# Summary of research results

## Introduction

The aim of this research project is to answer the question of how wing dams (or groins), which are often used to regulate large rivers, alter the high-water levels.

The wing dams narrow the bed as a riprap perpendicular to the bankline, which, if the bed change not considered, causes a rise in water level by reducing the cross-sectional area. A rise in water level is therefore inevitable in the period following the installation of the structures. Conversely, the narrowing of the riverbed will increase erosion, which will lead to a drop in the water level. The question is therefore what the combined effect of these two opposing effects will be.

This question is being asked on many rivers around the world. In the United States, for example, the Mississippi (middle and lower reaches) has been so heavily regulated by wing dam fields over the last century that the works no longer have a localized effect but are seen as a continuous intervention. The devastation of the Great Flood of '93 has brought the question to the fore: could the rising flood levels be caused by the wing dam fields? The relevance of the wing dam installation in Hungary is not negligible. Most notably, such structures can be found on the Danube, which started to be built in the first half of the 20th century. In the Upper Danube, in the Nagybajcs area of Hungary, there is a series of continuous wing dam fields where the effect of wing dams can influence the water level on a sectional scale.

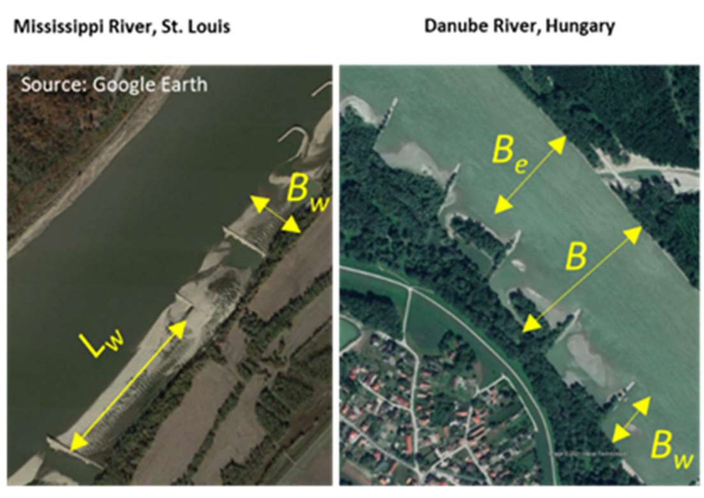


*Figure 1 - Rows of wing dams on the Mississippi (left) and the Upper Danube in Hungary (right)*

In this OTKA project, I focused on these two rivers to find the answer to the main question. In the project work, I relied on the continuous collaboration with Professor Gary Parker (University of Illinois at Urbana-Champaign).

## Literature research, data collection

I could manage to involve students in the research work and they were a great help in the literature research and data collection tasks. Through my contacts in the US, I was able to obtain several literature and data sources on Mississippi River, which I processed and organized in the form of a TDK (Scientific Student Conference) thesis with Vince Gieszer. I also conducted laboratory measurements with the student to measure the effect of wing dams. Although the test measurements gave promising results, unfortunately, since it is not possible to insert a substrate into the laboratory channel used, despite our attempts, we could not proceed with the experiments. With the help of Emese Nyiri, a student, we collected material on the domestic Danube from several books and publications, from the Water Archives, and from earlier VITUKI (Water Scientific Research Institute) sources (reliable data from 1882, i.e. before the river regulation works, were found).

The data sought were primarily the time, rate, construction method and typical dimensions of the works, as well as hydromorphological data on the river sections concerned, such as typical water discharge, water levels, bed slope, bed width, water depth, bed material, typical size and discharge of the bedload sediment. For both rivers, it was possible to obtain data set of sufficient quality to characterize the so-called dynamic equilibrium condition (a condition in which individual flood waves and low flow periods, although resulting in minor changes in the riverbed, cancel each other out over a longer time scale) for the condition prior to the installation of the wing dam fields. These data were suitable for parameterization of numerical models.

These studies provided the basis for the choice of the modeling methodology used and the definition of the variables to be investigated.

## Results

In presenting the results, I will not go into detail about the intermediate results that I have published in any form over the last three years.

