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Significance of Time Dependence in The Effect of Wing Dams on Water Levels

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Abstract

Mainly in the 20th century, many wing dams (spur dikes, groins) were built worldwide, primarily to improve the navigability of rivers. As the wing dams narrow the riverbed, the water depth increases. However, the accelerated flow increases bed erosion, which in turn causes the bed level to decrease. It is not clear how the two effects affect water levels, especially at high water, when the water flows over the wing dams. The study is further complicated by considering the added resistance and thus the slope change caused by such interventions, which also affects the sediment transport and water levels. The impact of wing dams on water levels has been studied mainly by trend analysis of measured time series. Trends have shown that the water levels of flood discharges are increasing in rivers with wing dams. However, it not clear when and with what properties the new equilibrium will be reached.
In the present study, we used a schematic model for calculating bed change and flow in a 1D manner to analyze the Middle Mississippi River. We found that the installation causes a sudden substantial local erosion, causing a significant sediment surplus downstream. This phenomenon has a local effect on the bed level, which also can stimulate the backwater effect. The passage of the sediment wave can take centuries for Mississippi-scale rivers. Our model results show that until the new state is reached, the water level initially increases (following the trend analysis results), but later decreases.

Keywords: Wing dam; Flood; Sediment; 1D; Time dependence

1. INTRODUCTION

From the second part of the 18th century, attempts have been made to improve the navigability of rivers by installing wing dams (spur dikes). The narrowing of the riverbed forced the increase the water depth so that the navigable water depth could be higher and the navigation conditions could be ensured even in the low water period. Indeed, the desired effect was achieved as expected. On the other hand, at the beginning of the interventions, even less attention was paid to the processes induced by the appearance of the wing dams, which in turn can have an unfavorable effect, e.g., on flood protection. This problem has perhaps been in the spotlight the most since the Great Mississippi River Flood of 1993 (Pinter, 2005), in connection with which more and more attention is being paid to the impact of wing dams on floods.

Studies published so far are mainly based on long-term measured time series analysis (Watson, Biedenharn, & Thorne, 2013). For example, Pinter & Heine (2005) and Pinter, Thomas & Wlosinski (2001) have investigated the effect of wing dams on floods in the Missouri and Mississippi rivers. Many important conclusions can be drawn from the time series analysis, forming the basis for further studies. So, for example, a strong correlation between the extent of wing dam incorporation and water level change shows up. These results suggest that wing dams contributed to a rise in water level during floods.

Another applied approach used for investigating the effect of wing dams on water levels can be found in a study based on the Manning formula, which assumes a prismatic channel with steady parameters. Szilagyi et al. (2008) also worked on the assumption of steady parameters. However, it can be assumed that, e.g., the bed slope changes significantly over time due to the narrowing of the bed by wing dams and the time-varying nature of sediment yield.

Trend analyses do not provide an opportunity to examine the impact of multiple triggers separately. And more importantly, they do not offer any suggestions for the future, but only the extrapolation. The results obtained by trend analysis do not have a physical basis, and do not provide an answer as to how a particular trend will change in the future.

This study explores the effect of wing dams on a large scale of space and time using a 1D morphodynamic model.

2. METHODS

Our study is based on coupled sediment transport and hydraulic calculation in a 1D approach (Parker, 2006). A vital point of the method is the consideration of temporality. The eroded sediment amount at a given section in the channel is transferred downstream over time. Another substantial effect that the model can consider is the backwater effect. This way, it is possible to assess the impact of the downstream alluvial deposit caused by the eroded bed material on the upstream water level.

2.1 1D Morphodynamic Model

The hydraulic behavior is solved based on the backwater equation:

$$\frac{\partial H}{\partial x} = \frac{S - C_f \frac{q_w^2}{gH^3}}{1 - \frac{q_w^2}{gH^3}} \quad [1]$$

where H is the water depth, x is the streamwise direction, S is the bed slope ($S = -\frac{\partial \eta}{\partial x}$), C_f is the dimensionless bed resistance coefficient, q_w is the water discharge per unit width and g is the acceleration of gravity.

