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Hydraulic analysis of a meander on the Danube River using a 2D flow model

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Abstract This paper presents the development, calibration and verification of a two-dimensional model for a Danube reach and its old cutoff meander. The considered meander was at one point separated from the main reach with a levee, which caused a series of unwanted environmental consequences. Aiming to stop the ongoing degradation of the meander, the validated model was engaged to investigate the effects different river works would have on its current state. The considered river works involved dredging in certain parts of the meander, while keeping in mind the negative effects these works can have on the environment, as well as possible widening of the existing opening in the levee. Numerical simulations showed that all the considered scenarios would result in a general increase of velocities, which is important from the aspect of sediment deposition. After a thorough evaluation of the results, it was found that by carefully selecting the locations where dredging should be conducted, no other interference is needed to put an end to the increasingly deteriorating situation in the meander. Computations confirmed that the suggested river works would increase the unit discharge in the entire meander, especially in its upstream part. The redistribution of flow around the island downstream of the levee (that formed during past years as a result of sediment deposition) was also predicted, where the flow would once again favor the left side of the island. This is a more natural path of flow that would aid the flushing of previously deposited sediment in this part of the meander.

Keywords 2D flow model · Cutoff meander monitoring · River works assessment · Hydraulic analysis

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Introduction

It is well known that different anthropogenic interventions cause morphological changes in rivers (Markocic 2012; Ercan and Younis 2009). The importance of this subject is demonstrated through the work of numerous researchers that keep trying to investigate the impact of various human interventions on natural watercourses (Kiss et al. 2008; Surian and Rinaldi 2003; Rascher et al. 2018; Habersack et al. 2016; Larsen and Greco 2002; Rodriguez et al. 2004; Mahmood et al. 2019; Bazzuri et al. 2018; Ksiazek et al. 2019). Habersack et al. (2016) tried to identify how the development of hydropower, flood protection, and engineering works on the Danube River influenced the sediment transport and river morphology. The authors found that, as a result of flood protection measures, the Danube is shortened in length (e.g., by 21% in Bavaria and approximately 12% in Hungary), with increased bed slopes, protected river banks without possibility of lateral erosion. It was determined that the main incentive for the alteration of river morphodynamics is the discontinuity of the sediment transport caused by hydropower plants. The Annex IV of the EU Water Framework Directive (ICPDR 2005) aimed to compile comparable data throughout the Danube basin to try and assess the transboundary and basin-wide issues. Analysis of sediment transport in meandering channels, influence of extreme discharges, effects of different hydraulic structures in rivers, and dynamic channel typology was conducted by a number of authors (Yimlaz 2008; Hamers et al. 2015; Surian and Rinaldi 2003; Korpak 2007). Although nowadays the goal of most human interventions is to return a certain system to its historical state (Falk et al. 2006), these activities are at the same time the source of many changes in rivers. For instance, Rascher et al. (2018) investigated the effects of the mining period on the former sediment routing in the Johnsbach Valley in Austria, while Viswanathan et al. (2015) analyzed a meandering river in Switzerland, the Thur River, that was straightened and confined to a channel.

Numerical models are often used to evaluate certain situations in rivers, e.g., flood scenarios (Vijay et al. 2007) and channel migration (Larsen and Greco 2002). The type of the model that will be employed depends on the occurrence that is investigated. When considering long-term effects and/or long river reaches, one should opt for a one-dimensional model (Horvat et al. 2017a; Birgani et al. 2017). In cases when a local phenomena is being investigated, both in time and space, one can choose a two (Horvat et al. 2015; Horvat and Horvat 2016) or even a three dimensional model (Gessler et al. 1999), depending on the present situation and the data available. However, one should keep in mind that using two- or three-dimensional models also implies the availability of data needed for the initial and boundary conditions in order to carry out such simulations. Duan et al. (2017) employed dozens of sub-grid elevation points to depict the bathymetry within a mesh element of a 2D shallow water model. This would allow the proposed 2D model to simulate the narrow open channel flow accurately and efficiently, while enabling the simulation of flow over complex terrain that is usually modeled using coupled one- and two-dimensional models. Researchers should also keep in mind the mathematical algorithms in the employed models, their advantages and disadvantages (Horvat et al. 2017b). In this paper, the authors utilized the HEC-RAS River Analysis System 2D Modeling to conduct the needed numerical simulations. The model is presented in great detail by Brunner (2016), and it was selected for two reasons. The firs one was the availability of data for the purpose of the conducted analysis, while the second was to study and gather experience using the selected model after developing a number of computational procedures for natural alluvial watercourses (Horvat et al. 2015, 2017a; Horvat and Horvat 2016). It should be noted that HEC-RAS was employed by a number of authors. In his work, Thompson (2003) used HEC-RAS to help examine the Blackledge River where a meander cutoff developed as a result of knickpoint migration combined with the influence of a moderate flow that helped the destruction of the present riprap. Birgani et al. (2017) investigated the influence of short dikes on the flow and sedimentation in Karun River, performed long-term simulations using the one-dimensional HEC-RAS model for various scenarios. Habib-ur-Rehman et al. (2018) conducted a performance evaluation of a 1D HEC-RAS model for modeling sediment depositions and sediment flushing operations for reservoirs.

This paper investigates an old meander of the Danube River that is stationed between rkm 1480.8 and rkm 1483.5 (southern Hungary). In order to reduce the danger from ice blockage throughout the Danube in Hungary, a series of river works were carried out aiming to increase the river's slope while decreasing its length (Korpak 2007). Similar work was carried out in Hungary on the Tisza River, where between 1855 and 1864 a total of 7 cutoffs were made on the lower Tisza River, resulting in reduction of length in this section of the river by 19 km (Kiss et al. 2008). One of the interventions carried out on the Danube River was cutting through the previously mentioned meander in 1897 and 1898, which lead to the formation of a river island called the Koppány Island. Cutting off the meander was done by constructing a 25-m-wide waterway while assuming that the river will continue its widening. After a few years, the waterway was between 210 and 300 m wide. Due to the slow development of the newly established reach, in the early 1900s, a formation of ice blockage was observed. Since this lead to increased flood risk, in 1910, the old meander was completely separated from the new reach by building a levee 640 m downstream of the branching point, thus completely preventing the water to flow through the cutoff meander. This allowed the new reach to take over the role of the main reach, while enhancing the sedimentation process in the cutoff meander. Consequently, the meander started narrowing, and decreased in width from the starting 450 m to about a 100 m during the period of 88 years. In addition, not enough water came to the cutoff, resulting in the development of a 100-m-long and 50-m-wide island downstream of the levee, while below this island the cross section started getting deeper and wider. On the other hand, due to the spurs placed in the downstream part of the main Danube reach, the deposition process was enhanced in the lower part of the meander. Therefore, when low water levels appear, the connection of the cutoff arm and the new main reach is only through a cca. 2-m-wide and 100-m-long route.