In line with the original plan, I have based my investigations on 3D numerical flow and bed change model studies. I was able to start this part of the task following the literature research. The procedure involved investigating the morphodynamic effects of wing dam fields installed in different layouts in a schematic 5km long test channel. Based on the results, my co-researcher and I concluded that the 3D model variants differ in the width of the original bed, the length of the installed wing dams and the distance between successive wing dams.

In evaluating the results, I approximated the changes (bank geometry, flow structure, bed material) calculated in the respective model versions with average values for the whole channel. My aim was to finally characterize the relationships describing the resulting change trends at the reach scale, i.e. with a mean value specific to a reach. The results showed that the morphodynamic impact of the installation of wing dams can be reliably characterized by two parameters: the average effective channel narrowing for the section and the change in bed resistance due to flow obstructions and bed change. My aim was to explore relationships that can be used to explicitly express these two parameters for a given wing dam allocation. This was a major part of the three years of work, as I defined further and further 3D model variants in an iterative process based on the current partial results. The result was that the effective channel narrowing can be well approximated as a function of wing dam length, wing dam distance and original channel width. Based on these results, I searched for an empirical correlation, which I continuously updated as the number of model variants increased. Previous data were presented at conferences where the methodology of the procedure was discussed. The final version was presented at a conference in September this year.

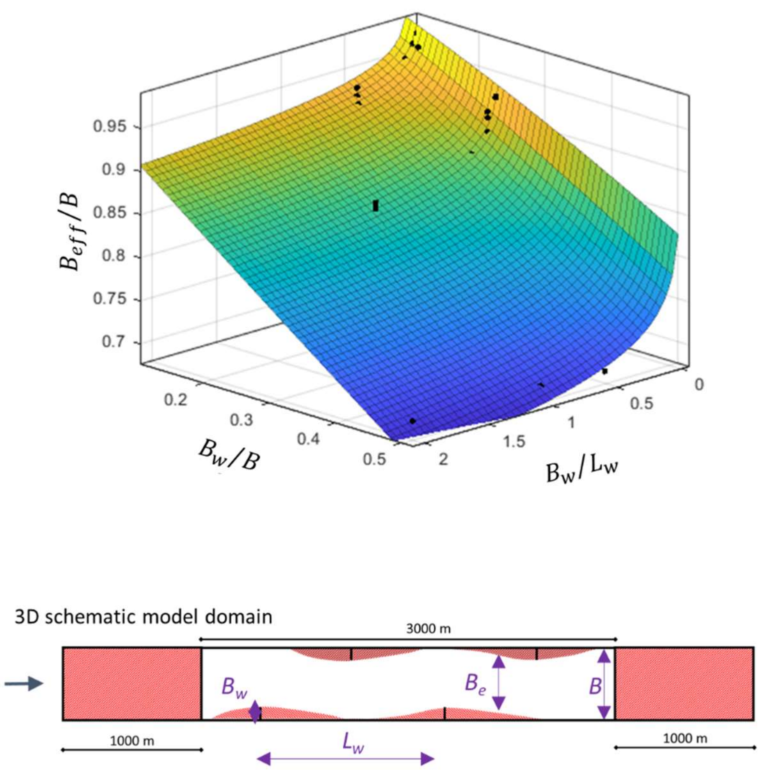


*Figure 2 - Determination of the effective pool constriction as a function of different wing dam placements ($B_{eff}$: effective channel width, B: original channel width, $B_w$: wing dam length, $L_w$: distance between successive wing dams)*

$$\frac{B_e}{B} = \left(-0.571\frac{B_w}{B} + 0.9808\right)\left(\frac{B_w}{L_w}\right)^{\left(-0.01808+\frac{B_w}{B}*-0.0791\right)} \quad (1)$$

The above figure and the relationship in Eq. 1 alone can be of great help in the optimal design of wing dam fields. Knowing the effective contraction, the expected stress increase and flow acceleration can be easily estimated.

