally less significant changes on the lower part (Fig. 14.) except locally at bridge piers.

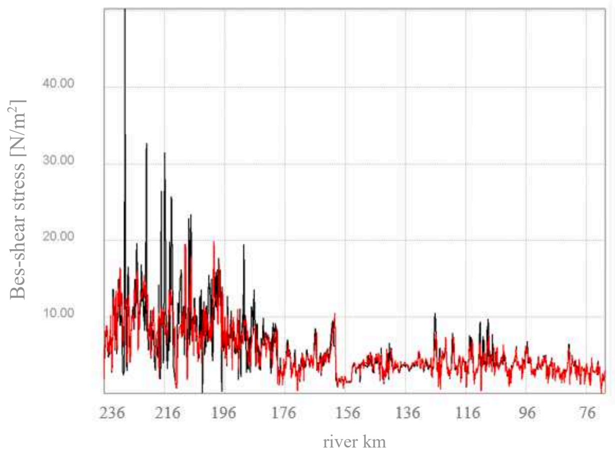

Figure 7. Longitudinal profile of bed-shear stress before (black) and after (green) 70 days of simulation.

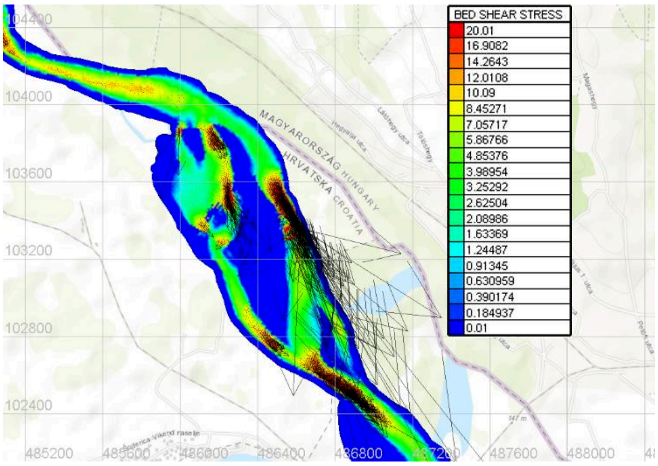

Figure 8. Initial bed-shear stress and bed-load transport rate vectors.

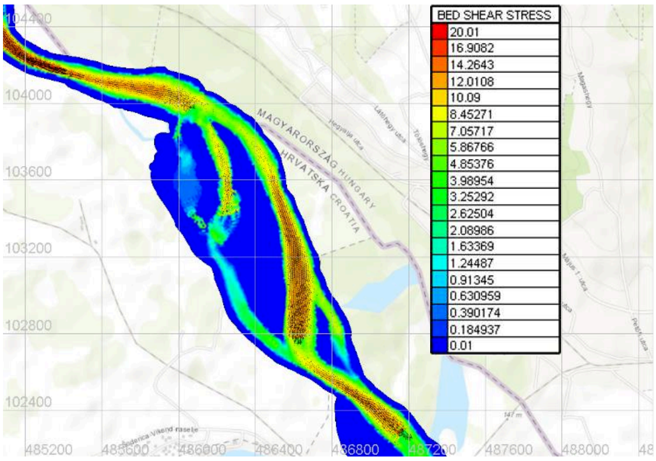

Figure 9. Final (70 days) bed-shear stress and bed-load transport rate vectors.

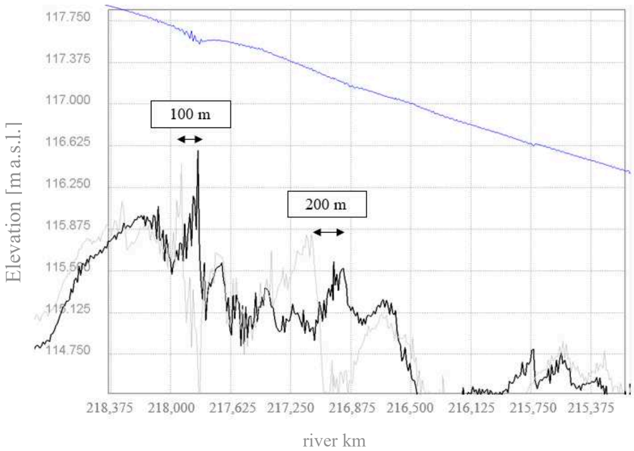

Figure 10. Moving bed formations before (grey) and after (after) 70 days of simulation.