Bed shear stress can be calculated as follows.

$$\tau_b = \rho C_f U^2 = \rho C_f \frac{q_w^2}{H^2} \quad [2]$$

where U is the cross-sectionally averaged water velocity.

The Shields number of sediment mobility can be expressed as:

$$\tau^* = \frac{C_f q_w^2}{RgDH^2} \quad [3]$$

where D is the grain size.

The sediment transport rate can be estimated as a function of the bed shear stress or Shields number. In our calculation, we used the original Engelund-Hansen (OEH) formulation (An et al., 2021), which takes the form (considering only one grain size):

$$q^* = 0.05(\tau^*)^{2.5} \quad [4]$$

where q^* is the dimensionless sediment transport rate (Einstein number).

Finally, the bed elevation was calculated based on the difference of the consecutive cross-sectional sediment transport rates, according to the Exner equation:

$$(1 - \lambda)\frac{\partial \eta}{\partial t} = \frac{\partial q_t}{\partial x} I_f \quad [5]$$

where λ is the porosity of bed, η is the bed elevation, q_t is the volumetric sediment transport rate of bed material load per unit width and I_f is a flood intermittency factor (denotes the part of the time that the bankfull water flow carries as much sediment as the actual annual water flow series does) (Paola, Heller, & Angevinet, 1992).

2.2 Implementation of the Effect of Wing Dams in A 1D Environment

Considering the wing dam (groin) fields (e.g. on one side of the channel, as drawn below), we assumed that the channel between the wing dams forms a separate channel (B_{wd}) in addition to the main channel (B_m)

constricted by the groin field. Energy equality ensures the connection between the two channels flowing in parallel, i.e., Bernoulli's principle holds. A sketch of the model can be seen in Figure 1.

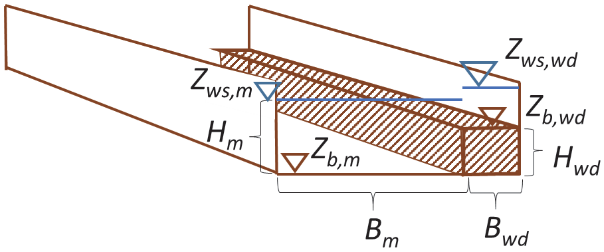

Figure 1. A sketch of how the groin field is installed in the model: the main channel and the channel region designated by region above the top of the wing dams (secondary channel) form two parallel channels. The channels can be characterized by different hydraulic parameters (H, U and C_f).

Further approximations are assumed:

- The original channel width is equal to the width of the narrowed main channel and groin field:

$$B_{initial} = B_m + B_{wd}. \quad [6]$$

- The bed level between the wing dams is the same as the level of the wing dams. I.e., the groin field is filled with sediment. This assumption gives the following water depths (see Figure 1):

$$H_m = z_{ws,m} - z_{b,m} \quad [7]$$

and

$$H_{wd} = z_{ws,wd} - z_{b,wd}. \quad [8]$$

- The atmospheric pressure on the water surface is the same in both channels.

Based on these considerations, Bernoulli's equation holds in the following form:

$$\frac{U_m^2}{2g} + z_{ws,m} = \frac{U_{wd}^2}{2g} + z_{ws,wd} \quad [9]$$

Furthermore, the fluid continuity equation also holds, i.e., the total water flow (total water flow discharge upstream or downstream the groin field) is equal to the sum of the flow discharges flowing in the two channels:

$$Q_{total} = Q_m + Q_{wd} = U_m H_m B_m + U_{wd} H_{wd} B_{wd} \quad [10]$$

Eq. [9] and Eq. [10] express the condition that the total water flow discharge is distributed in the two channels in such a way that Bernoulli's principle is satisfied in the cross-section. The hydraulic parameters can be calculated accordingly. The model, therefore, estimates the following iteration cycle within a hydrodynamic calculation step for one cross-section, and repeats it until the check in step 3 is satisfied:

i. Assuming a water flow discharge distribution between the two channels.
ii. Calculating the water level for both channels based on Eq. [1].
iii. Checking step according to Eq. [9].

