RESEARCH PAPER

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IMPACT ASSESSMENT OF RIVER REGULATIONS USING 1D MORPHODYNAMIC MODELING ON THE UPPER HUNGARIAN DANUBE

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ABSTRACT. The geometry of watercourses shows that they undergo continuous deformation towards a dynamic equilibrium state. Once this is reached, further changes in the bed can be observed, but they are not expected to cause significant deviations from the dynamic equilibrium state. The dynamic equilibrium state will likely change due to significant natural or artificial processes. The main question is what new riverbed geometry or flow conditions (peak water levels) can be expected. In our paper, we investigate the impact of past interventions on the dynamic equilibrium state of the Upper Danube in Hungary. We built a 1D morphodynamic model for the section under study. The model was improved by incorporating the mixed grain composition of the bed and bedload material and considering the backwater effect. The model was parameterised with data from the 19th century, i.e. the natural state. The model allowed us to perform a century-scale study. The model gave accurate results of 13 cm and 3 cm for the incorporation of the interventions and also predicted the backfilling in the studied section. Using the 1D approach, we obtained a model that can study a more extended section, such as a more than 100 km reach. The 1D model can provide a temporal estimate of the impact of each intervention, Such as the installation of wing dam fields and water dams and the elaboration of artificial cutoffs.

KEYWORDS: sediment transport, river regulation, 1D model, dynamic equilibrium state

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INTRODUCTION

For all rivers, morphological changes can be observed over time, the effects of which need to be characterized by approximating the dynamic equilibrium state. These changes can be caused by artificial interventions or by natural phenomena. Nowadays, increasing emphasis is being placed on predictions, which can also be necessary for the morphological characteristics of rivers. Natural changes can often only be estimated, but artificial interventions are preceded by planning or consultation, making predicting their impact easier. In the Upper Danube in Hungary, it can also be observed that some interventions have induced changes in riverbed geometry that were not or could not be considered in the design because of the lack of reliable tools (Farkas-Iványi, 2015; Tőry, 1952; Bogárdi, 1955, Holubová, 2004). For example, when deposition and gravel bank formation was caused by excess downstream sediment related to bed erosion from an upstream intervention. In this case, the upstream interventions caused navigational difficulties on the downstream reach, which required further interventions in the river section, which became problematic (Rákóczi, 1993). A suitable model could have predicted the effects of the upstream intervention.

In our study, we focused on a section of the Upper Danube in Hungary and investigated the artificial effects of this section. The section under study starts at Dunaremete and continues to Nagybajcs, as shown in Figure 1.

The Danube has already undergone a lot of regulation, such as the river regulation in the 19th century (1881-1885), where the then braided system (Figure 1.) was transformed into a single thread channel (Figure 1.), which provides better navigation conditions and improved flood protection (Tőry, 1952; VITUKI, 1954).

According to the literature, the length of the section was reduced by 10% (Tőry, 1952). The regulation has reduced by half the widths in the control sections. After regulation, the alluvium was enriched, filling several places. This resulted in the following regulation work (Tőry, 1952; Bogárdi, 1955).

A further intervention was the installation of wing dams/wing dam rows on the section between 1938 and 1944 (Tőry, 1952) (Figure 2.). This intervention is expected to induce morphodynamic processes that mainly benefit navigability. The braided system regulation upset the sediment balance, which resulted in intensive sediment deposition on the downstream section. The installation of the wing dams was expected to erode these problematic deposits, thus improving the flood risk management and navigability. The wing dams were constructed between 1938 and 1944 (Tőry, 1952). The constructed wing dams narrowed the original channel width by ~30% which means about 120 m in the Nagybajcs (rkm 1801) section.

Several studies have been conducted to investigate the effects of wing dams, which have supported the present work. Evaluation of field measurements and numerical modelling results were also available in the studies processed. The results showed that the consideration of the mixed grain composition plays a significant role in the development of the new equilibrium state (Holubová 2015; Wilcock and Crowe, 2003; Parker et al., 2024). The studies focused on a few km long sections and short time scales. Measurement-based studies (Liedermann et al. 2017; Holubová et al. 2015; Pomázi and

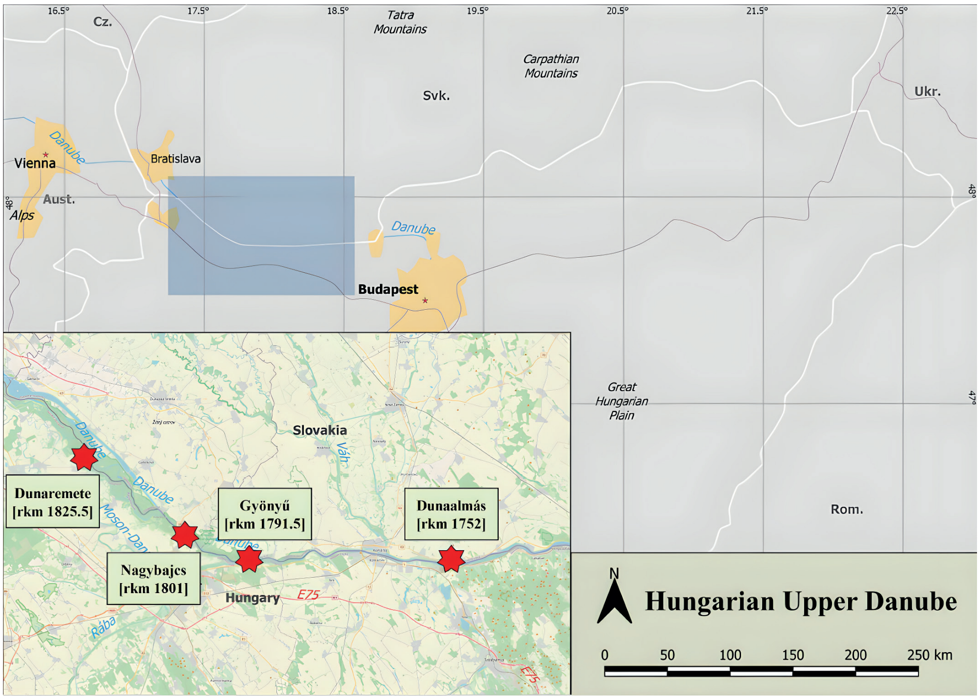

Fig. 1. Description of the section and sections studied on the Upper Danube in Hungary