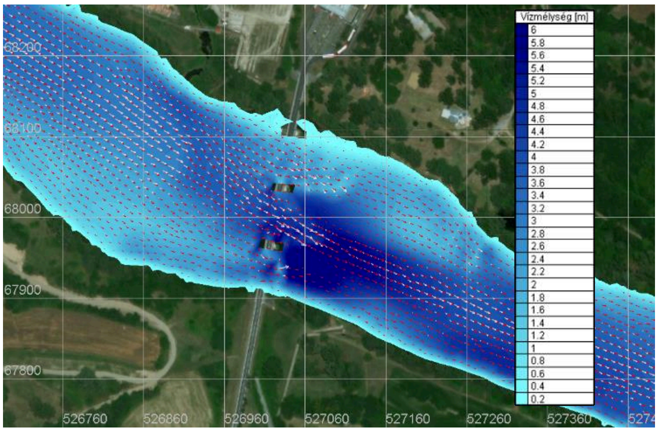

Figure 11. Water depth at Barcs with velocity (white) and bed-load transport (red) vectors.

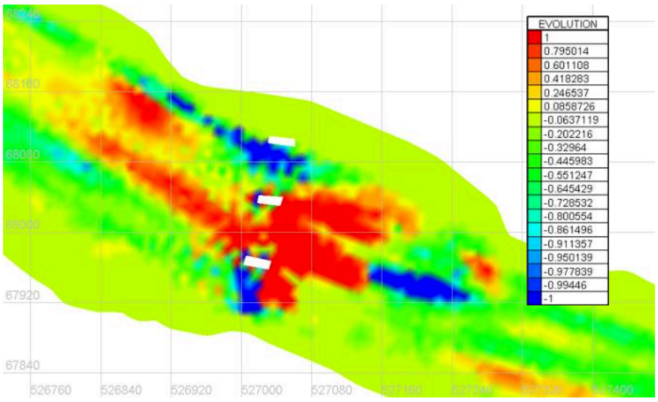

Figure 12. Bed evolution at Barcs after 365 days.

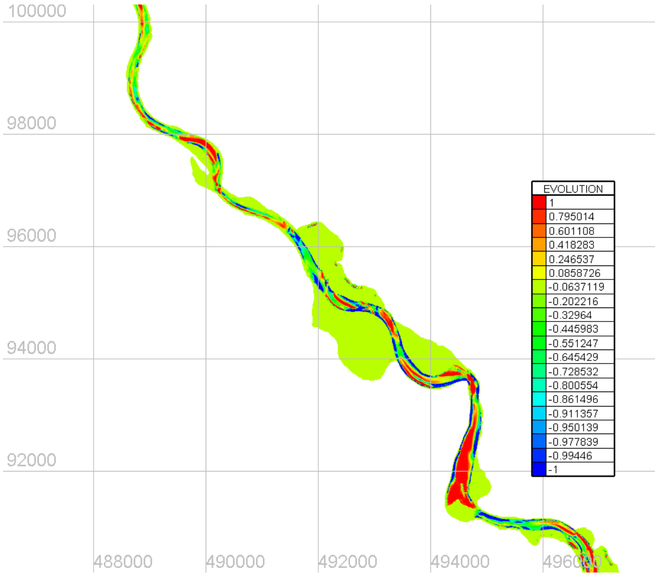

Figure 13. Major changes on the upper part after 365 days.

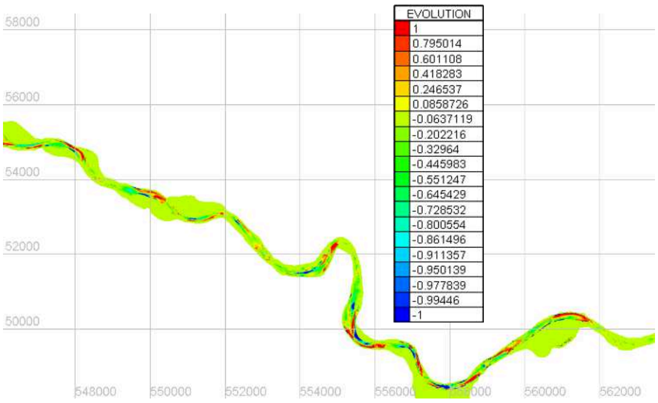

Figure 14. Minor changes on the lower part after 365 days.

C. Local simulations

Local simulations were also carried out at selected river reaches to analyse local tendencies in greater details. Such a simulation was the modelling of a flood plain channel at Heresznye in its natural and planned status (Fig. 15-16.). The planned measures included the widening and deepening of the channel to return it to its former role during floods. The flood plain channel is flooded at discharges above 700 m^3/s in its natural state and after the measures this threshold is lowered to 100 m^3/s.

