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Validating a Two-dimensional Sediment Transport Model on a Large Danubian Floodplain

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Abstract

Considering currently operative European and worldwide regulations, preserving and/or improving the state of remnant alluvial floodplains is a high-priority goal for experts. One of the threats is the decrease of lateral connectivity: due to the erosion in the mainstem riverbed and the sedimentation of the floodplain and its channels, the bed elevation gap slowly increases between the main channel and the side branches and oxbows of the floodplain. Without revitalization measures, this progress predicts severe ecological consequences. As an example, and as a continuation of our earlier work, we considered the Gemenc floodplain forest along the Danube, in Hungary. We set up a two-dimensional coupled hydrodynamic and sediment transport computational model to describe floodplain deposition dynamics. Model validation was carried out with historical data, i.e., two ground elevation sets measured in 1990 and in 2009, respectively. Our aim was 1. to show, how coarse resolution measured data can be used for validating a large-scale model in terms of sediment deposition processes, and 2. to interpret the first results on some areas exposed to strong deposition, after validation. Showing good agreements in three pillars: magnitude of estimation, spatial tendencies and spatial patterns, the model was deemed valid. We were also able to observe a clear gradient, along which areas could be categorized with high, medium and small extent of sediment deposition. With this model, the sediment dynamics in the Gemenc floodplain forest can be assessed, with special attention to the impact analysis of restoration measures to improve lateral connectivity conditions.

Keywords
deposition, CFD, adaptive hydraulics, historical data

1 Introduction

River floodplains have a major role in flood control, water retention, biodiversity, and human recreation [1, 2]. In the past, driven by then-prevailing concerns (settlements and agriculture induced land conversion), the rivers of the world were disconnected from a large proportion of their floodplains, e.g., the Danube in Europe [3, 4]. In the light of today's challenges [5], preserving remnant floodplains like the Gemenc forest along the Danube, in Southern Hungary is of high importance. This pursuit is further emphasized by past and ongoing projects regarding the Danube (e.g., Nutrient Reduction Project of the Global Environment Facility, Danube Floodplain Project, Danube4All Project [6–8]), moreover, European Union strategies, such as the EU 2030 Biodiversity Strategy

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also underlines the need for improving river connectivity. Thus, understanding long-term hydro-morphological processes in floodplains is a constant need.

In order to maintain floodplain biodiversity, inundations of a certain frequency and extent are needed (see e.g., the Flood Pulse Concept [9–11]). At the same time, such inundations also increase variability of the aquatic habitats [12]. Among the many factors driving this pulse, one is a practically constant elevation gap between the mainstem riverbed and the floodplain areas. Erosion in the riverbed and/or sediment deposition on the floodplain increases bed elevation differences and, without any measure, may weaken the process on the long-term by decreasing lateral floodplain connectivity [13, 14]. For predicting long-term elevation changes, the basis can be either measurements [15], or computational models (see e.g., [16, 17]). Process-oriented planning can deal with potential deposition zones by managing the triggering effect and inducing a new equilibrium state [18]. Such was proposed by [19] on the upper Rhine River, utilizing a hydrodynamic model. Following this principle, the connectivity loss can be reversed in a sustainable and durable way.

Following our previous project in the Gemenc floodplain forest, the aim now is to couple the used 2D hydrodynamic model [20] with sediment transport and validate its accuracy regarding floodplain deposition on a mesoscale. Using the ground elevations recorded in earlier field surveys (1990 and 2009), and the latest digital terrain model of the area (2013), a past time window was considered for deriving long-term elevation changes. These were compared to the model results, looking for matching tendencies. Once validated, the model can be used for our overall aim set in the previous research: to identify any areas on the floodplain that may be strongly affected by sediment deposition in the future and thus deteriorate lateral connectivity. Furthermore, the impact analysis of any planned sustainable management option can be performed based on the model, supporting decision-making.