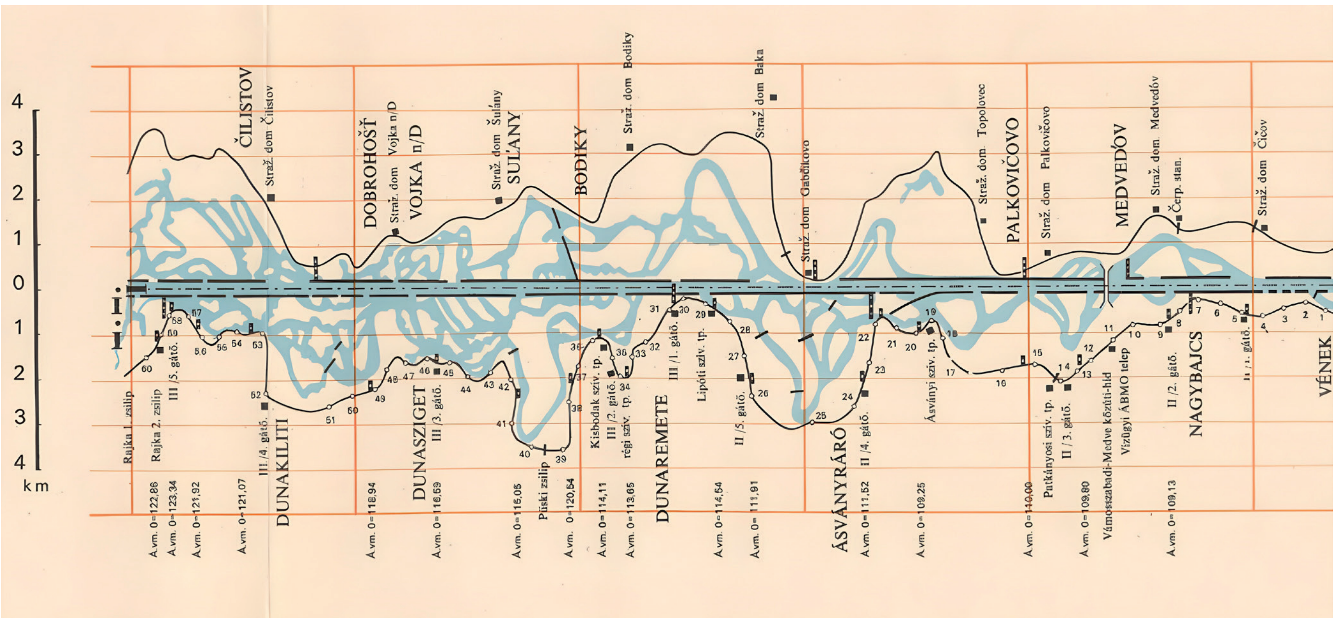

Fig. 2. Braided branch system on the Upper Hungarian Danube (VITUKI, 1954)

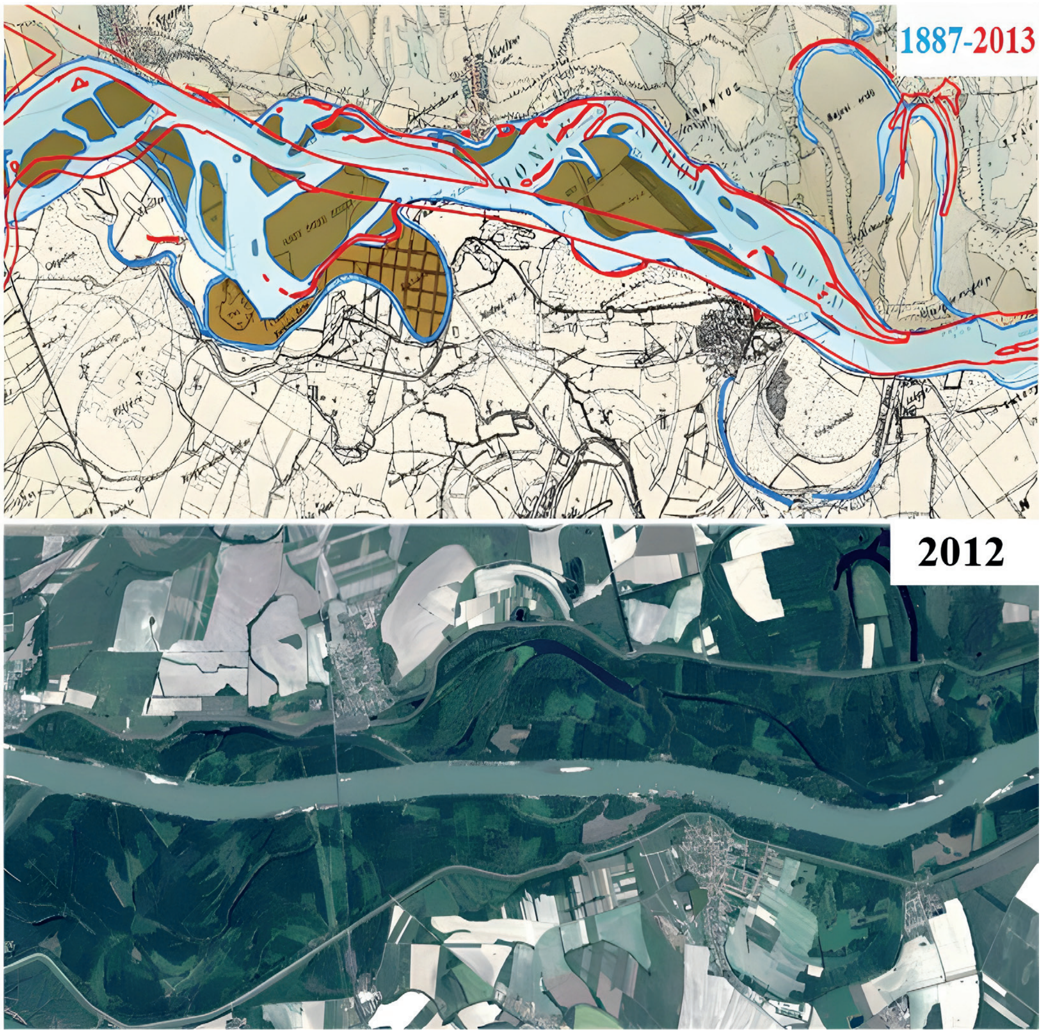

Fig. 3. Danube regulation before/after comparison (DuRe Flood project, 2015)

Baranya 2022) evaluated the present conditions. Numerical modelling-based studies were limited to a few months at most (Fischer- Antze et al., 2008; Baranya & Józsa, 2006). The studies showed no significant riverbed change trend in the examined sections. Based on these, it seems that the 2000s established the new equilibrium state, that is, the effect of previous interventions was no longer detectable.

However, examining the effects of interventions that are more extensive than local, both in space and time is necessary. We believe this is of great importance, as interventions can significantly impact the morphodynamics upstream and downstream.

Based on these, the present study aims to demonstrate that it is possible to predict the morphodynamic effects of reach-scale interventions using a 1D model that is able to take into account the mixed grain composition of sediment transport and is able to consider the interaction between upstream and downstream by applying backwater equation. In this way, we offer a validated tool capable of answering key questions for river regulation. In our particular case, what impact have river management interventions had on the equilibrium state? Can we predict the new dynamic equilibrium state and the time needed to reach it?

MATERIALS AND METHODS

Literature research

The literature search has been emphasized as it provides the model specification and parameterization. From the data collected over several periods, it is possible to identify morphological changes and processes. The impact of two interventions were investigated in this study, so the aim was to collect data before and after the two interventions. One of the two interventions is the braided system regulation in the 19th century and the building of wing dams in the first half of the 20th century. From the period of before the 19th-century regulation, not much substantial data is available. Still, literature research has provided with a very relevant data set: the Danube's longitudinal bed profile (Lanfranconi, 1882) which can be seen in Figure 4. It shows that the section did not follow a constant downward trend. However the upper section was characterized by a steeper slope, which decreased drastically as it reached the lower section. In accordance with previous papers (Holubová et al., 2004; Tőry, 1952), a slope break could be detected in this section under study, as shown in the longitudinal profiles. As additional data, we also found a longitudinal profile from 1910 (M. kir. áll. nyomda, 1910), 1949 (OVH, 1949), and 1970 (VITUKI, 1970).

The longitudinal profiles show that after the regulation in 19th century, the riverbed upstream Gönyű (rkm 1791.5) visibly deepens, while downstream Gönyű a considerable deposition process took place. Comparing the longitudinal profile from 1949 with the pre-regulation section (1882), it can be seen that there is less sedimentation upstream Gönyű (rkm 1791.5) and a gradually filling section downstream. What can also be observed are some significant local changes that an intervention, such as the installation of wing dams, could cause. The amount of sediment has always played an essential role in the ongoing river morphodynamics. The evolution of sediment transport can strongly influence the geometry of the riverbed.