2.3 Model Parameterization, Boundary and Initial Conditions

The 1D morphodynamic model concept was applied to the middle Mississippi River. This was done according to the paper by An et al. (An et al., 2021). In the paper, a 1,000km long (equivalent to the section between Cairo, 1,536 rkm - and Knox Landing, 506 rkm) schematized 1D morphodynamic model was established. Its parameters are described in Table 1.

These parameters applying the OEH sediment transport formulation result in an equilibrium bed slope (ignoring the wing dams) of $7x10^{-6}$ and an equilibrium bankfull water depth of 19.10m. We took this parameterization and the morphodynamic state as initial conditions in our study. We did not change the inlet and outlet conditions regarding the boundary conditions, so the water flow, sediment load, and outlet water level also remain constant.

Table 1. The applied model parameters, based on An et al. (An et al., 2021)

PARRAMETER	VALUE
Channel length, L	1,000km
Channel width, B	1,100m
Dimensionless bed resistance coefficient, C_f	0.0047
Flow discharge per unit width, q_w	31.82m^2/s
Flood intermittency factor, I_f	0.34
Equilibrium annual bed material load	58.5Mt
Characteristic grain size, D	0.426mm
Submerged specific gravity of sediment, R	1.65
Porosity of bed deposit, λ_p	0.4
Cell size, Δx	10km
Computational time step	10^{-5}year

During the various runs reported below, all we changed compared to the initial state was placing the groin fields into the channel.

In regard to the method of wing dam installation, three cases were distinguished. In the first case, the wing dams are installed simultaneously along the entire length of the channel, in one time step. In the other two cases, a construction pace was given, P (km/year), which indicates the length of the channel to be installed within one year. In one case, the installation starts from the inlet section and heads downstream. In the other case, just the opposite, the installation begins at the outlet and heads upstream. P takes the realistic constant value of 100 km/year.

Furthermore, the assumed length of a wing dam is 150m perpendicular to the river banks, i.e., with wing dam installation, the initial main channel (1,100m) is divided into a 950m and a 150m channel in the model. The level of the top of the wing dams was assumed to be equal to the level set by the initial bankfull water depth, which did not change over time.

3. RESULTS

Using the first model, we examined the case where the wing dams were installed simultaneously along the entire channel after ten years. An equilibrium state preceded it.

The results are shown in Figure 2. The four lines in each panel of the figure correspond to the time variation of a parameter (e.g. change in water surface elevation) at four distances x downstream of the upstream end of the reach: $x/L = 0.1, 0.4, 0.6$ and 0.9, where again L is total reach length. It can be seen that change in bed levels, water levels, local sediment load, and bed slope in all sections occurred immediately after the wing dams were installed. The intervention will initially increase water levels. However, the initial rise in water level is replaced by a step decrease. At least 50 years must elapse before the initial water levels are reached, i.e., processes that can be realized at a decades-long scale.

The examination of sediment load reveals that erosion caused by interventions significantly increases the sediment transport rate. The sediment yield of the lower sections can be up to 120% of the previous equilibrium yield for decades. This has a significant effect on local morphodynamic conditions.

The bed slope time series also show changes over many decades, with the same trend as observed in the sediment load figure. Based on this, we can conclude that when the new equilibrium state is reached ($Q_{b\,(t)}/Q_{b\,initial} = 1$) the bed slope will be smaller than the initial one ($S = 1.4 * 10^{-4}$), as indicated by the green and red curves). This is in accordance with expectations: as with the exact sediment yield, the equilibrium bed slope will be smaller for a narrower channel (Dunne & Jerolmack, 2020).

Figure 3 represents the model results when the modeled 2000 year time length is long enough to reach the new equilibrium state. The model setup does not differ from the model indicated in Figure 2.