As a result of river works throughout the complete Danube River reach in Hungary, especially works aiming to straighten the river, there was an increase of the river's gradient and a lowering of the river bed, as it is stated by Korpak (2007). Consequently, this lead to the decrease of water inflow to the analyzed cutoff meander, thus assisting its further deterioration. Aiming to improve the ecological integrity of the system, the levee was partially opened in 1998, and the river bed was dredged. This contributed to the overall improvement of the meander's state. As a result of the conducted works, flow through the cutoff was reintroduced during most of the year, resulting in morphological changes of the cross sections within it. Downstream of the levee, a river bed scour started to develop and keeps getting larger. The bed material from that location is being deposited on the downstream part that follows, making the possibility of flow in low water conditions questionable at best. Furthermore, sediment supply from banks influences the aquatic habitat by promoting the delivery of nutrients and/or contaminants stored in the floodplain (Higson and Singer 2015). As Brierley et al. (2010) stated in their work: "The effectiveness of management actions cannot be evaluated without ongoing monitoring and evaluation of outcomes."; hence, the aim of this work was to foresee whether considered river works would meet their intended needs.

Evaluation of available data

The investigated area consists of the old meander that was cut off in 1910 and partially opened in 1998 (at the location marked "Levee" on Fig. 1), and the new main reach of the Danube River presented on Fig. 1. As a consequence of the levee being opened, river bed downcutting (decreasing river bed elevations), erosion of the right bank, and deposition on the left bank started to take place, supporting the idea of continued migration of the cutoff meander.

The opening of the levee had a considerable influence on the meander, especially on its rating curve depicted on Fig. 2 for different time periods (measured values for Fig. 2 was provided by Tamás et al. 2014). As it can be seen, three sets of data are presented on this figure. The first set (marked with circles) is made up of measurements conducted in 1995 and 1996, 85 years after the levee was placed in the meander, but before it was partially opened. The second data set consists of measurements carried out between 1998 and 2004 (marked with triangles), which is a time period after the opening of the levee. By comparing these two data sets, one can easily see the dramatic change in the rating curve, namely, the partial opening of the levee resulted in increased discharges for the same water elevations. Taking into consideration the third data set that contains measurements from 2013 and 2014 (marked with squares), it becomes obvious that as years went by, the analyzed rating curve started deteriorating, resulting in a noticeable decrease of discharges in the meander.

Additional analysis of available data for the researched location permitted the composition of a summary statistics of annual water surface elevations. Three sets of 115-year-long data series were evaluated ranging from 1901 to 2016 in order to prepare

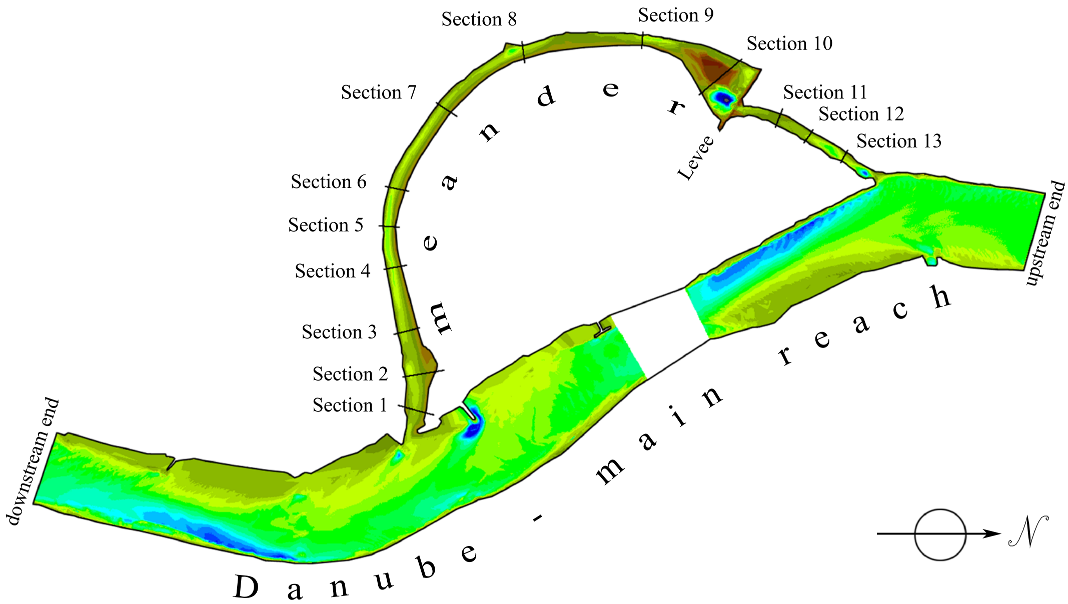
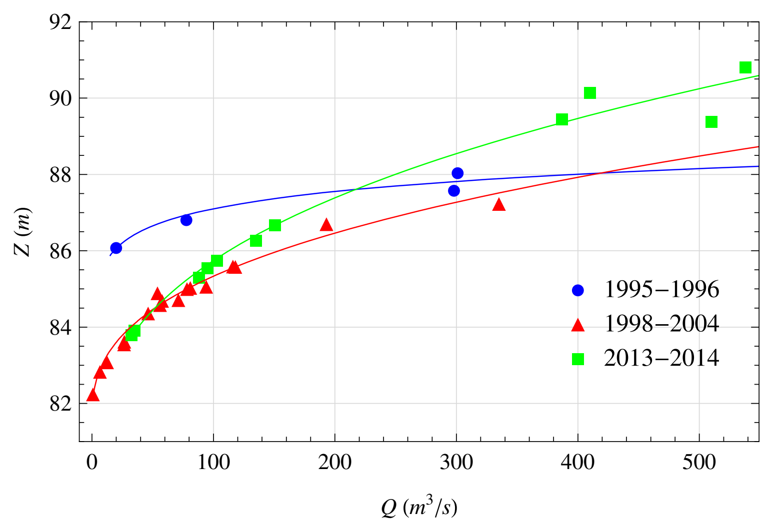