The study of bed resistance proved to be a more complex task. The difficulty is that the installation of wing dams does not merely add static resistance to the flow. Einstein's partition states that the bed resistance ($C_f$, dimensionless bed resistance coefficient) can be decomposed into two components: one is the so-called skin friction ($C_{fs}$), which represents the resistance between the flow and the surface of the grains. The other component is caused by the bed forms ($C_{ff}$, form drag).

$$C_f = C_{fs} + C_{ff} \tag{2}$$

The resistance of a riverbed can be expressed by the following relationship:

$$C_f = \frac{\tau}{\rho U^2}, \tag{3}$$

Where $\tau$ is the bed shear stress, $\rho$ is the water density and $U$ is the dept-averaged flow velocity.

The constriction of the channel caused by the wing dams alters the flow structures, which may change the composition of the bed material at small scales, but more importantly, it also affects the size of the bedforms and hence the induced bed resistance. For this reason, I used Einstein partitioning to process the data and calculated the components of the resistance separately. The results showed that the composition of the sediment did not change significantly. However, the magnitude of the change in resistance caused by the bedforms is significant and depends on the ratio of water depth to the extent of the bedforms. The original Einstein partition cannot take this into account because it assumes constant bed resistance ($C_f$ is constant). For this reason, I have modified the original Einstein partition form Eq. 2 to look for a relationship between water depth and the ratio of roughness height (relative roughness height) using the following two relationship:

$$C_f = \left(8.1\left(\frac{H}{k_s}\right)^{1/6}\right)^{-2}, \tag{4}$$

where $H$ is the water depth and $k_s$ is the roughness height (a length-dimensional parameter expressing the vertical distance from the bed surface to which the surface roughness causes a no-flow zone, i.e. where velocity $v = 0$).

$$k_s = k_{s,\,skin} + k_{s,\,form\,drag} \tag{5}$$

The sediment transport models used give a concrete correlation for the surface roughness height ($k_{s,\,skin}$), so I was able to calculate it directly from the 3D model results. Thus, in Eq. 4 (extended by Eq. 5), only the roughness height ($k_{s,\,form\,drag}$) due to the bed forms was unknown, which I could express. I have not yet found a published example of this type of expression for Einstein's partition. I searched for a correlation between the resulting relative bedform roughness height ($k_{s,\,form\,drag}/H$) and the flow characteristics, and the best relationship was obtained as a function of Reynolds number ($Re_p = \sqrt{gRD_{50}}D_{50}/\nu$, where $g$ is the acceleration of gravity, $D_{50}$ is the average grain diameter of the bed material and $\nu$ is the kinematic viscosity of the water).

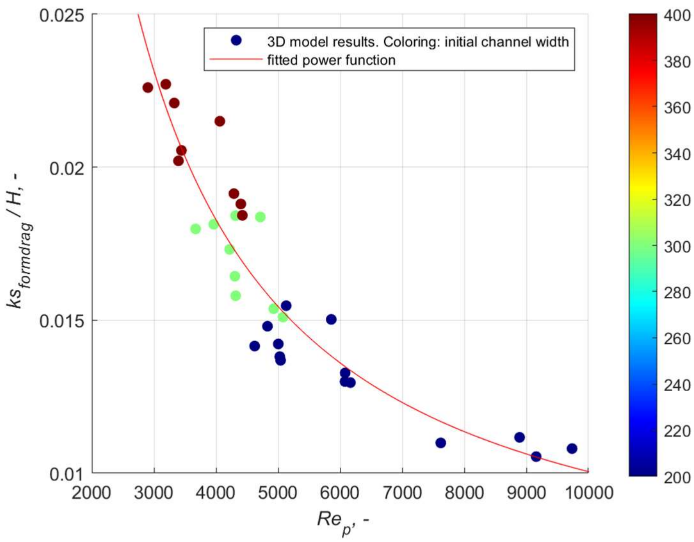


*Figure 3 - Relationship between roughness height due to relative bed form and Reynolds number*

The description of the relationship is of great importance, as it allows to describe precisely the dynamic change in the bed resistance due to the changing flow pattern during the process of bed change. This plays a key role in enabling the temporalization of the effects of the wing dams and the new dynamic equilibrium state to be investigated using a 1D numerical model. A major advantage of the 1D model compared to higher dimensional models is that, due to its low computational demand, the change over several centuries of a section of up to several hundred km can be calculated. To illustrate: in the 3D numerical model studies, the model run time for a 5km long test channel was 2-5 days, while the run time for a 1000 year bed change of a 1000km long section with a 1D morphodynamic model was 1 hour max.