2 Material and method

2.1 Study site

The area of interest stretches in the south of Hungary, between Danube rkm 1507 and 1460 and includes the river and its floodplain between the main levees (Fig. 1). It almost entirely includes the Gemenc Region of the Danube-Drava National Park, now also part of the Mura-Drava-Danube Transboundary Biosphere Reserve (e.g., [21]). The annual mean flow discharge of the Danube here is 2435 $m^3 s^{-1}$, with a respective 5–6 m water depth [22]. The floodplain width ranges between 500–10000 m, the former belonging to the closely embanked reaches downstream of the Gemenc forest. This area is one of the few intact floodplains along the Danube that, in its extent, still reflects the historical conditions (e.g., [23]). On the contrary, long-term changes of the floodplain are traceable, showing a decrease of aquatic habitats, induced mostly by river regulating measures (e.g., [24]). Several studies showed the constant riverbed erosion of this Danube reach [14, 22, 25–28], while the floodplain is aggrading, as well [29, 30].

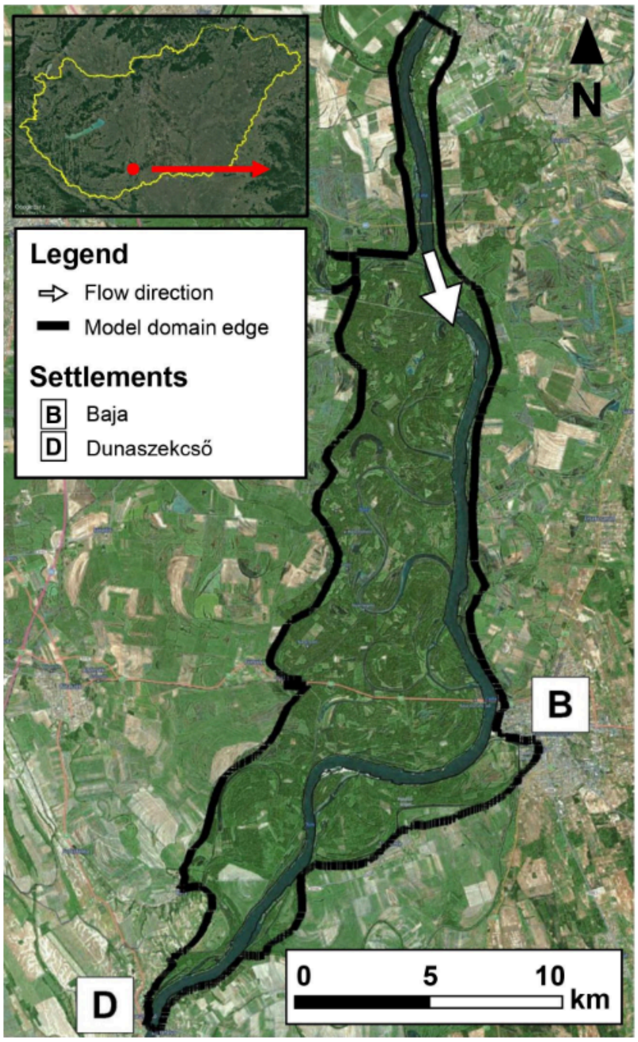

Fig. 1 The model domain along the Danube in the south of Hungary

2.2 Simulations

Adaptive Hydraulics Modeling System (AdH) was utilized to perform the two-dimensional (2D) hydrodynamic and sediment transport simulations [31, 32]. Its depth-averaged 2D module is freely available and was often featured in our previous works (see e.g., [20, 33]). The approach to hydrodynamics is the shallow-water equations. Sediment transport is governed by the 2D advection diffusion equation solved for the sediment concentration, and the method of calculating entrainment rates for bedload and suspended sediment can be chosen by the user. Considering that the river here consists of sand, we used a modified version of Van Rijn's equations for suspended entrainment [34], and the Garcia-Parker approach for bedload entrainment [35]. Note that in this study we focused on the simulation of floodplain sediment deposition processes and so bedload transport modelling of coarse sediment particles in the mainstem was not relevant. On the other hand, the correct definition of the fine sediment both in terms of grain composition and concentration played an important role.