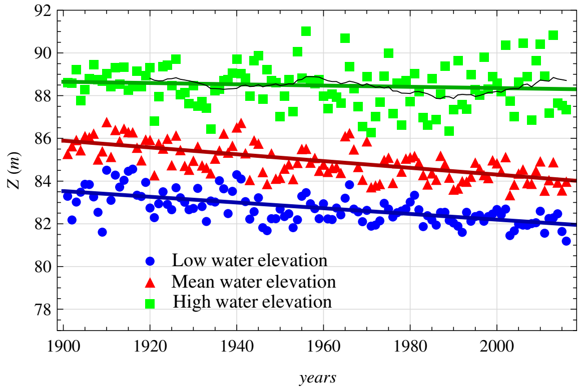
Fig. 1 The old meander and main reach of the Danube River

a statistical analysis presented on Fig. 3. Figure 3 a presents three sets of data: the annual low water levels (denoted with circles), annual maximum water levels (marked with squares), and the mean annual water levels (depicted with triangles) at the nearest hydrometric station, 2.7 km from the investigated meander. It can be concluded that, while the annual mean and low water levels have a decreasing tendency, the annual high water levels shape a nearly horizontal line.

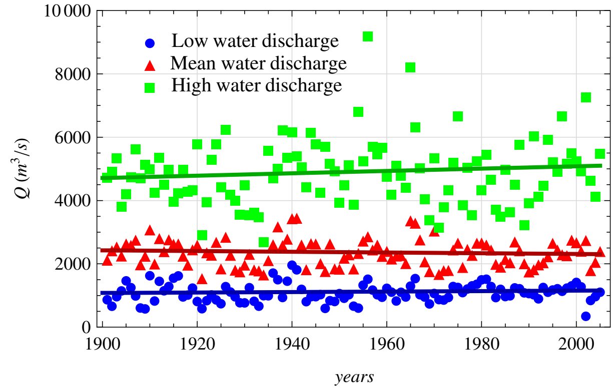
However, by taking into consideration the annual discharges displayed on Fig. 3b, one can determine if the descending water levels are a result of decreased discharges. Similar declining tendency of the minimum annual water stages was observed by Korpak (2007), where after evaluating the discharges which displayed no changes, the author came to the conclusion that the lowering water elevations are the result of river downcutting. Accordingly, the evaluation of the discharges throughout the years produced a nearly horizontal tendency line (Fig. 3b), indicating no substantial changes in discharges. Therefore, the only reasonable explanation of the decreasing minimum

Fig. 2 Historical rating curves of the meander



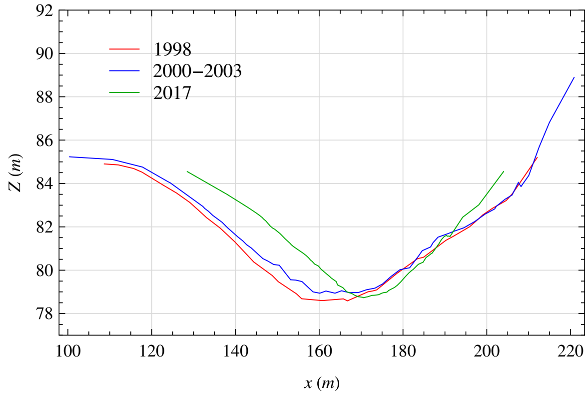


(a) Water level elevations

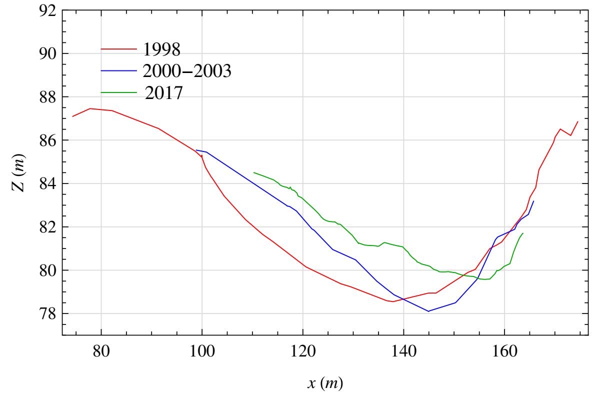


(b) Discharges

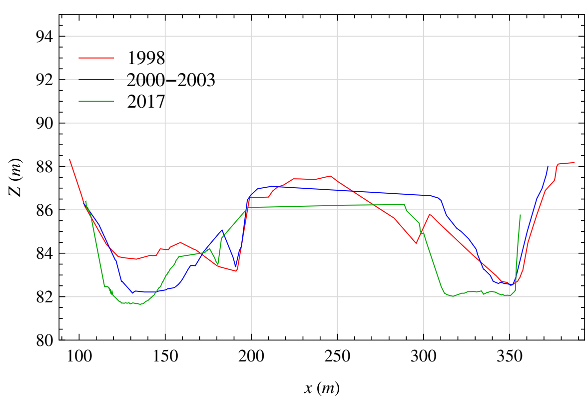
Fig. 3 Statistical analysis of water surface levels and discharges