The results mainly allow for qualitative analysis, and they are not suitable for the quantitative analysis of changes in water levels. According to this, it will take centuries, even millennia, to reach a new equilibrium state. This is the required duration for sediment from bed changes due to the construction of wing dams to be washed out from the 1000 km long reach length. Another significant result is that the new equilibrium water levels are lower than the original levels at all points in the channel.

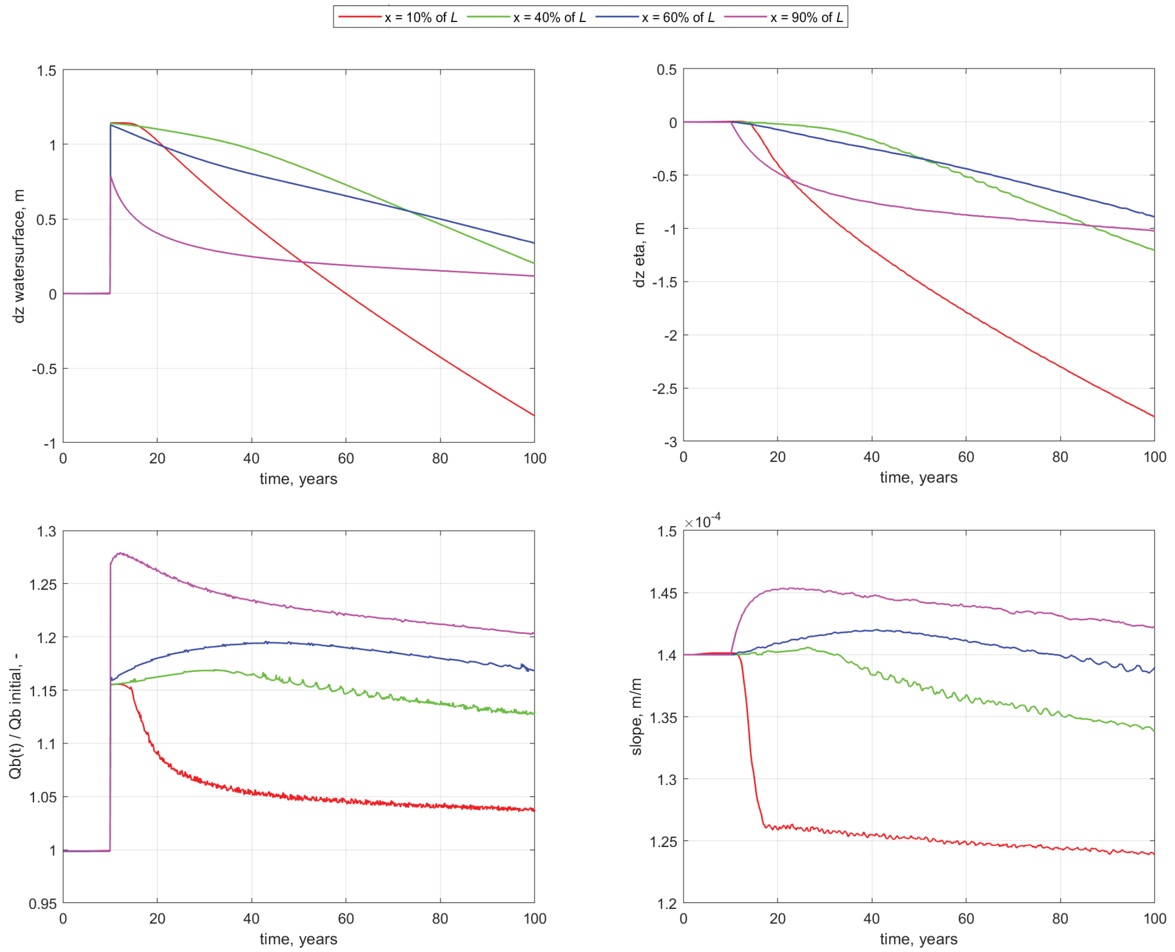

Figure 2. Water level change (top left), bed change (top right), sediment load change (bottom left), and bed slope change (bottom right) time series. The placement of the wing dams took place at an instant, after the 10th year, throughout the whole channel. Here x denotes distance downstream of the upstream end of the model. Thus "$x = 10\%\ of\ L$" denotes the streamwise location of a point that is located at 10% of the reach length downstream of the origin.