The model domain is shown in Fig. 1. The computation grid and the digital terrain model were available from a previous study [33] and were subjected to some changes, based on the data and findings of previous research [36, 37] and the demands of our current aim. The mesh consisted of slightly more than 580,000 triangular elements and ca. 292,000 nodes. The applied resolution was dependent on the terrain, with linear features (e.g., riverbeds, groins, levees) defined by a denser grid, while the rest of the area (e.g., forest patches, meadows) was represented with coarser resolution. The side length of the elements thus varied between 5 m – 80 m. The adjustment of the computation mesh was performed with AquaVEO's Surface-water Modeling System (SMS).

A 15–day period of a Danube flood observed in 2013 was simulated, including the peak, meaning thus an unsteady flow simulation. Boundary conditions seen in Table 1 were determined using past gauge records of Baja gauge station and the findings of the DanubeSediment project [38]. Time series of flow discharge and concentration of the transported sediment were assigned to the upper boundary, and water surface elevations were defined on the lower. A stationary water coverge correspondent to the initial flow discharge and zero concentration values were given as the initial condition. Two sediment classes were included in the model with grain sizes of 3×10^{-4} m (sand) and 10^{-5} m (fine sand). Calibration and validation of applied Manning's smoothness values for the three most relevant coverage types (channel, grass, forest) were performed in the referenced work, Manning's smoothness values were set accordingly. On the other hand, the main focus of this study was to validate the sediment transport model in terms of floodplain sediment deposition processes.

Table 1 Boundary conditions of the simulated 2013 floodwave

	Upper boundary		Lower boundary	
Days	Flow discharge [$m^3 s^{-1}$]	Concentration, fine sand [mg l^{-1}]	Concentration, sand [mg l^{-1}]	Water surface elevation [m. a. s. l.]
0	5210	89	89	89.96
1	5620	147	147	87.54
2	6120	206	206	88.24
3	6510	265	265	88.78
4	7160	324	324	89.69
5	7850	382	382	90.66
6	8390	441	441	91.41
7	8670	500	500	91.81
8	8600	500	500	91.71
9	8320	442	442	91.32
10	7780	384	384	90.56
11	7120	326	326	89.64
12	6690	268	268	89.03
13	6230	210	210	88.39
14	5880	152	152	87.90
15	5490	94	94	87.35

2.3 Validation

Following rehabilitation projects in the past targeting the area of interest, two sets of measured geodesic data were available and utilized for validating the calculated sediment deposition values. The Gemenc Floodplain Rehabilitation Study (henceforth: GFRS) was a part of a collaboration of the Netherlands and Hungary [39]. The measurements carried out within its frame in 1990 yielded ground elevations along several cross-sections of side branches, oxbow lakes, and the Danube River. The measured points can be seen in Fig. 2, labelled 'GFRS'. Later, as a component of the Nutrient Reduction Project of the Global Environment Facility (henceforth: GEF) [40], the area was addressed again for restoration measures. Ground elevations were recorded in 2009, the data consisting of thousands of registered points. This was a larger extent study than GFRS, the quantity of data points by this latter was in the order of hundreds. The measured points can be seen in Fig. 2, labelled 'GEF'. We georeferenced GFRS cross-sections from the scanned site plans, by matching them to satellite images through 3 reference points. The nullpoint and the direction of each cross-section were placed according to the site plans, but manually. Note that even by our best effort, this process inevitably yields a certain extent of error, deriving mostly from the line widths on the