Fig. 4. Row of wing dams at Nagybajcs, rkm 1801 (Google Maps, 2022[1])

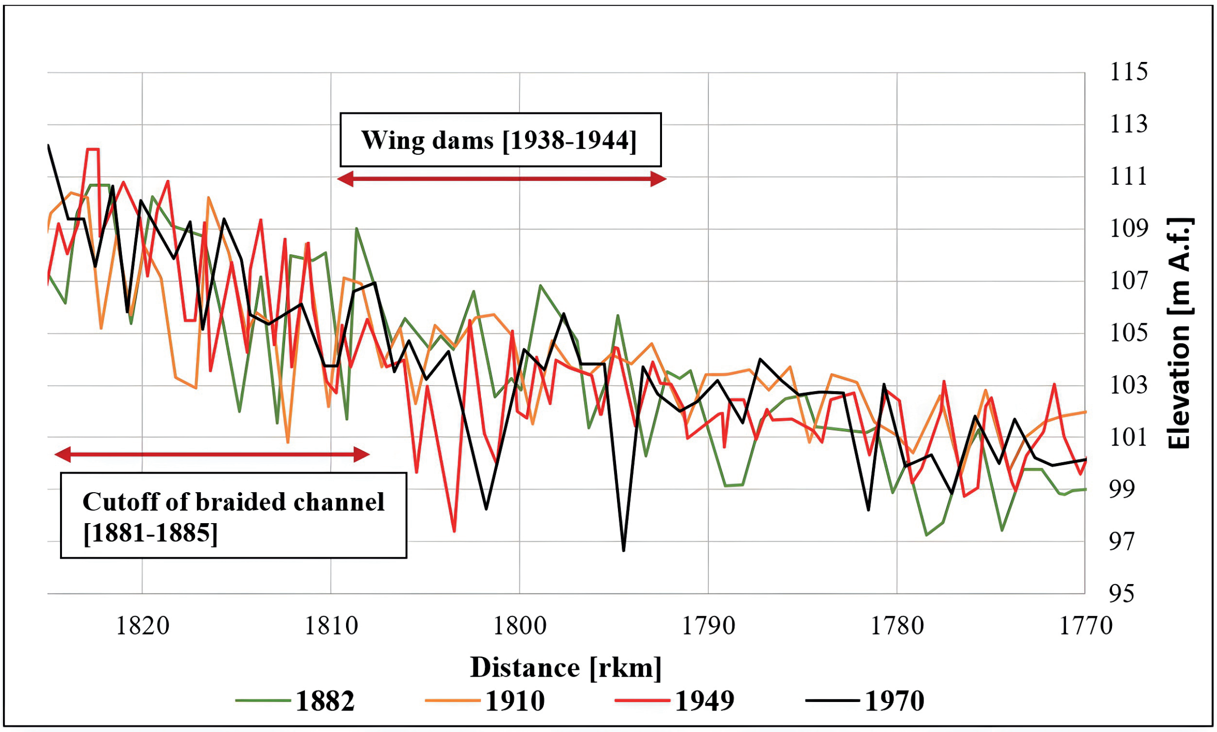

Fig. 5. A comparison chart of past longitudinal profiles

Based on the literature, we had sediment load data for two periods. Between 1952 and 1953, the yield at the Dunaremete (rkm 1825,5) section was 185400 t/year, while at Nagybajcs (rkm 1801), 22000 t/year, and at Dunaalmás (rkm 1752) 38850 t/year (OVF Hydrographic yearbooks 1886-1990[2], Pomázi and Baranya 2020). These data show that erosion is present between Dunaremete (rkm 1825) and Nagybajcs (rkm 1801), and the sediment load of Nagybajcs (rkm 1801) also shows that selective erosion may be the cause of the decline there, as pointed out by several studies (Tőry, 1952; Bogárdi, 1955). The second period is between 1966 and 1992. During this period, the sediment loads were 730607 t/year at Dunaremete (rkm 1825), 483873 t/year at Nagybajcs (rkm 1801) and 65000 t/year at Dunaalmás (rkm 1752) (OVF Hydrographic yearbooks 1886-1990). The later data show that erosion is still present, but not to the same extent as the older data illustrate. For the sediment, not only the sediment load was significant, but also the grain composition.

The section's grain size and sediment values are taken from the measurements made between 1952 and 1953. The average sediment grain size (D_{50}) was 18 mm at Dunaremete (rkm 1825), 7.5 mm at Nagbajcs (rkm 1801), and 0.245 mm at Dunaalmás (rkm 1752) (Bogárdi, 1955).

[1] https://www.google.hu/maps
[2] https://www.vizugy.hu/print.php?webdokumentumid=1524, 2022

The sections' average bed material (D_{sg}) size was 19 mm at Dunaremete (rkm 1825) and 13 mm at Nagybajcs (rkm 1801) (Bogárdi, 1955). The data shows the differences between individual sections. The distance between Dunaremete and Nagybajcs (rkm 1801) is only 25 km and the typical grain size in the Nagybajcs (rkm 1801) section is less than half of the Dunaremete (rkm 1825) value. The decreasing values also confirm the selective deposition within the section.

Another essential data point in our study is the grain composition curves. We aim to develop an inhomogeneous model that considers interactions between several fractions. With this kind of approach, selective erosion can also be investigated. In the section under study, this is a fundamental. The slope break upstream of Gönyű (rkm 1791.5) has a slope rate of 25-40 cm/km on the section and steeper and steeper sections towards Austria (Goda, 1995). Downstream of Gönyű (rkm 1791.5), the predominant slope is 8-10 cm/km or less (Tőry, 1952; Holubová et al. 2004, Rákóczi and Sass, 1995, Rákóczi, 1979).

Four parameters were used to test the model's accuracy. These data were from the contemporary riverbed level at Dunaremete (rkm 1825), the location of the slope break (Holubová, 2004; Tőry 1952), the bed slope upstream and downstream of the reach, and the average sediment diameter in the Dunaremete (rkm 1825) and Nagybajcs (rkm 1801) sections.

1D morphodynamic model setup

The 1D model performs the calculation steps for a whole section, establishing a link between adjacent sections. The approach and simplifications used in the model were based on the online notes of Professor Gary Parker (Parker, 2004[3]). In the model, we approximate the cross-section with a rectangular section and do not consider the floodplain, only the bankfull channel. Because of this approximation, the model takes into account the bankfull discharge. The bankfull discharge along with the intermittency are used to describe the equilibrium bankfull morphodynamic state. Intermittency is the time fraction that shows the morphodynamically active time fraction (Parker, 2004).

The model is based on a system of equations that give the equilibrium stage (Eke et al., 2014; Naito and Parker, 2019).

Continuity equation for a liquid:

$$Q_W = UHB \tag{1}$$

Q the flow discharge [m³/s], *U* the section average velocity [m/s], *B* width of the section [m] and *H* the water depth [m].

Momentum equation:

$$\left(\frac{\tau_b}{\rho}\right) = C_f U^2 = gHS \tag{2}$$

In the equation τ_b is the bed shear stress [N/m²], ρ is the density of water (1000 kg/m³), C_f is the dimensionless bed resistance, *g* is the acceleration of gravity (9,81 m/s²) and *S* is the bed slope [-].

The continuity equation for a sediment:

$$Q_b = Bq_b(R+1) \tag{3}$$

Q_b the sediment load [kg/s], q_b the specific sediment load [kg/sm] and *R* the underwater weight of the sediment.