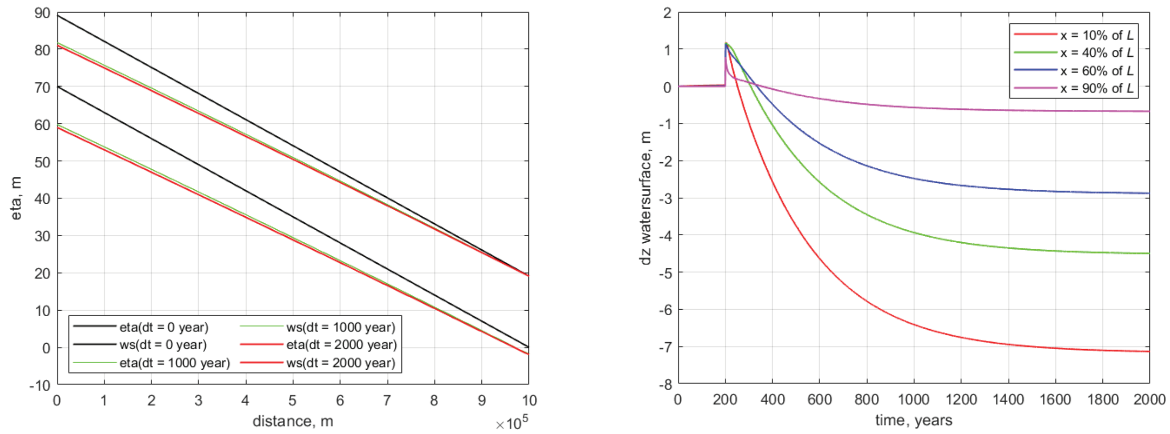

Figure 3. Bed- and water level profiles (left) and water level change time series (right). The placement of the wing dams took place at an instant, after the 200th year, throughout the whole channel. The new equilibrium state develops by 2000 years.

The results of the two installations in opposite directions (upstream to downstream versus downstream to upstream) are shown in Figure 4. The difference in water levels is significant: in the decades after installation, the rise in water level can be almost double if the installation direction is downstream. However, there is no such similar difference in bed change. Thus, the change in water levels is not caused solely by the evolution of the local bed level.

Sediment load time series show that values change very slowly after nearly a decade. The time-series do not reach the initial sediment yield (demonstrated by a value of 1) in a century, i.e., no new equilibrium is reached in 100 years.

The bed slope time series shows a similar trend. However, after a strongly varying period of nearly a decade after installation, a slow but marked monotonous declining trend can be identified.