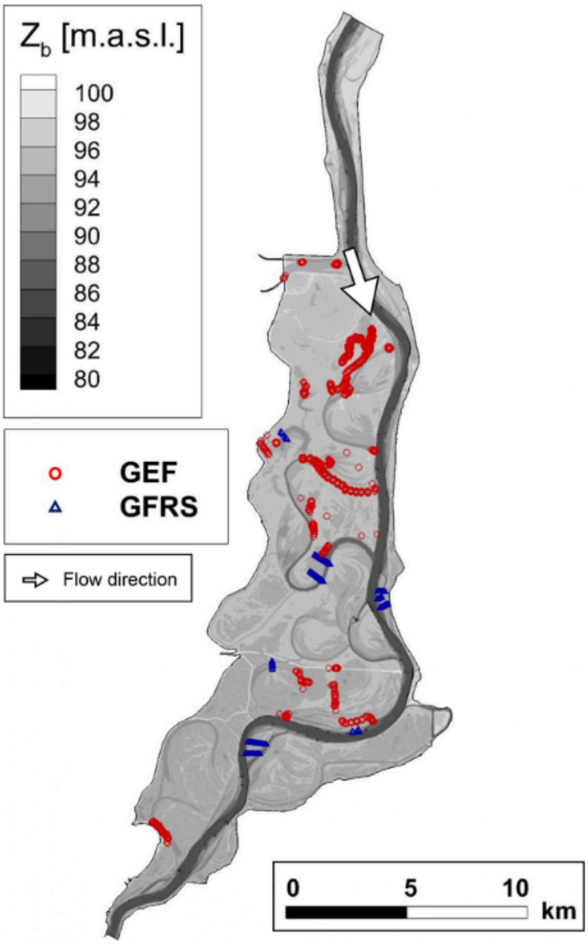

Fig. 2 The location of the two sets of past measured points on a grayscale ground elevation map created from a 2013 LiDAR survey

scanned documents. Afterwards, locations were assigned to the measured elevations by basic co-ordinate geometry operations. Contrary to this, GEF data were originally listed as XYZ points. Since the two datasets had little overlap in terms of point location, both were separately compared to the model terrain that was derived from a 2013 LiDAR survey. Hence, we considered long-term changes in ground surface elevation in the area between 1990–2013 and 2009–2013 and checked the model results against these (Fig. 2).

3 Results and discussion

An extract of the computed (cumulated) sediment deposition against time, along with the respective flow discharge, is shown in Fig. 3. Data points falling into the Danube mainstem were excluded from visualization and from post-processing, too, and only the remaining area was considered. In the end, deposition rates were in the range of 0 and 1.99 m. Note that the maximum is an outlier, as Fig. 4 shows, at ca. 97% of the points simulated deposition rate was under 3 cm. Meanwhile, long-term elevation changes were not exclusively positive, and had a greater range (–5.5 m – 7.8 m). Possible explanations for this large amplitude include past dredging, georeferencing errors, and resolution issues (i.e., different allocation of computation nodes and measurement points leading to interpolation bias).

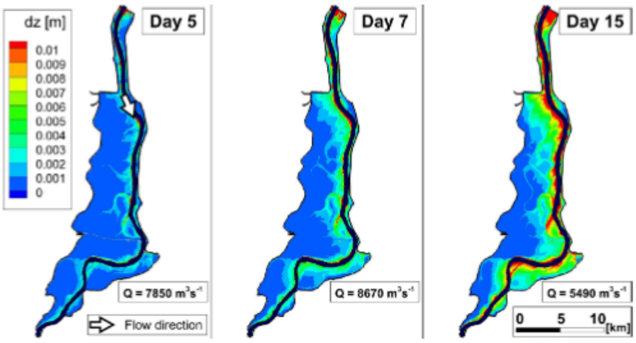

Fig. 3 Cumulative deposition during the 15-day simulation, in three time steps, with the corresponding flow discharge shown.

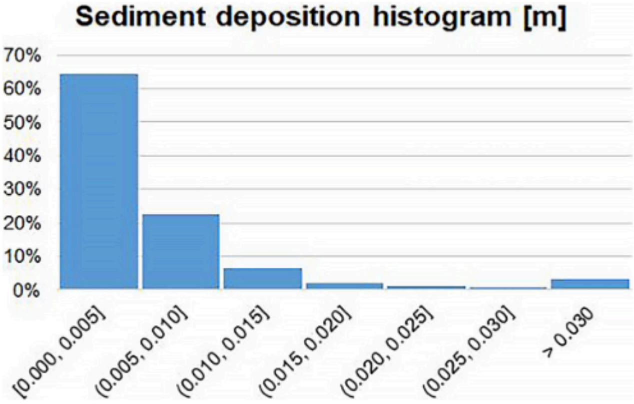

Fig. 4 Percentile histogram of the simulated deposition values at the computation nodes of the model domain