1D model contexts

The hydrodynamic variables were estimated with the backwater equation:

$$\frac{\partial H}{\partial x} = \frac{S - C_f \dfrac{q_w^2}{gH^3}}{1 - \dfrac{q_w^2}{gH^3}} \tag{4}$$

In the equation, *Sf* is the fall of the energy line.

In the following equation, *Fr* denotes the Froude number, which is a dimensionless number and can be calculated as follows:

$$Fr = \frac{U}{\sqrt{gH}} \tag{5}$$

The dimensionless bed shear stress can be calculated using the following equation:

$$\tau * = \frac{\tau_b}{\rho gRD} = \frac{HS}{RD} = \frac{C_f U^2}{RgD} \tag{6}$$

Based on the shears stress, the bedload transport formulas are able to estimate the sediment discharges. In the present 1D model, we applied the Wilcock and Crowe formula in order to consider the mixed sediment behavior, such as the selective erosion and bed armouring process. The grain composition is the moving layer and the active and inactive layers of the bed vary in grain composition. So, the transport between these three layers must always be calculated, and then the change in grain composition caused by these must also be modelled for each cell (Wilcock and Crowe, 2003).

The change in the bed elevation of a given cell was calculated from the difference between the sediment loads calculated for the cell of the preceding section and the cell of the following section, using the Exner equation.

$$\left(1 - \lambda_p\right) * \frac{\partial \eta}{\partial t} = \frac{\partial q_b}{\partial x} \tag{7}$$

Steps in the calculation of the Wilcock model:

1. Determination of the dimensionless bed shear stressfor the average grain size as a function of sand content
2. Determination of the reference bed shear stressfor the average grain size as a function of the dimensionless slip stress
3. determination of the reference bed shear stressof the i-th fraction as a function of the reference bed shear stressfor the average grain size and the diameter of the i-th fraction and the diameter of the average grain size
4. Calculation of the dimensionless sediment load of the i-th fraction from the ratio of the reference bottom-slip tension to the bottom-slip tension
5. Calculation of the sediment load per unit width of fraction i-th as a function of the dimensionless yield, fraction ratio and slip velocity
6. calculation of the concentration of the i-th fraction as a function of sediment load, water depth and water velocity

[1] http://hydrolab.illinois.edu/people/parkerg/morphodynamics_e-book.htm

Modell validation

For the model parameterisation, the reach averaged bankfull channel width before interventions were set based on an earlier 0D model-based study in 2020 (Dunaremete: ~600 m) (Nyiri, 2020).

The inlet section of the model was Dunaremete (rkm 1825). The bankfull discharge at Dunaremete is 4100m^3/s (OVF, 1886-1990). Since no data on bed material was available from the 19th century, we assumed that the bed composition didn't change significantly. Therefore, we set the grain size composition curves determined in 1954 as the initial boundary condition (VITUKI, 1954) . The outflow section was the Dunaalmás section (rkm 1752), in order to place the slope break at Gönyű (rkm 1791.5) in the middle of the domain. The grain composition at Dunaalmás (rkm 1752) was determined in a similar way to that at Dunaremete (rkm 1825). The outflow bed level was set at Dunaalmás (rkm 1752), i.e. 97.27 m.A.f (Lanfranconi, 1882). The initial longitudinal profile was calculated assuming a constant bed slope typical downstream of Gönyű (rkm 1791.5), which is ~ 9 cm/km (Tőry, 1952). The measured value of 1953-54 for the inflow sediment load was given, i.e. 185400 t/year (OVF, 1886-1990). After parameterization, the model was run until to get the best match with the real longitudinal profile from 1882, which took 600 years.

As shown in Figure 5, the break is well represented, and the model places it at about rkm 1792.9. Considering that the break is not exactly at Gönyű (rkm 1791.5), this is considered acceptable (Table 1).

The calculated bed elevation at the inlet section is 110.69 m.A.f., while the recorded value is 110.61 m.A.f. (Lanfranconi, 1882), so the model decimetre accurately reproduced the initial level. Regarding the values of the bed slope, the literature defines the slope upstream of Gönyű (rkm 1791.5) as 25-35 cm/km (Tőry, 1952), while the model gave this as 30 cm/km, which slopes within the range of the recorded. Downstream of the slope break, the literature specifies 8-9 cm/km (Tőry, 1952), while the model gave a slope of 8 cm/km (Table 1).

To validate the model, we also considered the calculated average grain sizes of the model, which are shown in Figure 6.

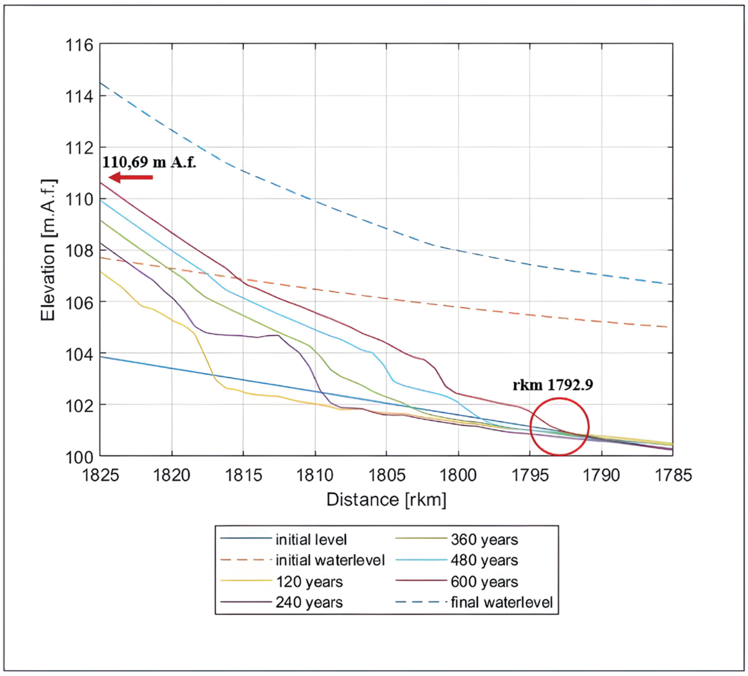

Fig. 6. Calculated longitudinal bed profiles

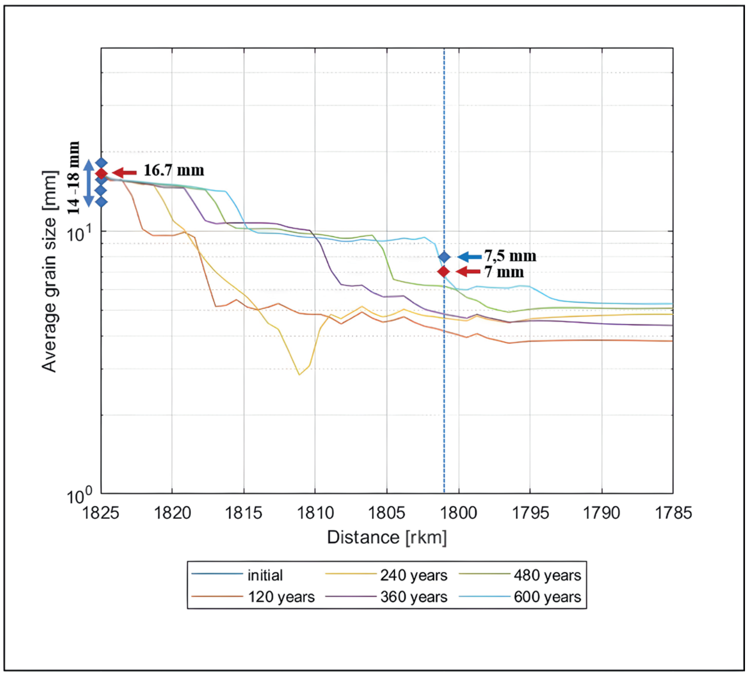

Fig. 7. Change in average grain size

Based on Figure 6, the model calculates 16.7 mm average bed material grain size in the initial section at Dunaremete (rkm 1825), which according to the literature was between 14-18 mm (Bogárdi, 1955; Tőry, 1952), so the model result is considered to be correct. For Nagybajcs (rkm 1801), the model's grain diameter is at 7 mm, which is also very close to the 7.5 mm found in the literature (Bogárdi, 1955).