In parallel with the 3D numerical modeling tasks, I worked on 1D numerical model building and development in the hope that the relationships revealed by the 3D results could be implemented in a 1D environment. For the Upper Danube in Hungary, I developed a 1D morphodynamic model with a student in the form of a TDK thesis. With the verified model we investigated the effects of interventions carried out in the last century and a half (meander cutting at the end of the 19th century, wing dam installation and the construction of the Bős Hydropower Plant). In that model, the impact of the wing dam installation was considered using an approximate method (the bank resistance caused by the wing dams was estimated with a constant value, the extent of the bed narrowing was also estimated with an approximate value). The results of these studies led to the construction of a well-documented and validated 1D model, which I used as a basis for estimating the water level change caused by the wing dams. I adopted the parameters developed and verified in previous collaborative work by Professor Gary Parker (An et al., 2021) on the Mississippi River.

The main results of the project are presented below. I have investigated how the construction of wing dam fields in the Mississippi River and the Upper Hungarian Danube River reach changes the high water levels. A fundamental morphodynamic difference between the two rivers is that the bed material of the Hungarian Danube is gravel-sand mixture ($D_{50} \approx 10,0mm$), which provides the opportunity for so-called bed armouring. The essence of this phenomenon is that the grain composition can vary spatially and temporally to create a bed surface from which the finer sand fractions disappear, resulting in a much more resistant bed surface. In contrast, bed material in the Mississippi River is homogeneous fine sand ($D_{50} \approx 0{,}4\,mm$) and therefore the bed stability (critical shear stress that determines the extent of erosion) cannot change.

The following figure illustrates the schematic channel design. For both rivers, I have used the same section length for comparability, which was 40 km in total. Only the downstream half of that length has been regulated by wing dams. In the initial, unregulated condition, the section is in a dynamic equilibrium state. In both cases, the outflow water level is constant and does not change with the water level.

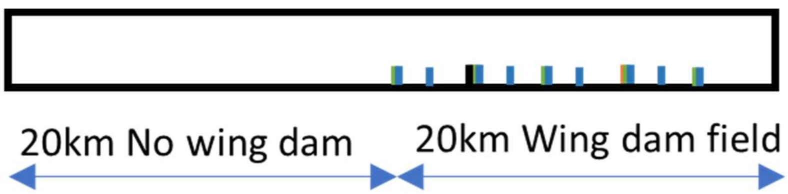


*Figure 4 - Schematic outline of the channel*

The figure below shows the calculated water level difference ("dz watersurface elevaton" axis) longitudinal sections ("distance" axis) for two rivers, for different wing dam allocations ("$B_{effective}/B$" axis). In all cases, I investigated the bankfull condition expecting that higher flow discharges undergo the same water level change assuming unchanged geometry of the floodplain. The models show 200 years of change.

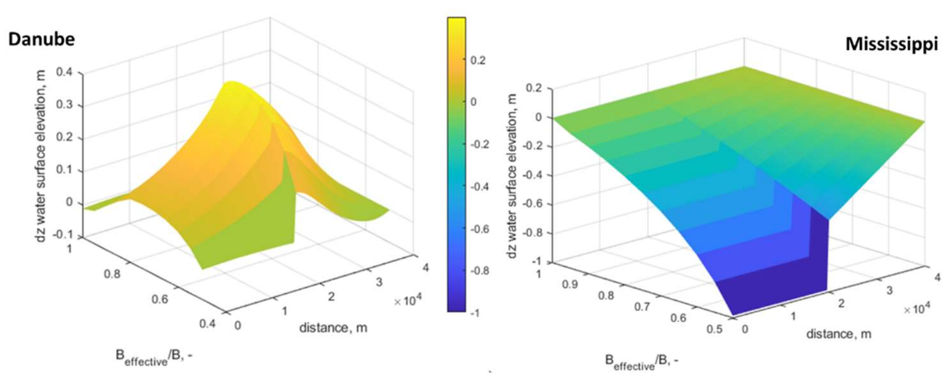


*Figure 5 - Changes in water level for the Danube (left) and the Mississippi (right) under different wing dam field allocations*