Due to the potential error of georeferencing GFRS site plans, its data were used in a bulk manner, rather than concluding from the individual points, or even cross-sections. Data points (n = 434) were divided upon their position and those falling onto the floodplain (i.e., not the Danube riverbed or other channels) were considered henceforth (n = 283). We defined the average elevation change at these points between 1990 and 2013, which was +12.27 cm. On the other hand, we listed the floods in the time window that could possibly inundate the selected 283 floodplain points, based on the flow discharge time series of the Baja gauging station for the period between 1930 and 2016, which was available from earlier works [20, 37]. Considering, on one hand, the mean ground surface elevation of these points, and on the other hand, peak flow discharges of past floods and corresponding water surface elevations, a 5000 m^3 s^{-1} flow discharge threshold was determined. Floods with a higher peak were listed in Table 2, with their year, excess flow discharges and exceedance durations. (Floods within one calendar year were distinguished by letters, see e.g., 1999a, 1999b.) Based on the excess flow discharges and exceedance durations of these past flood events and using the modeled average sediment deposition of the 2013 flood event, we estimated an average deposition rate for each of the listed floods (column 4 of Table 2).

The sum of these (lowermost row of Table 2) was ca. 3 cm. The simplified estimation, the complex path systems of the floodplain, the possible delay in the receding of a floodwave and other factors pointing towards a longer duration of the water coverage are suggesting this sum to be a lower estimate. This assumption brings the compared values (12.27 cm and ca. 3 cm) closer, and as such, allows for accepting those with matching magnitudes of centimeters.

In comparison, recorded points from the GEF project were much more numerous (n = 3400), so these covered more areas with a denser allocation and already had co-ordinates. A side branch on the right bank, Rezéti-Danube had its upstream 3.5 km reach covered with measured cross-sections at 200–300 m distances. We aggregated (averaged) these cross-sections into 4 points (inlet of the side branch, and three more points downstream), in order to visualize changes in elevation and deposition along a gradient of distance from the Danube main stem. A clear relation was found: the farther a location is from the Danube, the less deposition and the smaller increment in long-term terrain elevation can be observed. With the simulation and the measurement data displaying matching spatial tendencies, this observation also corresponds to the presumed validity of the model.

Table 2 List of floods between 1990 and 2013, supposedly inundating the selected GFRS point locations

Year	Peak flow discharge over threshold [m^3 s^{-1}]	Duration of threshold exceedance [days]	Estimated deposition [m]
1991	1664.3	7	1.246E−03
1994	924.0	9	8.897E−04
1995	275.0	6	1.765E−04
1997	1811.7	22	4.264E−03
1999a	486.0	5	2.600E−04
1999b	540.0	7	4.044E−04
2000	306.0	7	2.292E−04
2001	170.0	3	5.456E-05
2002a	1435.7	7	1.075E−03
2002b	2423.6	12	3.112E−03
2005a	407.2	4	1.743E−04
2005b	540.0	4	2.311E−04
2006a	3177.3	17	5.779E−03
2006b	721.7	7	5.405Ey−04
2007	1006.9	7	7.541E−04
2009	1580.0	11	1.859E−03
2010	2692.7	12	3.457E−03
2011	1019.3	5	5.453E−04
2013	3575.4	16	6.120E−03
Sum:			3.117E−02

The most certain way to validate the simulated sediment deposition would be matching the results to measured data (e.g., deposition height) of the modeled event. To our knowledge, there were no such surveys carried out in the Gemenc forest after the 2013 Danubian flood. Note, that satellite signal issues generally hindered our efforts in recording high precision elevation data, due to the vegetation coverage. Even in a leafless period, trunks and branches are dense enough to block the signal of a real-time kinematic GPS. Alternative methods, e.g., levelling or installing a base station subsystem could have provided a solution, but were beyond scope in this case, regarding both time and effort. To complete the model validation with a qualitative comparison though, we consider a case study from the Austrian section of the Danube. With the lead of the University of Natural Resources and Life Sciences of Vienna (BOKU), a complex documentation of the 2013 flood was prepared regarding the Austrian reach, with insights on the thickness of the deposited sediment [41]. Due to differences in transported grain size, concentration of both suspended and bed load sediment, their measurements cannot directly be compared with our model results, but regarding the spatial variability of the deposition degree, comparison is certainly possible. Fig. 5 shows an Austrian reach of the Danube in the vicinity of Mitterkirchen. When compared with Day 15 sub-image of Fig. 3, the two sites show very similar patterns, i.e., the largest depositions forming channel belts along the main stem, thicker deposits in the closer side branches, than in the farther channels, and an overall clear gradient along the distance from the Danube. The values of course differ by almost two orders of magnitude, which is most likely due to the difference in suspended and bedload sediment grain size and their concentrations. This comparison demonstrates that the model acceptably represents flood-related morphological patterns.