Implementation of the interventions
Regulation of the braided river system

Prior to the regulation, the Upper Hungarian Danube was braided, and the aim of the regulation was to create a main riverbed that would provide better navigation conditions and improved flood protection. Figure 1 shows the braided character of the studied reach. The artificial cutoffs of the meanders have also shortened the length of the river and thus increased the slope.

The artificial cutoffs were implemented by the fact that the length of the river shortened, so the model accounted for this by reducing Δx cell size by a reduction factor, which was 0.9 (Tőry, 1952).

In addition, the width of the newly created main channel was known from the records. For the 19th century intervention plans, data were available on the extent to which certain sections were narrowed (Tőry, 1952). For the Dunaremete (rkm 1825) section, a planned width of 420 m was used, of which a 325 m channel width was achieved (Tőry, 1952). The model used a width of 325 m on this base.

Installation of the rows of wing dams in the model

The descriptions show that two sets of consecutive row of wing dams were built on the section under study between 1938 and 1944 (Tőry, 1952), one on the section between rkm 1807-1805 and the other on the Nagybajcs-Vének section (rkm 1802-1793). These two rows were included in the model as one continuous wing dam line, because between the two, gravel bars were formed, which narrowed the bed to a similar extent as the wing dams. For this reason, the entire section (rkm 1807-1793) had the same narrowed bed width, that is, it could be considered as a continuous section. The morphodynamic effects of wing dams were implemented in the model with additional equations, which we took from a foreign paper (Török & Parker, 2022). The core of the procedure is that the cross-section are considered to be divided by the wing dams into two parts: one of which will be the narrowed main channel and the other is the wing dam field. However, the hydraulic parameters of the two channels are not identical. The paper recommends using the following two equations to calculate the flow in the two channels. The Bernoulli equation is valid in the following form:

$$\frac{U_m^2}{2g} + z_{ws,m} = \frac{U_{wd}^2}{2g} + z_{ws,wd} \quad (8)$$

Moreover, the continuity equation also hold.

$$Q_{total} = Q_m + Q_{wd} = U_m H_m B_m + U_{wd} H_{wd} B_{wd} \quad (9)$$

By supplementing the original equations with these equations, the system of equations to be solved becomes definite, i.e. the 1D flow pattern in the narrowed main channel can be calculated for each cross-section

MODEL RESULTS

Regulation of the braided river system

Figure 7. shows longitudinal bed profiles from the time of the natural state (solid light blue line) and from the period after the artificial meander cutoffs (but before the wing dam installation). The calculation started from 1880, because that is when the cutoff work started and ended in 1910 for which there was a recorded longitudinal profile dataset. The model results show that the intervention caused about 2.5m bed incision within the affected section (rkm ~1810), while there was a significant, almost 1m rise in the bed level in the downstream of the interventions (downstream of rkm ~1810).

The difference between the calculated and measured bed levels, as well as their average for the section, were also calculated, which can be seen in Figure 8.

As shown in Figure 8, the period 1880-1910 shows a bed level decrease of 1 m on average. The average erosion was also calculated from the model results, resulting in a 1.13 m decrease. The difference between the records and the model results is 13cm, Which indicates the accuracy of the model.

Figure 9 shows the average size of the bed material. It can be seen that initially the average grain size decreased, that is, the bed became finer (orange line). This may be because the bed armor that had formed earlier was broke up as a result of the narrowing (Rákóczi, 2000). Later, however, the bed material became coarser, and eventually returned close to its original dimensions, meaning that the bed armor could develop again (continuous light blue line).

The breakup of the bed armor resulted in the deposition of a large amount of sediment on the downstream. Presumably, this deposition caused the increase of the water levels in the examined section (dashed lines in Figure 7). This flood protection risk caused the plan of wing dam installation in the section where significant sediment deposition took place.

Table 1. Summary table of validation

	Measured data	Calculated data
Dunaremete bed level	110.69 m.A. f	110.61 m.A. f
Location of the slope break	~rkm 1791.5 [Gönyű]	rkm 1792.1
Slope above the break	~25 cm/km – 35 cm/km	30 cm/km
Slope below the break	~ 8 cm/km – 9 cm/km	8 cm/km
Dunaremete average grain size	18 mm – 14 mm	16.7 mm
Nagybajcs average grain size	7.5 mm	7 mm