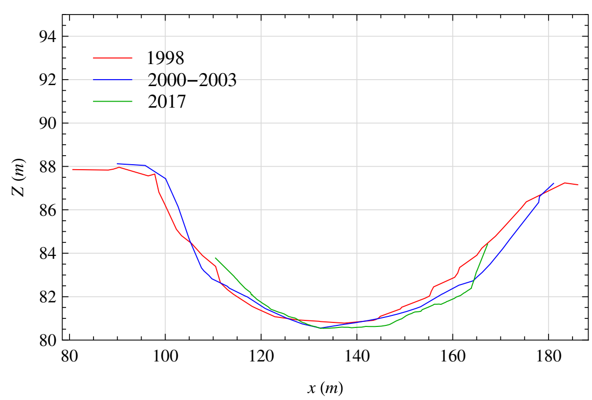
(a) Cross section No.4



(b) Cross section No.9

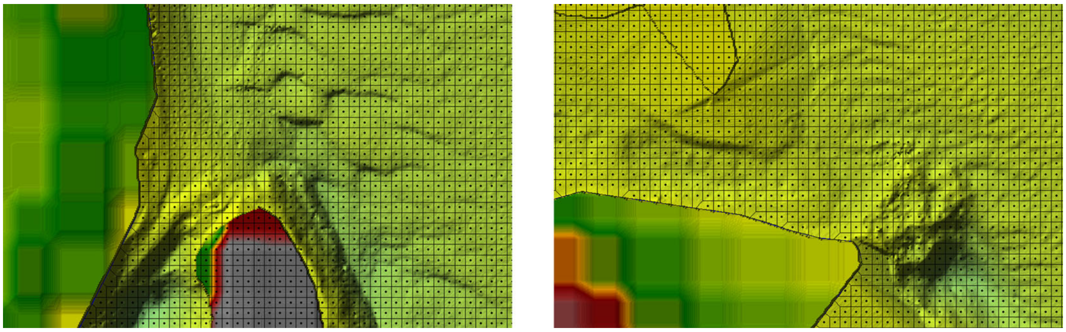


(c) Cross section No.10



(d) Cross section No.12

Fig. 4 Temporal changes in the cross sections of the meander



(a) Detail - Meander inlet (b) Detail - Meander outlet

Fig. 5 Computational grid

and mean water stages is that downcutting occurred here as well. Continuing the study, the authors introduced a moving average on the yearly maximum water elevation values, that displayed a periodical variation. In other words, maximum values of the water levels will have a decreasing tendency for about 50–60 years after which the trend will change and the values will start increasing. Subsequently, the cycle will repeat itself, producing morphological changes in the analyzed meander once again. In order to refine the process of finding the parameters that influence the analyzed occurrence the most, a multivariate analysis could also be used (Pastor et al. 2016).

In order to monitor the state of the meander after the partial opening of the levee, 13 cross sections were selected for continued survey presented on Fig. 1, some of which are displayed on Fig. 4. By comparing the shape of a cross section over the years, the morphological changes become obvious.

The presented cross sections are section No.4, No.9, No.10, and No.12. Each figure shows the bed elevations at three different periods, in 1998, 2000–2003, and 2017, making it possible do identify the transformation of these sections through time. Since all of the analyzed cross sections were measured in years after the opening of the levee, it is evident that the morphological changes which can be observed are an ongoing process. Section No.4 is near the downstream end of the meander (Fig. 1). By evaluating its evolution through time, it can be recognized that while the right bank seems to be stable, the left bank is subject to deposition. Cross section No.9 is placed around the middle of the meander. The evolution of this cross section suggests a continued meandering trend that is clearly displayed on Fig. 4b, namely, on the left bank deposition can be identified, while its right side is being eroded. The following section (No.10) is stationed across the island developed due to increased deposition in the meander (Fig. 4c). It is obvious that since the levee was opened, the island has a tendency of being slowly washed away, while the river bed seems to be moving towards the left, away from the main reach. Finally, section No.12 (Fig. 4d) is placed near the upstream end of the meander. By assessing its alteration throughout the years, one can conclude that this section is seemingly stable, since no significant changes can be detected.

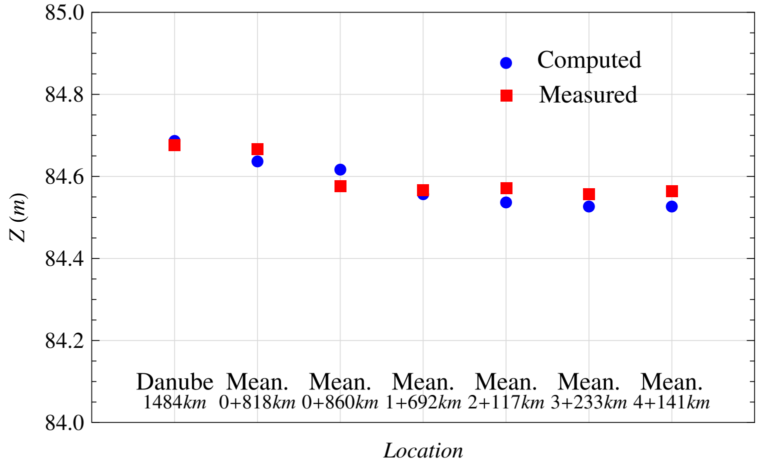
Table 1 Numerical parameters

Parameter	Value	Unit
Theta (weighing factor)	1.0	$(-)$
Water surface tolerance	0.01	(m)
Volume tolerance	0.01	(m)
Max. iterations	20	(m)
Flow tolerance	0.1	$(\%)$
Minimum flow tolerance	1.0	(m^3/s)
Time step	1.0	(min)

Model development

The necessary data for the numerical model was gathered from different sources and consists of bed geometry, known discharges in time on the upstream end of the modeled reach, and known water levels on the downstream end. Furthermore, water levels throughout the meander and main reach were accessible for calibration and verification.

Fig. 6 Model calibration results

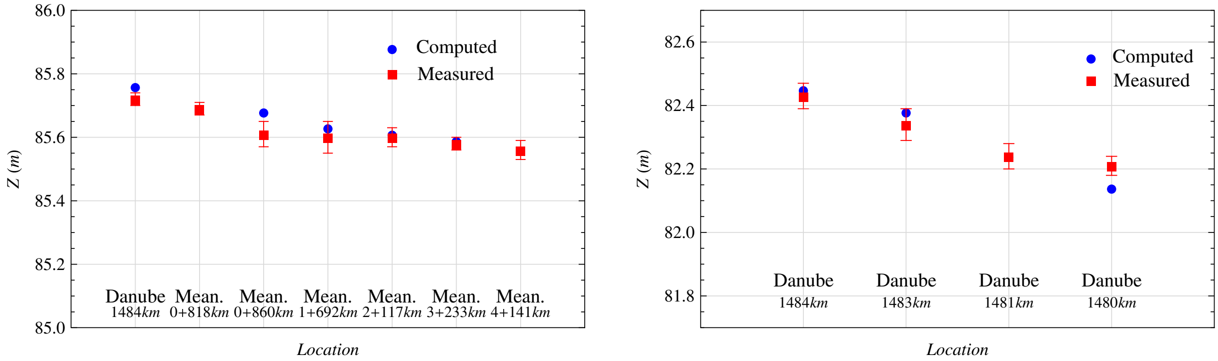


The bed geometry for the main reach was acquired through measurements conducted in 2016, while the meander bathymetry was attained in 2017. The measurements were carried out using the EM 3002 multi-beam echo sounder that has extremely high-resolution and dynamically focused beams which allow it to execute detailed river bed mapping. The main reach of the Danube River was also measured, with the exception of a reach segment stationed between rkm 1482+027 and 1482+457, as seen on Fig. 1. In order to complement the missing data, this segment of the river bed was interpolated.

Using the gathered river bed data, a digital terrain model was built using the AutoCAD Civil 3D program. Subsequently, the terrain model was exported as a TIFF file to be used in the HEC-RAS River Analysis System 2D Modeling software. The computational grid was constructed with computational points 5 m apart, resulting in 199227 computational points in total. Details of the computational mesh are presented on Fig. 5.