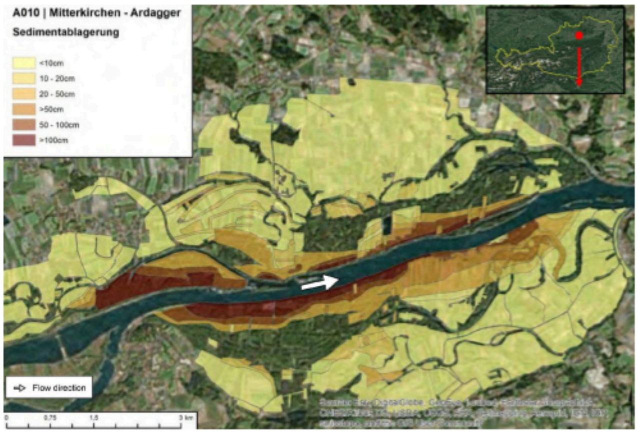

Fig. 5 Deposition in the Danube floodplain, in the vicinity of Mitterkirchen, Austria, measured after the 2013 flood event ([41], slightly modified)

The surface area of the model domain is ca. 175 km^2. This counts as higher than the average, as e.g., in [42, 43] sediment transport was simulated on approximately an order of magnitude smaller domains. On the other hand, in [44] there were a larger domain but also larger and thus fewer computation cells. By all means, simulations on such a large area require great computing capacity, especially for sediment transport. A possible optimizing measure would be to lower the resolution of the model mesh, which was done reasonably, following terrain features (see in Material and Method). On one hand, this leads to a looser interpretation in decreased resolution areas, providing less nodes with computed variables, and larger intervals with interpolated values. On the other hand though, these areas are assumed to display the lowest magnitude changes. This is a trade-off, optimal for our aim of considering the whole Gemenc forest as one complex system and observing the processes on an aggregated, mesoscale level. It also supports broader, overall approaches for validation, rather than demanding microscale agreements. Consequently, given that the model results proved to be homogeneous with measurement data in magnitude, spatial tendencies and patterns, the sediment transport model was deemed valid, the estimated depositions were accepted.

With the validated model we are able to run simulations that are characteristic regarding sediment deposition, not only for flood events, but for long-lasting mean flow conditions as well. It is also possible to categorize areas by deposition rates based solely on the already modeled 2013 flood. As shown in Fig. 3, the most affected areas (>1 cm) are the branches with constant flow, the riverbank zone, and the mouths of shallower cut-off side branches. A medium degree of deposition (0.3–1 cm) characterizes the channels of these former side branches and the wider vicinity of the riverbanks, while the least affected areas (<0.3 cm) are the oxbows spurring from side branches and the surface of the relatively distant floodplain. The strongly affected areas act as direct 'gates' between the mainstem and the floodplain. Thus, the crucial deposition rates naturally derive from the sudden, large gradients in water depth and flow velocities along these gates. These are the patches that need the most attention when planning long-term maintenance measures in order to retain floodplain connectivity.

4 Conclusions

The remnant Gemenc floodplain forest along the Danube River, Hungary, is also exposed to decreasing lateral connectivity through the growing elevation gap between the riverbed and the floodplain channels. Along the lines of process-oriented planning, some areas could be appointed for engineering measures to take place at, so that the initiated hydro- and morphodynamical processes can trigger a new equilibrium on the problematic spots. The first step towards process-oriented planning is to get around sediment transport in this area and utilizing a model, with which the equilibrium and its pre-requisitions become more predictable. The validated model can also be used to estimate the impact of any future intervention, making it a useful tool for decision-making and landscape planning in environmental management. A follow-up step can be the simulation of a longer, mean flow regime period, as that can also be characteristic regarding sediment deposition.

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