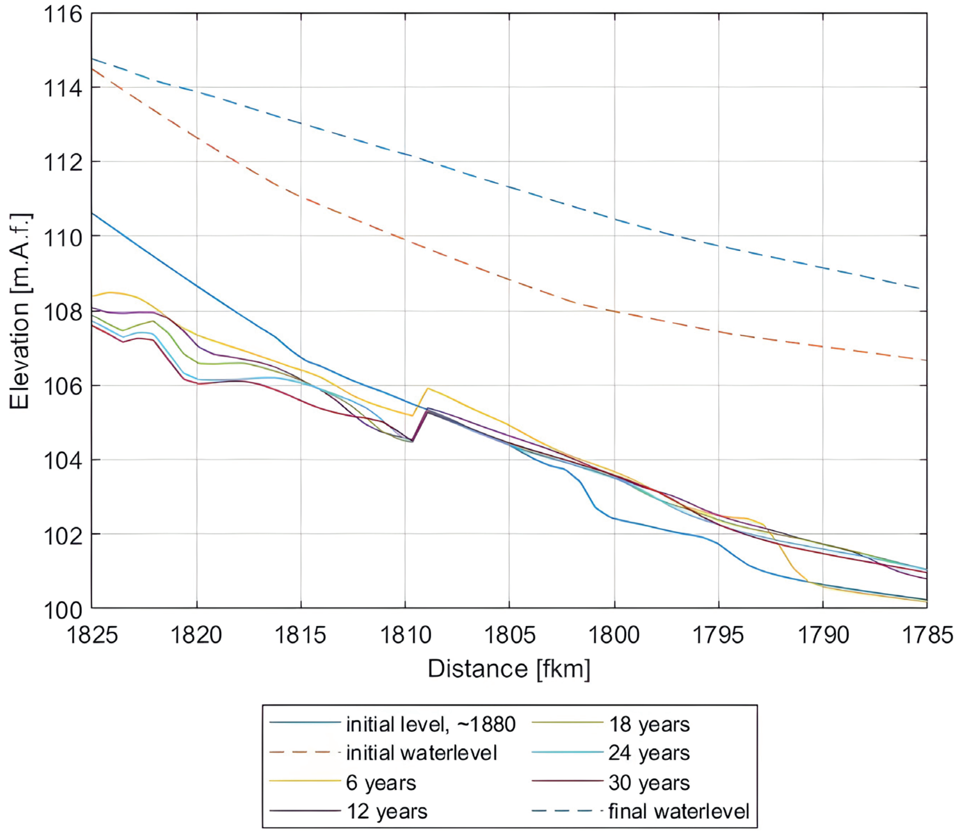

Fig. 8. Calculated longitudinal bed profiles– artificial cutoffs

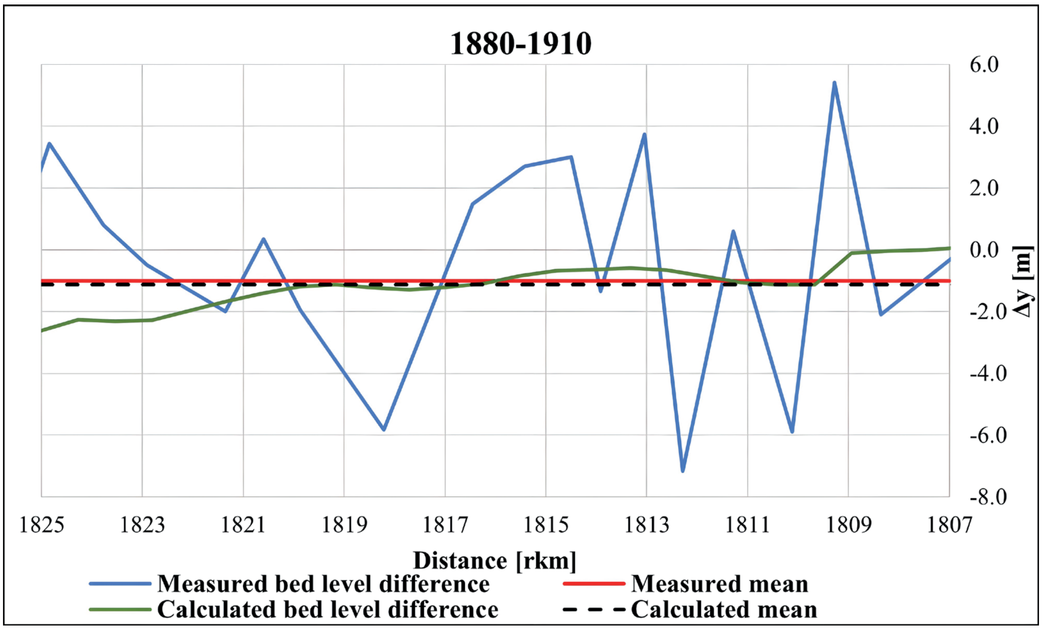

Fig. 9. Comparison of bed level differences – artificial cutoffs

Installation of the wing dam line in the model

The impact assessment of the wing dams was carried out for the following period. The model test was started from 1938, when the wing dams were actually installed on the section and was run until 1949 for which there was recorded longitudinal profile dataset. The result of the model run is shown in Figure 10.

The 1949 status is marked in red. It can be seen that with the construction of the wing dams, the riverbed is beginning to erode, which is one of the expected effects from wing dams. The model shows an average bed incision of about ~90 cm on average for the wing dam section after 10 years. Figure 11 shows the recorded bed changes along the investigated section.

As can be seen in Figure 11, the value of the average bed change is shown by the orange line, which shows an erosion of nearly 1.5 m. The value of the average bed change is shown by the orange line, which shows an erosion of nearly 1.5 m. Based on the topography (Figure 11), it can be seen that there are wing dams on both sides of the river in two places, which caused drastic local depressions (Nyiri et al. 2023). This also significantly affects the average bed erosion value. However, the model cannot take this local effect into account. For this reason, we ignored the two local erosion effects when compiling the results. The lines for the measured values in Figure 12 have already been constructed in this way.

Figure 12 shows that the average erosion rate of the riverbed in this section was 89cm, whereas the model