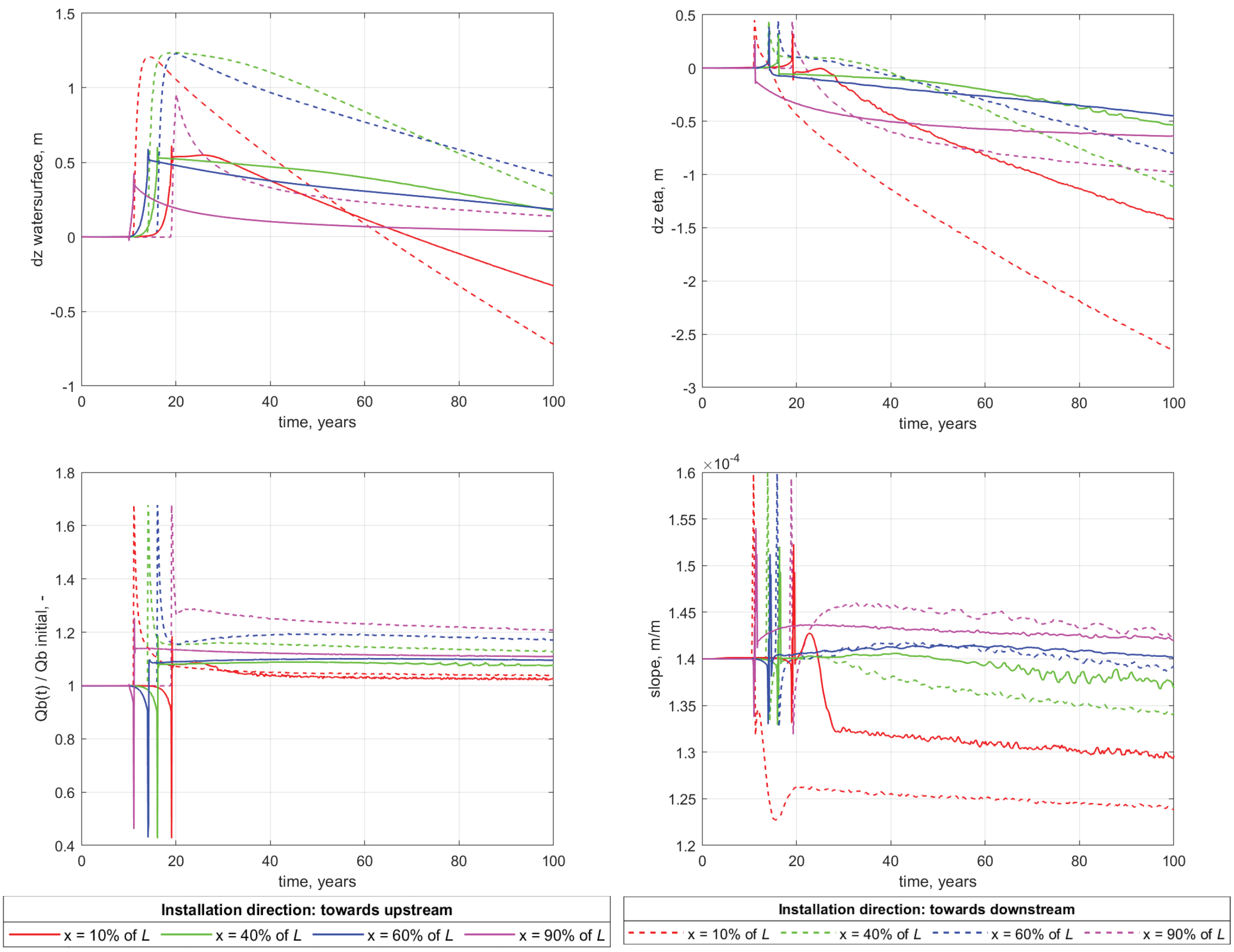

Figure 4. Water level change (top left), bed change (top right), sediment load change (bottom left), and bed slope change (bottom right) time series. The placement of the wing dams began after the 10th year. The installation was carried out at a 10km/year construction pace. In one case (solid lines), the installation proceeded from the outflow section in the upstream direction. In the other case (dashed line), the construction moved opposite, starting from the inflow section. The notation "$x = 10\%\ of\ L$" etc. is explained in the caption of Figure 2.

4. DISCUSSION AND CONCLUSIONS

Our study points to the vital role of temporality in studying the morphodynamic effects of wing dams. Significant changes in bed and water levels occur with the installation of groin fields. A precise quantitative analysis of water level changes cannot be attempted based on our study. But a new result is that a slow declining trend follows a rapid increasing trend in water levels. That is, changes over time are significant because of the characteristics too. Therefore, the use of steady models can be misleading in examining the impact of wing dams on water levels. Substantial changes in sediment load affect the bed level and water level in space and time, which influences the water levels of more distant sections via backwater.