Model calibration and verification

For the upstream boundary condition, known values of discharges in time were used, while setting known water level elevations through time as the downstream boundary condition. In the process of calibration, the authors had measured values of water elevations in one cross section on the main reach of the Danube River, and in six cross sections within the meander, all from measurements executed in March 2017. The model was validated using two sets of water level measurements. The first set was from April 2013 where



(a) Model verification - 1^{st} scenario (b) Model verification - 2^{nd} scenario

Fig. 7 Results of model verification

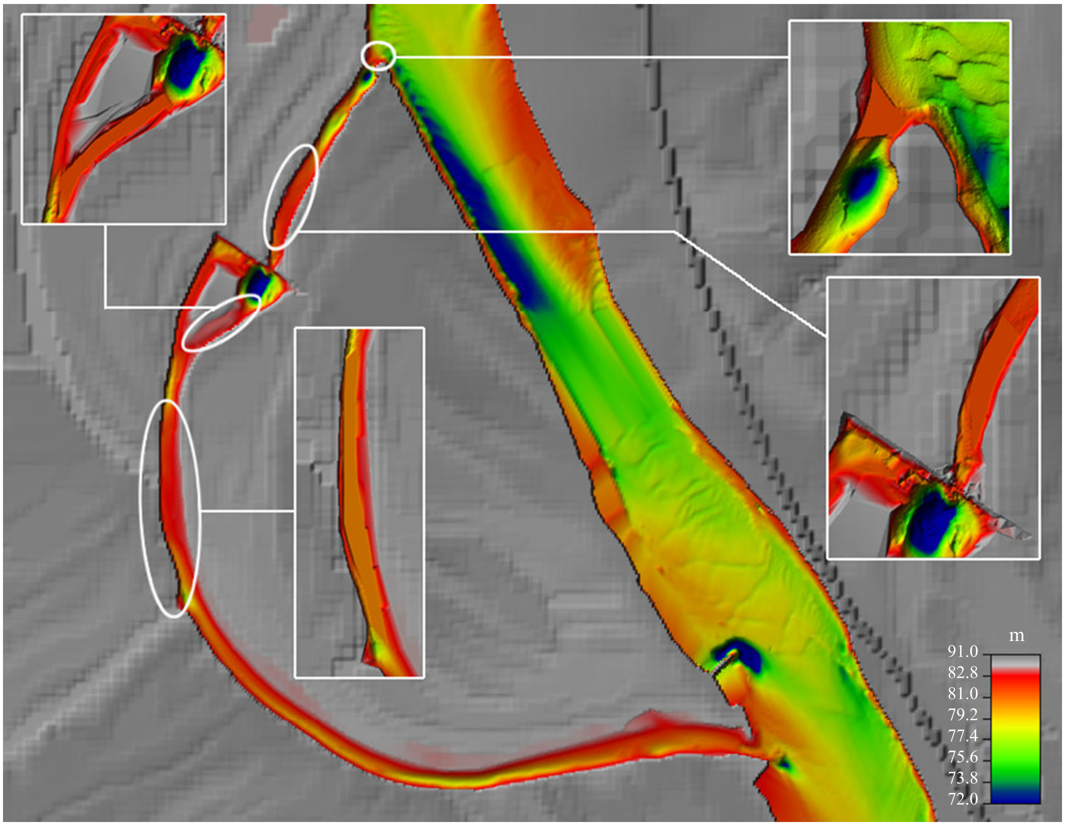


Fig. 8 River bed geometry after dredging

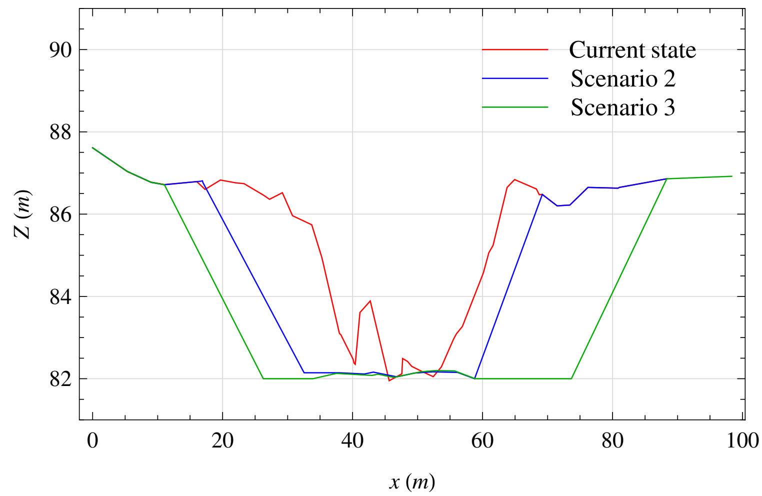
the authors had known water elevations in six cross sections through the meander including one additional cross section on the main reach. The second set of data, used for model validation, was from measurements performed in October 2011 when water elevations were acquired in four points across the main reach. As mentioned earlier, boundary conditions were compiled from known discharges in time on the upstream boundary, and known water level elevations on the downstream boundary for the model calibration, both of the verifications and all of the investigated scenarios.

For all computations, the 2D HEC-RAS full momentum solver was employed. Other important numerical parameters used for the simulations are listed in Table 1.

The modeled area was divided into three parts regarding the Manning's roughness coefficient, the main reach of the Danube, the meander, and the Koppány Island. The calibration was done by altering the values of these coefficients in order to attain satisfactory accordance between the measured and computed water elevations. Finally, the value of Manning's coefficient for the Koppány Island was set to $0.06\,m^{-1/3}s$. The value of the coefficient for the main reach was $0.0345\,m^{-1/3}s$, while for the meander it was $0.043\,m^{-1/3}s$. The calibration was conducted by simulating the time interval from March 23rd to April 6th 2017, which corresponds to the time interval of the conducted water surface elevation measurements.