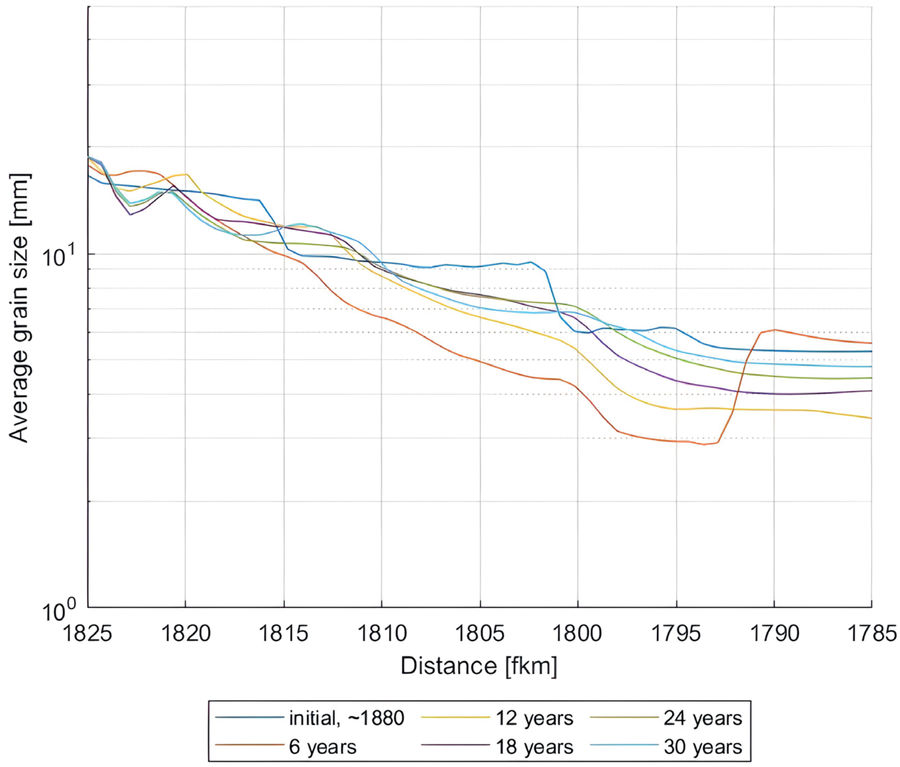

Fig. 10. Change in average grain diameter– artificial cutoffs

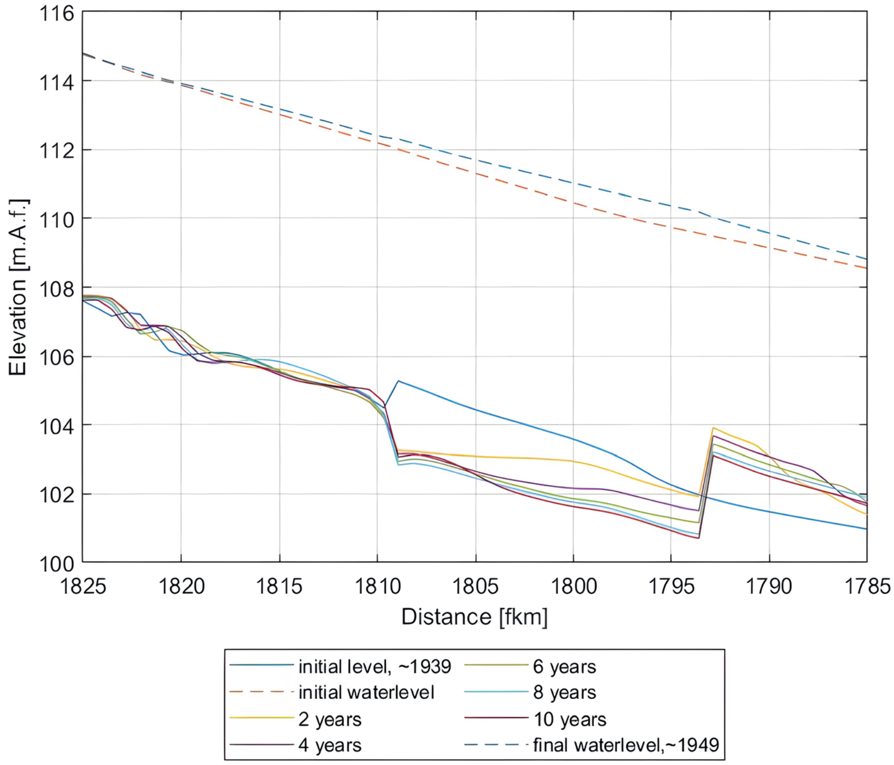

Fig. 11. Calculated longitudinal bed profiles– wing dam installation

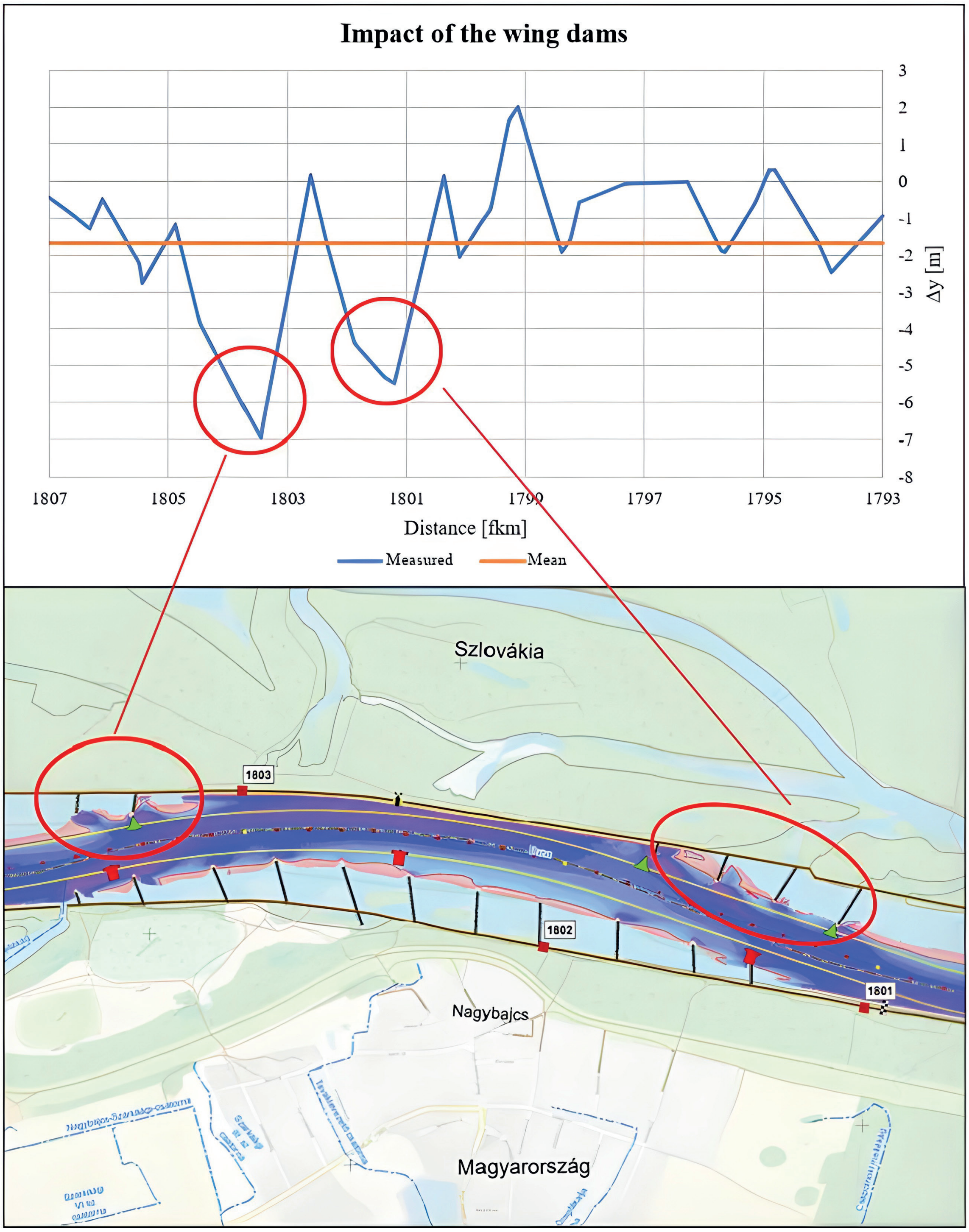

Fig. 12. Changes in bed level at the wing dam between 1938 and 1949 (ÉDUVIZIG, 2022)

resulted in 92cm. This means that there is only a difference of 3cm between the average values of the model and the recorded changes.

Figure 13 shows the change in the bed material. It can be seen that the bed material became significantly coarser in the section affected by the intervention, which indicates the development of the bed armor.

DISCUSSION

River control intervention with wing dams is a fairly common methodology. Finding examples of it all over the world, as a result of which the exploration of the morphodynamic reaction is an important research question. The most widespread methodology for the investigation is based on the statistical analysis of the measured parameters (bed level and water level). On this basis, it was shown, for example, in the case of the Mississippi, Missouri and Rhine rivers (Pinter et al. 2006), that the bed level clearly decreased due to the wing dams. The one we examined showed the same trend. In general, therefore, it is expected that the bed level will decrease. However, from the point of view of the examination of water levels, the expected trend is not so clear. In the case of the Mississippi and Missouri, the trend clearly showed rising water levels, at least in a couple of decades after installation (Pinter and Heine 2004). It has not yet been investigated how long this trend can be expected, or whether it may be followed by a downward trend. In the case of the Rhine River, however, no water level rise was observed. Although in our study we treated the results with reservations regarding the water levels, since they were not validated, we experienced an increasing trend.

