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Paper 31 - Optimizing design of river training works using 3-dimensional flow simulations

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ABSTRACT: In past centuries, many rivers worldwide have been engineered to mitigate flood threat and to facilitate river navigation needs. The constructed river training works have regularly proven to be effective in maintaining depth and position of the main channel which is crucial for navigation purposes, but after years of operation some of the existing structures have become outdated and require design updates. In some cases the designs require updates because of changed conditions in the river, in other cases because of changed management objectives or because of new insights into flow-structure interactions. In this study, we give examples of why river engineering works may require design updates and demonstrate how 3-dimensional flow simulations may aid in achieving improved designs that serve navigation needs and additional river management goals.

1 INTRODUCTION

The Rhine River in Europe and the Mississippi River in the U.S. both have a long history of engineering efforts to stabilize the rivers main channel and to facilitate safe and efficient river navigation. Federal funding of navigation improvements along the Mississippi River and its navigable tributaries began in 1824 with the passage of the first River and Harbors Bill. This bill primarily provided money for the removal of large woody debris (snags) and modest improvement of ports along the Mississippi and Ohio Rivers. Subsequent River and Harbor Bills brought the first federal funding of river training structures to the Mississippi River in the late 1830s. The purpose of these structures was to maintain the width and depth of navigation channel in order to keep river traffic going, which was a crucial means transportation during the past two centuries and remains so today. As of 2005, the Mississippi and its tributaries were attributed with handling 624 tons of freight annually, having value of more than $70 billion dollars (Kruse et al., 2009).

The Rhine River in the Netherlands has an even longer history of river training works. Early efforts date back to 1671, from just before the period of the Franco-Dutch war (1672-1678). In those times, the River Rhine was an important part of the Dutch Defense Waterline, but the river was not functioning as desired due to relatively low river flows. The famous Dutch scientists Christian Huygens and Johannes Hudde were called upon to help in managing and redesigning the river and in doing so laid the foundations of modernriver engineering (Van de Ven, 1976). In the 19th and 20th centuries extensive engineering works of the Rhine branches lead to the regulated river as it still largely looks today, now having a fixed position and standardized widths and depths (Van de Ven, 2004). Only after severe flood threats at the end of the 20th century it became clear that some regulation works had restricted the river too much, and that it was now necessary to reverse some of the earlier regulation works to reduce flood risk. Subsequently, the devised Room for the River program included measures such as removal of obstructions, creating additional flow and storage areas, while stimulating spatial quality and maintaining suitable conditions for river navigation (to be completed by 2015, see also www.roomfortheriver.nl).

Because of the apparent importance of river training structures in rivers as the Mississippi and the Rhine here we summarize the different functions and side-effects that river training structures may have. Next, we argue that with the availability of modern investigation techniques we should strive for multi-functional use in their design. Examples are given of traditional and modern designs that aim to provide such multi-functional uses. Next, we show how detailed 3D flow simulations around training structures can aid to further optimize their functioning.

2 FUNCTIONS AND IMPACTS OF TRAINING WORKS

2.1 *Channel stability and bank protection*

Traditionally, the primary function of river groynes or similar training works were the stabilization of the river bed by bank protection and the extraction of land- and building material by sediment collection in the groyne fields. With increasing importance of shipping throughout history, groynes more importantly served to maintain sufficient water depths for navigation by deepening the river channel through the narrowing of the flow profile.

2.2 *Breaking-up ice cover*

In the Netherlands, one of the earlier intended functions of groynes was to break up ice-cover during winter floods. An extensive river improvement plan was initiated after the disastrous winter floods of 1809 and 1820 to prevent formation of ice dams in the river Rhine. Measures included that the river's main channel would get a specified (normalized) width, and side channels were closed off to equalize ice-flow capacity and to prevent ice storages in the floodplain from entering into the main channel. The normalized width was achieved by introducing river groynes, of which the crest heights were designed to approximately equal the average flood level under ice conditions. Consequently, in the upstream part of the river the groyne crests were designed relatively higher, because the surface slope under ice conditions is steeper than under normal flow conditions. The side-slopes were chosen at 1:2 along both sides of the groyne. On the upstream side, this slope appeared necessary to lift up and break-up the ice deck. On the downstream side, the steep slope served to create flow turbulence strong enough to prevent attachment of ice onto this slope and to counter formation of ice dams in the downstream groyne field.

After 1964 the river Rhine did not freeze anymore because of thermal discharges. It is expected that in the future these thermal discharges will decrease and that, therefore, ice formation may again become an important issue on the River Rhine.

2.3 *Impacts on flood levels*

A side-effect of groynes is that they increase roughness of the river by causing energy loss of the flow in the groyne fields. If groynes become submerged, vertical mixing patterns arise in the wake of the submerged groynes. These recirculating flows in the vertical plane feed on the flow energy from the bulk flow field, causing the overall flow velocity to slow down and, subsequently, the water level to rise (e.g Azinfar & Kells, 2011). The size and intensity of the recirculation zones is influenced by the side-slopes of the groyne (e.g. RIZA, 2001; Bloemberg, 2001).

A difficulty in quantifying the impact of groynes on flood levels, is that in the field there is no suitable reference situation to which to compare the empirical data to. Furthermore, making estimates on absolute flood level impacts through modeling studies is also difficult because of the complexity of the hydrodynamics and morphodynamics involved. As a result, the degree of flood level rise due to training structures is still under debate. In particular for the case of the Middle Mississippi River the discussion is still ongoing, which mostly centers on the question of reliability of empirical data (see USGAO 2011; Huthoff et al. 2013). In contrast, in the Netherlands, the Dutch Waterway authorities have generally accepted that groynes significantly impact flood levels, which led to the inclusion of groyne lowering as one of the flood mitigation measures within the Room for the River program.