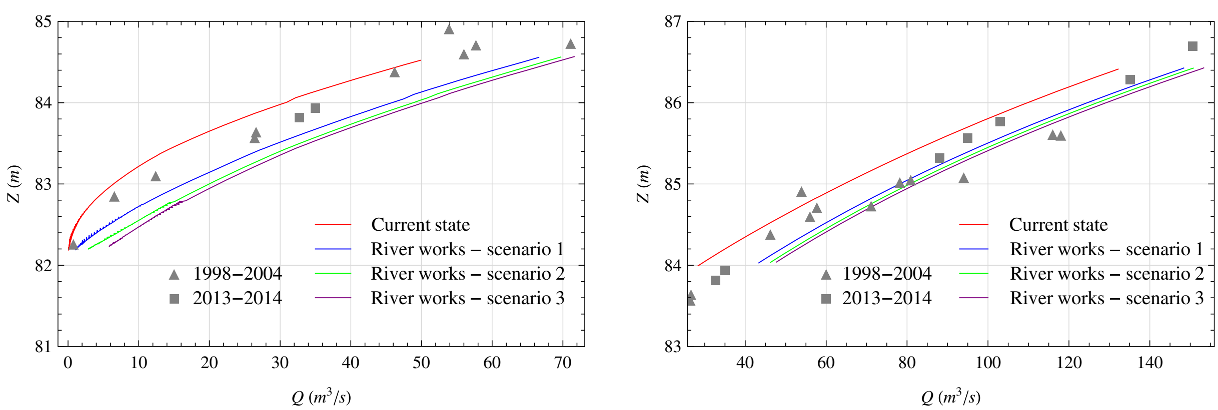
The calibration results are presented on Fig. 6, where the circles denote the computed values of water level elevation, while the squares indicate the measured values. The comparison of the data was done at one cross section on the main reach and six cross sections within the meander. As presented, the accordance between measured and computed water levels is reasonable (the maximum error was + 4 cm, while

Fig. 9 Opening in the levee



the average error was - 1 cm). Therefore, the next step was to use the calibrated model for the process of verification.

As mentioned earlier, the validation was completed using two sets of measurements where the first consists of water levels measured in April 2013 (simulated time from 6th to 25th) in one cross section on the main reach and six cross sections on the meander (Fig. 7a). The second set was gathered in October 2011 (simulated time from 1st to 15th), and it contains known water level elevations in four cross sections along the main reach of the Danube River (Fig. 7b). In both cases of validation, the statistical error for the measurements is depicted as three standard deviations. After a detailed analysis of the results, it is reasonable to conclude that the calibrated model is capable of producing trustworthy results, since it was validated using two different sets of measurements and generated reliable results both times. It should be noted that the calibration was performed for discharges around $1300\,m^3/s$ (range from 1100 to $1600\,m^3/s$), while the verifications were conducted for discharges of approximately $3700\,m^3/s$ (range from 2800 to $4400\,m^3/s$) and $2300\,m^3/s$ (range from 1000 to $3500\,m^3/s$). The model's ability to generate pleasing accordance between measured and computed values when applying discharges that are out of range from the ones used for calibration shines light on the robustness and reliability of the presented model. Accordingly, the following step was to employ the prepared model to



(a) Rating curve for low water levels

(b) Rating curve for mean water levels

Fig. 10 Comparison of rating curves for low and mean water levels investigate the influences possible river works would have on hydraulic and morphological changes of the analyzed meander.

Model application

The previously calibrated and verified two-dimensional flow model was engaged to evaluate the influence considered river works would have on the investigated meander. Aiming to increase the hydraulic conveyance of the meander, two types of river works were analyzed, dredging the river bed and widening of the existing opening in the levee. In order to keep the river works as environmentally friendly as possible, the dredging was considered only on those parts of the meander that were most exposed to sedimentation. The sites selected for the dredging are presented on Fig. 8, along with the present state of the river bed.

The designed bed elevation of the dredged parts in the section of the meander upstream from the levee is 81.50 m. At the same time, the bed elevation of the existing opening in the levee is 82.00 m. Although, the latter elevation can not be lowered due to the requirements for safe shipping on the Danube River, the authors evaluated the possibility of widening the existing opening in the levee to 25 m or to 50 m, while keeping its bed elevation (Fig. 9). Consequently, the bed elevation of the upstream part of the meander will be 0.5 m lower than the bed elevation of the opening in the levee. Therefore, the opening will take on the role of a broad crested weir and accordingly govern the inflow in the meander from the main reach of the Danube River.

Downstream of the levee is an island (Fig. 8) that divides the flow through the meander into two directions. The left side of the bed is proposed to be dredged to elevation of 81.50 m. Additionally, the river bed downstream of the island (the middle part of the meander) is proposed to be dredged to the bed elevation of 80.50 m in order to increase low water level discharges. The width of all suggested dredged areas is 30 m. The river bed geometry after the considered dredging is presented on Fig. 8. It should be noted that the figure presents the current state of the river bed, while the dredged geometry is given within white squares connected to the locations they belong to.

The two types of river works that were considered were organized to form three different scenarios. The first scenario employs only dredging, without any additional river works. The second utilizes the previously described dredging complemented with widening of the opening in the levee from the current 18–20 m, to 25 m, without changing its bed elevation (Fig. 9). Finally, the third option consists of dredging and widening of the opening in the levee from the original 18–20 m to 50 m, also without any changes in its bed elevation (Fig. 9).

Employing the validated model on the current state of the investigated reach, it can be shown that the rating curve for the meander has continued to deteriorate in comparison with the last measured data, Figs. 2 and 10. Results depicted on Fig. 10 present the changes in the rating curve that resulted from the three considered scenarios of river works for low and mean water levels. It can be seen that dredging significantly improves the water level - discharge curve compared with the current state. The second scenario, where the levee would be widened in addition to dredging, results in even greater increase of discharges, while the third scenario gives additional improvement in this respect. A numerical overview of the discharge increase emanating from the three considered scenarios is given in Table 2.

Figure 11 depicts the velocity distribution along the meander for the current situation and for the three considered scenarios, providing an insight into the influence that the proposed works would have on this hydraulic parameter.

Figure 11 a presents the section from the upstream of the meander to downstream of the levee. This section includes the scour situated immediately downstream of the levee as well. By comparing the presented results, it is self evident that all of the investigated scenarios produce a general increase of velocities, which is important from the aspect of sediment deposition. A more in-depth analysis confirms the earlier verdict that the third scenario provides the greatest velocity increase, the second scenario gives slightly smaller velocities, and the first scenario the smallest. Nevertheless, the difference between velocities for the current state and whichever scenario are much greater than the difference between any of the evaluated scenarios when compared among themselves. One can observe a sudden increase of velocity at approximately

Table 2 Average increase of discharge for the proposed river works

Scenario		Average increase of discharge (m^3/s)		
	Water level range (m)	81.99–82.99	82.99–84.49	84.99–86.19
1.		4	15	15
2.		7	18	18
3.		11	20	20

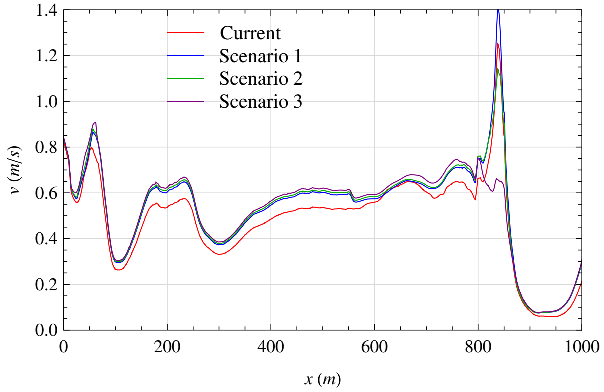
0+840 km for all of the considered cases, except the third scenario. This abrupt increase is the result of the narrowed cross section where the levee is located. A noticeable decline of velocities at this location for the third scenario is a consequence of the extended opening in the levee (Fig. 9), yielding smaller velocities. Further down the meander, a sudden decrease of velocities can be detected. The cause of this can be found in the 17-m-deep scour located at this section, resulting in reduction of flow velocity.