The Figure shows that the water level rises for the Danube for any spur design, but falls for the Mississippi River in all cases. In the case of the Danube, this is explained by the formation of the bed armor: the effect of the channel constriction is that the higher bed shear stress will create a more resistant bank surface, and therefore the equilibrium bed shear stress will be higher in the new equilibrium state compared to the original state (which also means higher bed slope and water level). The results also show that the highest water level rise is expected for the ~25% effective channel constriction.

For the Mississippi River, since the composition of the bed material does not change, I was able to explicitly derive the relation of the bankfull slope (S) to the new equilibrium condition, using a system of equations to describe the dynamic equilibrium condition (Parker, 2004):

$$S = C\left(B^{2/5}\right)\left(C_f^{\ 1/10}\right), \tag{6}$$

where $C = 7{,}27 * 10^{-6}$.

From the equation it can be concluded that the slope will definitely decrease in the case of wing dam installation (the value of $B$ will definitely decrease, and the 3D model results show that $C_f$ will typically decrease but will increase by a maximum of 5%). Since in a dynamic equilibrium state the bed slope is parallel to the water surface, the water surface slope will also decrease, which will eventually result in lower water levels.

For both rivers, however, it is true that the water depth increases, so that navigation conditions are definitely improved by the introduction of wing dams.

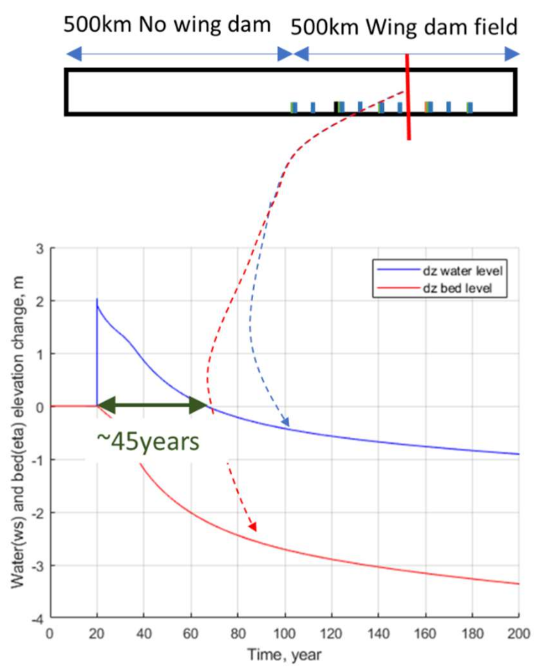


*Figure 6 - Time series of bed and water level changes calculated with a 1D model in a wing dam section of the lower Mississippi River (wing dams installed in year 20) - all installations at once*

Temporality plays a key role in the study of the process of changes in the riverbed and water level. This is illustrated in the Figure 6, where I consider a case where wing dams are installed in the lower half of a 1000km section of the Mississippi, which is a realistic approximation (An et al., 2021 & Brauer, 2011). Immediately at the moment of installation, a significant rise in water level is visible, which is observed for almost 45 years. Afterwards, however, the water levels are lower than without the spur, and the new dynamic equilibrium is not fully reached even after 200 years (the blue and red curves are not horizontal even after 200 years). The model results lead to the conclusion that since the rising and falling trends can last for a long time, we can experience a rise in the water level even in the Mississippi River (where water level drop is expected for the new equilibrium state) for many decades after the intervention.