Based on all the cases modelled here, it can be seen that even the best-designed intervention pace takes decades to reach the highest water levels. After that, water levels will drop significantly, which will take decades to be realized! It may take up to a millennium for a whole new state of equilibrium to emerge. This suggests that the impact of the installation of wing dams may be felt even after several centuries in the case of a Mississippi-sized river. However, in reality, the actual and new equilibrium water levels are not solely determined by the wing dams. This would only be the case if, for centuries, no effects other than wing dams took effect. Thus it cannot be stated that the water level is lower than the initial one at the final new equilibrium state. This is because other phenomena (e.g., dams, sea-level change, climate change, etc.) are also known to impact water levels significantly.

However, the results suggest that there is no clear answer to whether wing dams raise or lower water levels in the case of Mississippi-sized rivers. The answer depends on how long it has taken after installation. In the case of a real test, it is also necessary to specify the pace of wing dam construction and possible abrasion of wing dams. It is possible to refine our study by taking more precise parameters (width of wing dams, elevation of wing dams) and further factors into account. For example, it would be necessary to specify the channel resistance of the secondary channel contributed by the wing dams (Yossef, 2004), even based on 3D bed change calculations (Török & Parker, 2021). Furthermore, sediment trapping of groin fields can significantly affect the temporality of downstream sediment loading and the backwater effect.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

An, C., Gong, Z., Naito, K., Parker, G., Hassan, M. A., Ma, H., & Fu, X. (2021). Grain Size-Specific Engelund-Hansen Type Relation for Bed Material Load in Sand-Bed Rivers, With Application to the Mississippi River. *Water Resources Research*, *57*(2), 1–25. https://doi.org/10.1029/2020WR027517

Dunne, K. B. J., & Jerolmack, D. J. (2020). What sets river width? *Science Advances*, *6*(41), 1–9. https://doi.org/10.1126/sciadv.abc1505

Paola, C., Heller, P. L., & Angevinet, C. L. (1992). The large-scale dynamics of grain-size variation in alluvial basins, 2: Application to syntectonic conglomerate. *Basin Research*, *4*(2), 91–102. https://doi.org/10.1111/j.1365-2117.1992.tb00146.x

Parker, G. (2006). *1D Sediment Transport Morphodynamics with applications To Rivers and Turbidity Currents*.

Pinter, N. (2005). One step forward, two steps back on U.S. Floodplains. *SCIENCE*, *308*(5719), 207–209. https://doi.org/10.1126/science.1108411

Pinter, N., & Heine, R. A. (2005). Hydrodynamic and morphodynamic response to river engineering documented by fixed-discharge analysis, Lower Missouri River, USA. *Journal of Hydrology*, *302*(1–4), 70–91. https://doi.org/10.1016/j.jhydrol.2004.06.039

Pinter, N., Thomas, R., & Wlosinski, J. H. (2001). Assessing flood hazard on dynamic rivers. *Eos*, *82*(31). https://doi.org/10.1029/01EO00199

Szilagyi, J., Pinter, N., & Venczel, R. (2008). Application of a Routing Model for Detecting Channel Flow Changes with Minimal Data. *Journal of Hydrologic Engineering*, *13*(6), 521–526. https://doi.org/10.1061/(asce)1084-0699(2008)13:6(521)

Török, G. T., & Parker, G. (2021). Investigation of the impact of river interventions on fluvial morphodynamics. In I. W. Seo, J. H. Hwang, Y. S. Park, & S. Kwon (Eds.), *9th Interventional Symposium on Environmental Hydraulics* (pp. 104–105). Seoul, Republic of Korea.

Watson, C. C., Biedenharn, D. S., & Thorne, C. R. (2013). Analysis of the Impacts of Dikes on Flood Stages in the Middle Mississippi River. *Journal of Hydraulic Engineering*, *139*(10), 1071–1078. https://doi.org/10.1061/(asce)hy.1943-7900.0000786

Yossef, M. (2004). The effect of the submergence level on the resistance of groynes - an experimental investigation. In *The 6th Int. Conf. on Hydroscience and Engineering (ICHE-2004)*. Brisbane, Australia.