Figure 11b shows the remaining part of the meander, downstream of the scour to the outlet of the meander. It can be said that all the scenarios yield an increase in velocities. Furthermore, the change in velocities for any of the scenarios relative to no river works are much more prominent than the difference between velocities when comparing the three scenarios. It should be noted that at around 1+500 km into the meander, there is a short section where all the considered river works show reduced velocities compared to the current state. This occurrence is a consequence of dredging, i.e. the increase of flow profile. Since the increase of discharge is not enough in comparison to the flow profile's expansion, reduced velocities are in this case inevitable.

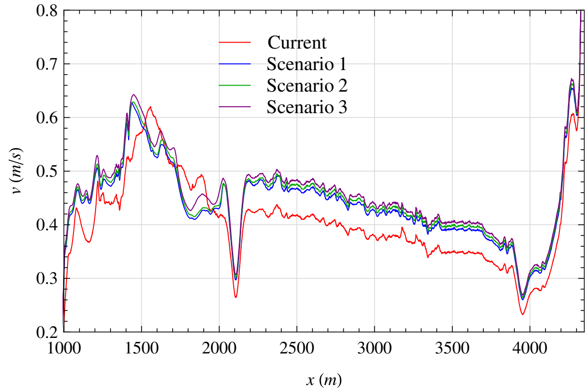
Discussion

After evaluating the influence of the three considered scenarios, the authors selected the first approach (dredging only, described in Section 2) as the most reasonable. The justification for this choice can be found in the possible intensive river bed evolution that would occur after widening the opening in the levee. Naturally, this would be an unfavorable consequence, since it would require further interference in order to slow down the bed morphology changes. Furthermore, the first scenario provides the necessary depth for low water levels, as well as an improved rating curve. Accordingly, in the this section, only the selected (first) scenario is discussed in more detail.

Figure 12 shows the velocity distribution across the investigated area for the present state, marked as "Cur-



(a) From inlet to levee



(b) From levee to outlet

Fig. 11 Velocity distribution along the meander

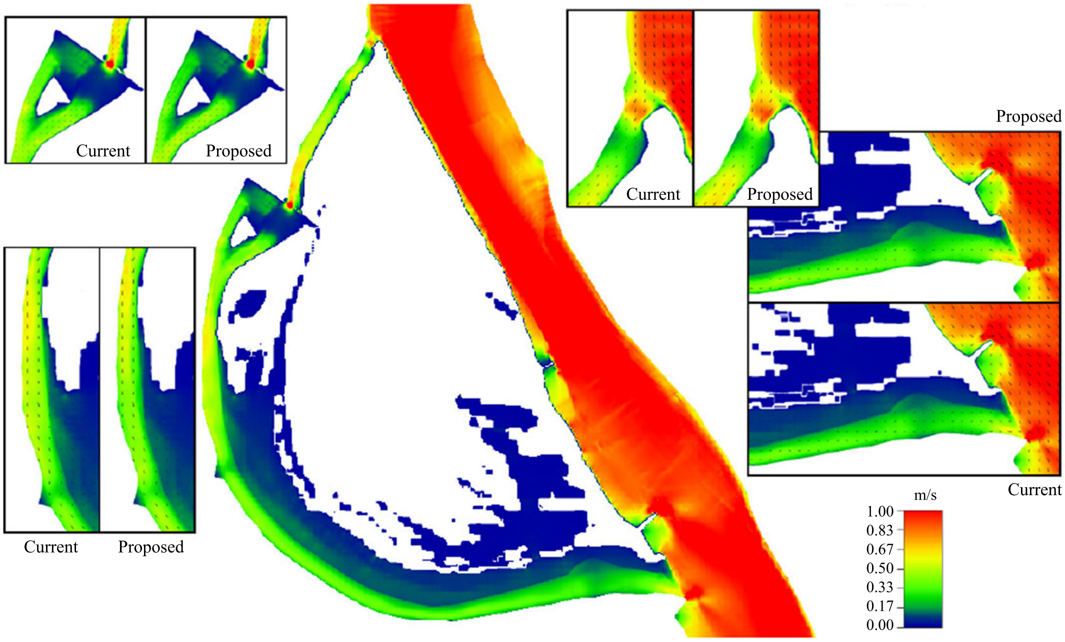


Fig. 12 Comparison of velocity distribution before and after dredging

rent", and after implementing the selected option of river works marked as "Proposed". Careful comparison of the current and proposed scenario leads to the conclusion that dredging would allow the reduction of velocities in the right-hand side (relative to the island) of the meander immediately downstream of the levee, while increasing them at the meander's inlet. It is noteworthy to point out that even though the bed at the inlet was lowered, the velocities were increased nonetheless. This supports the results presented on Fig. 10