In reality, the wing dams were built into the channel over nearly 60 years (Brauer, 2011). The figure below shows the result of a model scenario where the wing dams are installed on the designated 500km section over 60 years, at a constant construction pace, randomly selecting the current installation section. Based on the available data, this scenario, which best approximates reality, shows that the water level rise did not occur as a sudden rise in water levels, but as a nearly 30-year rising phase. This is followed by a slow decreasing trend, which falls below the original water levels nearly 70 years after the regulations began. This slow rising and falling water level change is consistent with the behavior of previous measured water level time series (Brauer, 2011). The prolonged construction also influences the bed change: due to varying longitudinal bed load discharge distribution, the bed change does not describe a monotonous downward trend during the construction period, but shows a varied behavior.

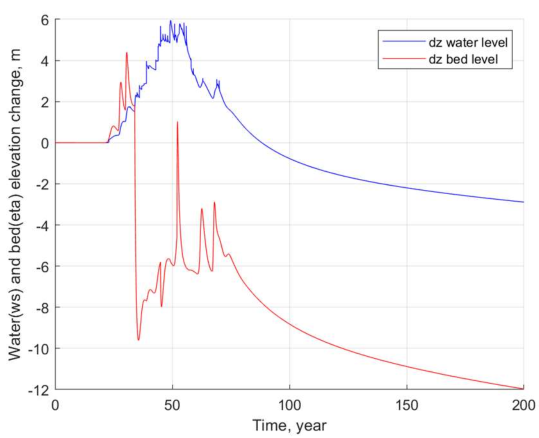


*Figure 7 - Time series of bed and water level changes calculated with a 1D model in a wing dam section of the lower Mississippi River (wing dams installed in year 20) – installation in 60 years*

For this project, Professor Gary Parker and I saw great potential in the use of the 1D model. For this reason, we started 1D model building and development from the initial phase of the project. In the process, we developed a method to implement the morphodynamic effects of wing dam fields in a 1D model. We also investigated how to account for the effect of bank stability. Although this study was initially considered as a minor side issue, in the end we obtained a very interesting and novel result in the analysis of the morphodynamic effect of riparian vegetation. We found that the role of the riparian vegetation is highly dependent on the bank material: if the bank, or rather the bed material, is a fine textured cohesive material (silt, fine sand), then the presence of vegetation (due to the weight of the trees) reduces stability, causing bank erosion and channel widening. On the contrary, if the bed material is coarser, granular soil, the vegetation (due to its root network) increases the stability of the bank, resulting in a narrowing of the bed. The results were finally published in Scientific Reports. The article was awarded the Pro Progressio Foundation's "BME's most important scientific publication of 2022". This study took a lot of time, including the publication process (the manuscript went through 1 review round in Nature

Geoscience and 2 review rounds in Nature - Communications Earth & Environment, which took more than two years in total).

The impact of river regulation on the Danube in Hungary over the last century and a half was studied with Emese Nyiri, which won her the 1st prize of the National Scientific Student Conference (OTDK I). A manuscript of the results is being prepared and is planned to be submitted to a Q1 journal (Water Resources Research), the foundational results were already published in the Hungarian journal called Hidrológiai Közlöny and in the bulletin of the XL National Meeting of the Hungarian Hydrological Society.

## More results

My colleague Balázs Sándor and I worked on the depth-averaged description of the complex flow in meanders. My role was to investigate the flow-bed interaction in meanders, i.e. to map the phenomenon describing the meandering character. We developed a mathematical model to investigate the curvature formation process and the "curvature lag effect" already known in meanders (there is a spatial offset between the maximum of curvature and the maximum of bank erosion in meanders: bank erosion is typically located downstream of the curvature). In the area of model application and model validation, we were greatly assisted by Kory Konsoer (Louisiana State University), whose field measurements in the meanders of the Wabash River in the US were used in our studies. The manuscript written by the three of us has been submitted to the journal Advances in Water Resources and is currently under review.

We aimed to further develop the 1D morphodynamic model with Professor Gary Parker. We are working on a description of the development of the chain of meanders. Of domestic relevance is the original straightening of the Tisza River. In the pre-regulated state, the Tisza was characterized as a highly meandering river, which was straightened by artificial meander cutoffs. It is not possible to assess the impact of river regulation without knowing the reference condition at the time. Our aim is to develop a large-scale model that allows reconstructing the morphodynamic state of the river in its contemporary, near-dynamic state. It will allow the spatial and temporal effects of interventions (similar to the effects of wing dam installation) to be carried out. I have chosen as a sample section the section of the Ipoly River near Hont, where a multitude of overdeveloped bends are found in their natural state. We have already carried out a multi-day measurement campaign involving several students to assess the bend development process, which will serve as a basis for the 1D model development. We are currently working on the model development task with student Benedek László Nagy.