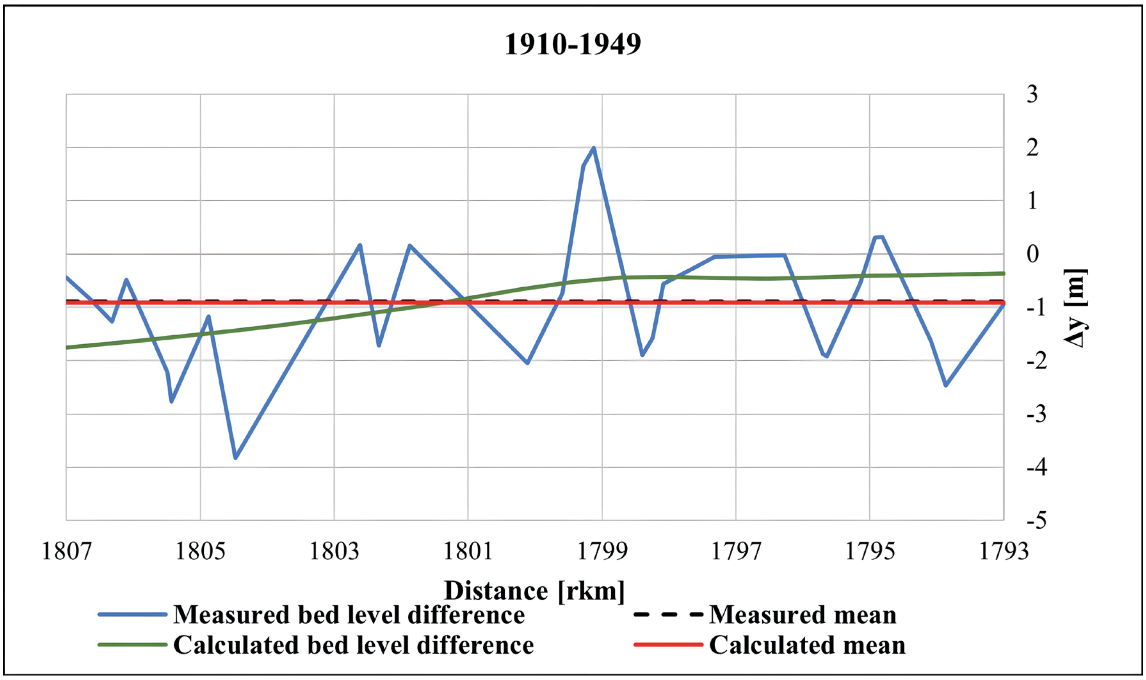

Fig. 13. Comparison of bed level differences – wing dam installation

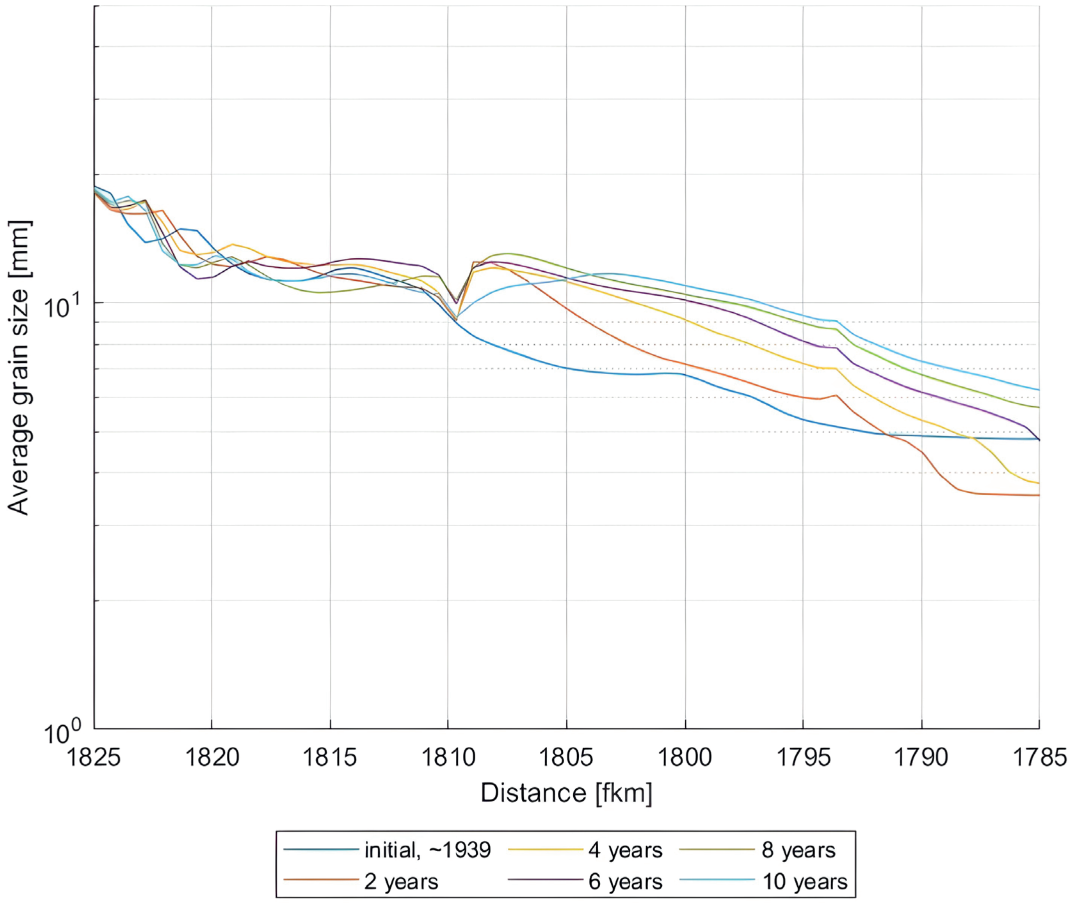

Fig. 14. Evolution of grain sizes

1D morphodynamic model presented in this study provides an opportunity for sensitivity tests and thus an investigation method to reveal the effects that cause water level changes can be revealed. That is, statistical analysis of measured water levels and a 1D morphodynamic model complement each other very well, even in studies of this kind.

CONCLUSIONS

Through the example of the Upper Hungarian Danube, we saw that there is a huge need for tools that can demonstrate the large spatial and temporal morphodynamic effects of artificial river control works, but there is no available means for this. Especially not for cases where the riverbed with a mixed grain composition can have such a complicated morphodynamic processes (bed armoring, selective erosion and deposition) that simpler sediment transport models cannot even be taken into account. For this reason, our goal was to develop and validate a tool capable of calculating the morphodynamic effects of various artificial river control interventions on a large spatial and temporal scale in the case of rivers with a mixed grain composition.

In our study, we investigated the morphodynamics of a selected section of the Upper Hungarian Danube, focusing on the effect of artificial interventions. The inlet section of the studied reach is Dunaremete (rkm 1825) and the outflow section is Dunaalmás (rkm 1752), with a longitudinal slope break located between these two sections in the vicinity of Gönyű (rkm ~1790). The development to a model which is able to take into account inhomogeneous bed material and bedload was crucial as bed armoring and selective erosion play an important role in forming the bed, including the sudden break in longitudinal profile (Holubová et al., 2015; Liedermann, 2017; Baranya et al., 2008). To gain this experience, we applied the sediment transport model developed by Wilcock and Crowe (2003) for mixed grain composition. A detailed literature search was carried out to be able to validate and calibrate our 1D model. The aim was to assess the impact of interventions with the model. Since the first intervention was river regulation in the late 19th century, it was necessary to have a pre-river regulation state. This state was estimated with the model in such a way that the results showed a good agreement with the location of the break in the longitudinal profile, the value of the upstream and downstream slope and the composition of the bed material. Based on these, on the one hand, the model was validated for the state before the interventions, and on the other hand, this is how we prepared the initial conditions for further model studies.

The first model study was the investigation of the artificial meander cut-offs in the 19th century. The intervention not only changed the bed geometry, but also the sediment transport, not to mention the shortening of the river. The model test showed that the average bed level decrease calculated from the literature was estimated quite well by the model, with only a 13 cm difference between the two average values. The nature of the phenomenon itself was well captured by the model. That is, the intervention caused an important bed level rise in the downstream sections, which eventually resulted in water level rise. Presumably, this triggered the second intervention on the deposited section.

In a second study, a wing dam row from Medve (1807 rkm) to almost Gönyű (1791.5 rkm) was fitted to the existing model. The effects of wing dams were taken into account using a procedure in which the narrowing of the main channel and the distribution of the flow discharge between the main channel and the wing dam field are considered. Based on the comparison of the modelled and measured bed changes, we concluded that the 1D model can reliably predict expected bed changes and changes in the bed material. For example, it can be seen that the bed material on the bottom of the spurs has been significantly refined.

The model tests showed that the presented 1D model is able to reliably assess the impact of the interventions. Keeping in mind the limitations of 1D modelling, we have presented a procedure that can complement the studies based on higher dimensional models. The presented tests exemplify that the 1D model can be a good alternative for the investigation of morphological processes of several decades or even centuries taking place in a river section of up to a few hundreds of kilometers. A higher-dimensional model is still necessary to examine local morphological features, for which the presented 1D model can provide good initial and boundary conditions, even in the case of a bed with a mixed grain composition.

Characterizing the conditions before river regulation, which was typically carried out at least a century ago in the case of large navigable rivers (e.g., Mississippi River), is a big challenge. In the case of such questions, the presented 1D morphological model-based study can play a major role.

The model can also help improve the design of future interventions.

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