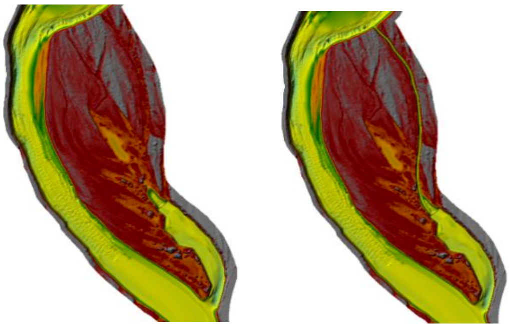

Figure 15. Natural and planned state of the flood plain channel.

Figure 16. Natural and planned cross-profile of the flood plain channel (the cell size of the calculation grid was 1 meter).

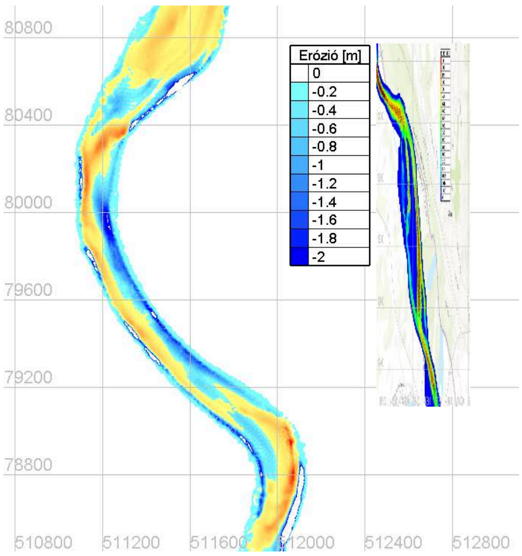

Figure 17. River bed evolution after 365 days at 363 m^3/s.

The previous simulations also included this site so bed evolution results were available on the 10 meter based TIN for 363 m^3/s discharge shown on Fig. 17. These low-flow results indicate slight deposition along the main channel and erosion along the convex bend.

Two dimensional HEC-RAS simulations were done on a 1x1 m cell-sized grid to estimate inflow discharges at different flow conditions. Results are shown in the table below:

INFLOW AT DIFFERENT FLOW REGIMES

Discharge in Drava [m^3/s]	*Inflow to flood plain channel [m^3/s]*
100	0.8
200	4
400	15
800	42
1000	60
1500	120

As the simulation used the diffusion wave approximation validation runs were done with fully-dynamic setup as well. These indicated that inflow discharges are slightly (~10%) overestimated due to higher velocities in the model. Finally two of the above listed situations were selected for morphodynamic simulation.

One of variants was to simulate 800 m^3/s on the Drava River for 550 days based on the planned state of the flood plain channel (Fig. 18.). This discharge is 153% of the average annual discharge of the past 10 years, so a relatively high value lower than any of the maximum discharges in these years. The main river bed presented erosion on the convex bend and deposition of sediment on the concave bend. The flood plain channel however suffered much more dramatic changes. The cross-section has broadened and filled up intensively, resulting in heavy sediment load arriving to the lower part of the channel. High bed-shear stress values (~10 N/m^2) are present initially but they gradually decreased to 5 N/m^2 after 10 days. These values represent a drag force capable of moving coarse pebbles (d<32 mm) while coarser gravels and artificial surfaces withstand it easily.