The students who have joined the research project have received, besides my supervision, OTDK I, New National Excellence Program, TDK III, TDK II, Kontur István TDK Special Award, Fontus Scholarship (Blue Planet Foundation) excellence awards/scholarships for their research work which is integrally connected to the project.

## Change in the budget plan

The amount for students in the budget was not fully used up because the students received funding for their research from other grant sources (Fontus scholarships, New National Excellence Programme). I wanted to avoid double funding.

The amount set aside for Open Access publications was not necessary.

## Summary, outlook

In the design of this project, I set the goal to investigate water level changes caused by wing dams, mainly using a 3D numerical morphodynamic model. I have completed the work packages detailed in the research plan: exploring the morphodynamic conditions and wing dam placement variants to be investigated. Based on these, I performed different model versions. To process the results, I developed my own novel processing procedure so that the effect of each intervention variation could be characterized at the reach scale. An empirical correlation between hydraulic and morphological data was established, which allows to characterize the effect of each intervention in a simple way: the degree of channel narrowing and the relative bed resistance caused by the intervention can be calculated directly as a function of the hydraulic and wing dam placement parameters. By implementing the relationships in a self-developed 1D mofodynamic model, the large spatial and temporal effects of wing dams can be calculated. The results show that the bed material of the river under study determines the expected water level change in the new equilibrium bed: for sand bed rivers, the water level is expected to decrease, while for gravel bed rivers it is expected to increase. I have presented this using model verified for the Mississippi (sand bed) and the Upper Danube in Hungary (gravel bed). An important result is that for gravel bed rivers, the ~25% channel constriction causes the largest water level rise. The model results also show that in all cases the water level increases initially after the installation of the wing dam fields and then starts to decrease due to bed erosion. Reaching a new equilibrium state may take several decades or even centuries, depending on the dimensions of the river and the intervention.

The 1D morphodynamic model development was used to investigate the morphodynamic effects of riparian vegetation. The results were published in a Scientific Reports paper, which was awarded the Pro Progressio Foundation's "BME's Most Outstanding Scientific Communication of 2022". Due to a delay in the publication process outlined in the research plan, the publication of the results of the wing dam problem is still in progress.

I have further strengthened my collaboration with Professor Gary Parker on this project. I developed a successful application for the MTA Visiting Researcher Programme with the professor. He spent 4 months in our Research Group last year under this program, which gave a great boost to our joint studies. Through him I also managed to establish a professional relationship with Jeffrey Nittrouer (Texas Tech University), who accepted our invitation to visit our University for a week in October 2022. Joint research plans are being developed with him. With the help of Professor Parker, I contacted Kory Konsoer (Louisiana State University), with whom we have started joint studies on the morphodynamics of meandering rivers (we have a joint paper submitted to the journal Advances in Water Resources). On the domestic front, I contacted László Bertalan

(University of Debrecen), under whose leadership we submitted an OTKA proposal on the morphodynamic investigation of small rivers in Hungary in this year.

Working with students was an important pillar of the project. Successful applications for TDK and other grants are a good prove of fruitful collaborations. For the TDK conference in 2023, 3 students have applied with my topic and supervision. The students all did very useful work mainly in the fields of literature research, 1D morphodynamic model development and 1D morphodynamic investigation of the Upper Danube in Hungary. I would definitely like to continue the collaboration I have started with them.

The results of my research have been published in an informative article on the HUN-REN website in 2023 and I was a guest on a radio programme on Klubrádió - Green Club in February 2023. During these events I promoted the results of my project.

The present OTKA project specifically facilitated the development of my professional international relations, the foundation of successful joint work with students, and the development of further, internationally recognized research directions, in addition to the progress of the research work set out in the research plan.

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