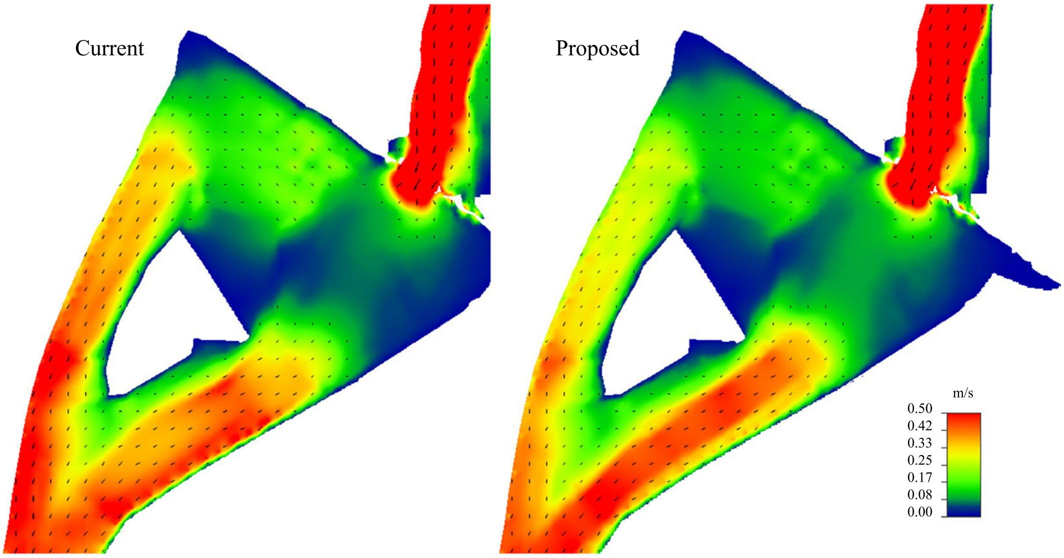


Fig. 13 Flow field detail

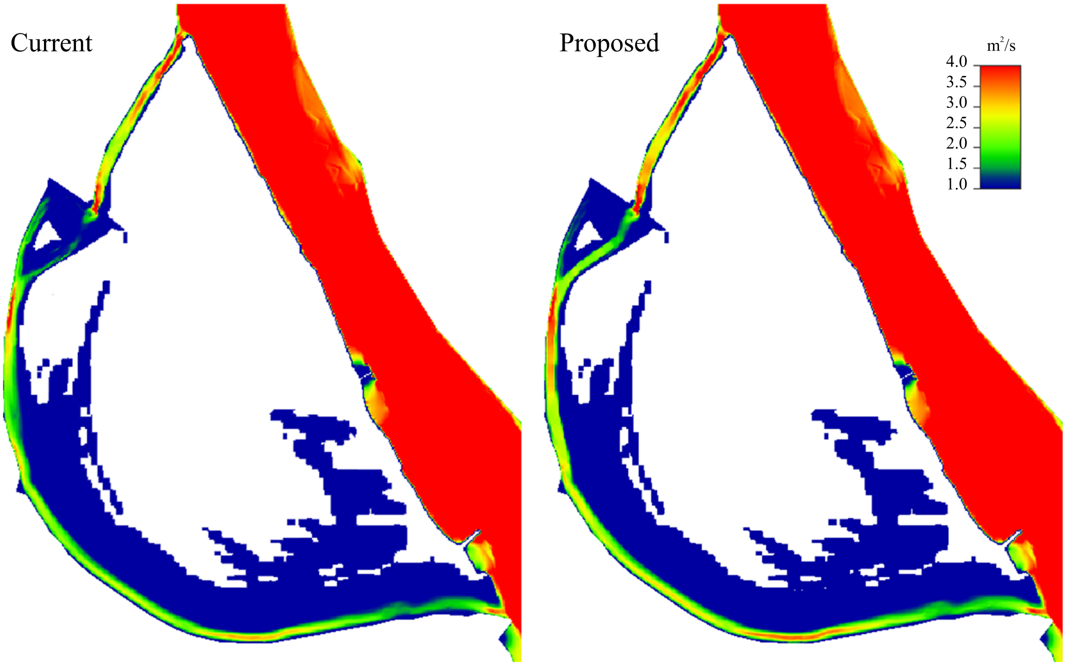


Fig. 14 Unit discharge distribution

in Section 2, where it was concluded that dredging would result in increased discharges throughout the meander. Moreover, increased velocities at the inlet would help counteract the deposition of sediment at this location. Although it is impossible to say that deposition will certainly not occur without employing a proper sediment model, increased velocities are an essential step in that direction. On the other hand, reduced velocities downstream of the levee (Fig. 13) suggest that a velocity redistribution would develop after the planned dredging. This would result in more water flowing on the left side of the island formed downstream of the levee, which is the natural, and thus preferred path of flow.

In the time period leading up to the current state, increased velocities kept eroding bed material immediately downstream of the levee, as can be seen on Fig. 1, resulting in a 17-m-deep scour. At the same time, this eroded material filled up the meander bed on the left-hand side of the island downstream of the levee, thus redirecting the flow towards the right-hand side of the island. Employing the proposed river works, the flow would be guided towards the left-hand side, which would fortify the flushing process of previously deposited material and help restore the natural state of this section.

Finally, another interesting hydraulic parameter that should be evaluated is the unit discharge throughout the studied domain, presented on Fig. 14.

It is evident that the suggested river works would increase the unit discharge in the entire meander. This is especially noticeable on its upstream part. The redistribution of flow around the island downstream of the levee is also apparent, where the flow once again favors the left-hand side of the island. This is a more natural path of flow that will through time aid the flushing of previously deposited sediment in this part of the meander.

Conclusion

The state of the analyzed meander is of crucial importance to the sustainable habitat management of the area. This issue becomes even more pressing when one considers that the researched Danube reach, along with its meander, is located in the Duna-Dráva National Park in Hungary. Understanding the hydraulic regime, along with detailed flow fields can significantly contribute to the successful management and remediation of endangered aquatic habitats.

Detailed analysis of the gathered data proved that there is a declining tendency of mean and low water levels on the Danube River at the researched location, leading to a considerable reduction of water that can get into the investigated meander. A partially opened levee in the meander makes the problem even more complex from an engineering point of view. In order to assess the present hydraulic situation, and evaluate and propose river works that could improve the situation at hand, a two dimensional hydraulic model was calibrated and verified for the examined domain. After conducting hydraulic computations for all the considered interventions, as well as for the current state, the simulation results enabled the authors to compute rating curves, analyze flow fields, velocity distributions and unit discharge distributions. Subsequently, dredging of the meander bed on specific locations was proposed, since it can significantly improve its hydraulic regime for mean and low water elevations on the Danube River with the least possible interference in the environment. The recommended solution does not require further widening of the levee opening, although this remains an additional option.

Finally, it can be stated that the employment of hydraulic models can be very beneficial when dealing with the reconstruction and/or monitoring of aquatic habitats, since providing an appropriate water regime for these water bodies is essential. Although the conducted computations for the proposed river works yielded an improved rating curve for the meander, they also predicted an increase of velocities on key locations. This upsurge in velocities indicates a possible improvement in the sediment regime as well. However, in order to gain a better insight into the sustainability of the recommended intervention with regard to sediment processes, in future research a flow and sediment transport model should be employed.

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Compliance with ethical standards

Conflict of interests The authors declare that they have no conflict of interest.

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