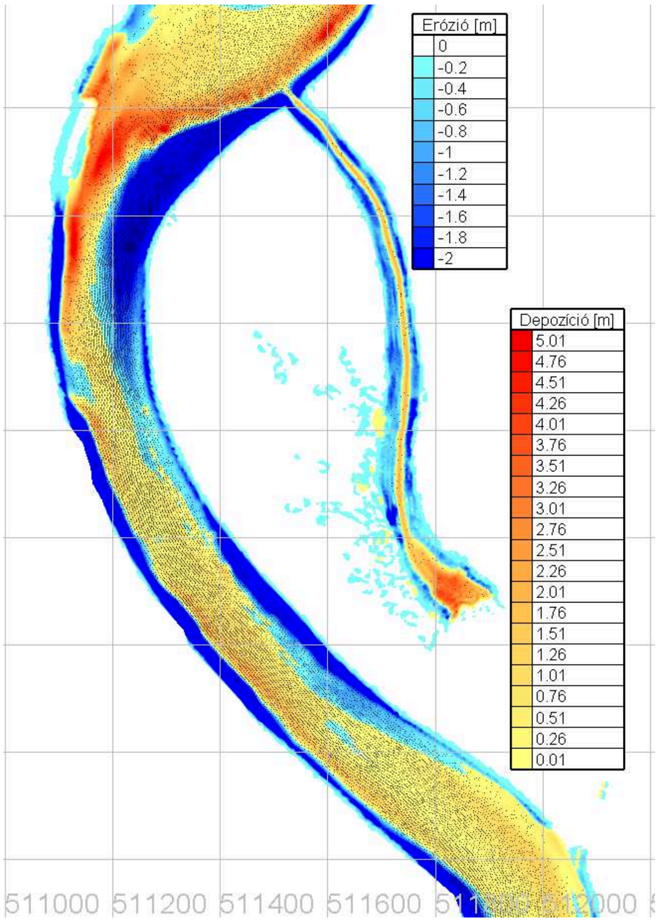

Figure 18. River bed evolution after 550 days at 800m^3/s.

The second simulation was done at 1500 m^3/s which is well representing the high-flow conditions, it was surpassed 3 times in the past 10 years. The simulation lasted for 180 days but it is important to note that such high discharges only occur during floods and usually last for a few days. It means that the tendencies may be right but the magnitudes are overestimated at the end of the simulation. While analysing the results (Fig. 19.) we see as the water straightens its flow path by eroding the island between the main and flood plain channels. The inflow area of the flood plain channel is also heavily affected and an even greater sediment load is washed downstream along the channel. At the end of the simulation the geometry of the flood plain channel almost returned to its current natural status.

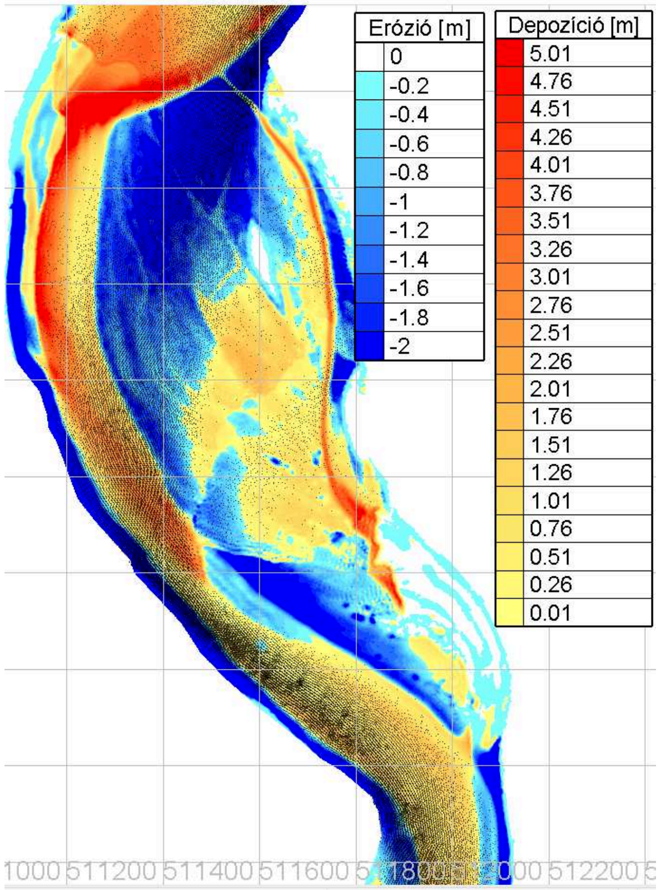

Figure 19. River bed evolution after 180 days at 1500m^3/s.

IV. Discussion

Several model variants were run during the current study and all showed acceptable numerical performance both in speed and stability. Sediment transport models generally started with increased transport rates and converged to the measured magnitudes after the first few days depending on the temporal ratio between the hydrodynamic and morphodynamic models. After these initial run-up periods all results fell in the range measured and previously published values of this reach of the Drava River.

The cohesive models were not successful due to the significant interaction of the sediment classes and river bed armouring. The proper approach in case of Drava River would be the modelling of mixed sediment with several classes in both the non-cohesive and the cohesive size range.

The local study on a fine TIN of 5 meters gave valuable results regarding the intervention to a naturally stable status of the Heresznye flood plain channel. The simulated variants showed heavy deformation of the artificial cross-section taking into account only locally available bed material. Simulated bed-shear stress values highlighted the need for coarser bed cover.

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