2.4 *Ecological value*

It has also been claimed that river training structures enhance physical-aquatic habitat heterogeneity and provide needed habitat niches for some endangerd species and other aquatic organisms (for the situation along the Middle Mississippi see Gordon, 2004; Davinroy et al., 2011). However it appears to be difficult to confirm or quantify these claims (Remo et al. in press).

3 DESIGN EXAMPLES

3.1 *Traditional designs*

The most common river training structures found along the free flowing reaches of the Mississippi River (i.e., not pooled for navigation by locks and dams) are groynes (also known as spur dikes or wing dikes), bendway weirs, L-head dikes and chevron dikes (i.e. U-shaped dikes). Groynes are generally rock structures placed approximately perpendicular to the bank line to focus flow into a single channel. Bendway weirs are underwater rock structures emplaced in the outside bend of a channel and angled ~30° upstream of a line perpendicular to the bank. The purpose of these structures is to focus flow into the center of the channel around bends in order to maintain adequate channel depths and widths for navigation. L-head dikes are groynes with a section extending downstream from the channel and generally parallel to the channel line. Like groynes, the purpose of L-head dikes is to focus flow into a single channel (Parchure, 2005). Chevron dikes are U-shaped rock structures in which the closed end faces upstream. The purpose of chevron dike is to focus flow in order to deepen the navigation channel and reduce dredging of the navigation channel (Gordon, 2004). All of these structures are built with boulder sized limestone rip rap (>260 mm). With the exception of bendway weirs, all of the training structures are emergent at flows range from ~mid-bank or lower river stages. Groynes generally become submerged during mean river discharges.

River training structures along the Mississippi River are not evenly spaced along the river. These structures tend to be grouped together at specific "problem" locations (generally crossings or bends). In addition, the specific material height, width, side slope and spacing of these structures vary with location and conditions along the Mississippi River. These parameters are generally determined using physical models and/or professional judgment (USACE, 2010). Table 1 gives an overview of typical dimensions of navigation structures on the Middle Mississippi and Missouri Rivers. This information is derived from USACE collected hi-resolution multi-beam sonar data and other USACE data files.

Table 1: Dimensions of navigation structures on the Middle Mississippi River (NA = not available).

		Structure Type		
		Groynes	Bendway	Chevrons
Length	Average (m)	93	206	215
Width	Average Top (m)	3	NA	10
	Average Bottom (m)	25	NA	35
Height	Average (m)	4	NA	4
Side Slope	Average (m/m)	1/1.3	NA	1/2
Spacing (within group)	Max (m)	500	305	470
	Min (m)	100	100	160
	Average (m)	180	198	320

In the Netherlands, training structures are predominantly flow-perpendicular groynes that have lengths between 50 and 80 m and spacings of on average 200 m (e.g. Verheij 1997). The spacing depends on the normal width, desired depth and on location on the inside or outside of the river bend. The river Waal (normal width = 260 m) has an average spacing of 220 m on straight river sections. In sharp outside river bends the spacing between groynes is generally smaller (at some locations approximately 100 m) to prevent the mean flow to penetrate far into the groyne fields. The groynes become submerged about 25% of the time (e.g. Verheij 1997). The top width of the groynes is about 2 m and the side slopes of the Dutch groynes are approximately 1:3.

3.2 *Innovative designs*

In recent years, innovative river training designs have been considered and implemented in the Mississippi and Rhine Rivers. For example, along the Waal branch of the Rhine River a pilot study using longitudinal dams is now planned for construction, aiming at lowering flood levels while maintaining river navigation conditions and stimulating nature values (Schoor & Eerden, 2011). The construction of the longitudinal dam, where flow in a groyne-field is replaced by an effective side-channel flow (behind the longitudinal dam), includes several openings in the dam for the exchange of water, sediment, ice and biotics. These gaps are about 225 m wide and can also easily be filled up again if they appear to create unwanted side-effects. With such a flexible design, where the dam openings function as steering parameters to a wide range of impacts, even after construction the design can easily be optimized to conditions in the field. Currently, monitoring plans are devised to assure that after construction the desired impacts are achieved, or, if needed, to point out necessary design adaptations. For optimizing the design an initial monitoring period of three years will be carried out, supplemented by additional laboratory and numerical investigations. Numerical flow studies have already shown that the considered design may be very effective in reaching the desired target for flood level lowering and improve conditions of the navigation channel (larger depths, less transverse flows), such that costly dredging activities may be reduced in the future (Huthoff et al., 2011).

Along the Middle Mississippi the USACE has experimented with designs as L-head dikes, detached dikes, bendway weirs, Chevron dikes, and "W" dikes primarily aiming at maintaining depth of the navigation channel (USACE, 2010). Design of these structures have mostly relied on laboratory scale models, which focused on qualitative morphodynamics effects, but could not indicate potential impacts on water levels during floods. It has been claimed that these structures also have beneficial impacts for river ecology.

4 NUMERICAL FLOW SIMULATIONS

Laboratory experiments have traditionally been used to investigate how changes in designs of training structures impact hydrodynamics and sediment transport. These existing studies can now also be used to validate numerical computer programs, which, after validation, can then be applied to investigate wide ranges of design modifications. Here we demonstrate such an approach and emphasize its potential for further practical application.

For validation of the simulations, we make use of the laboratory experiments as carried out by Azinfar and Kells (2011). In these experiments a simplified groyne geometry was set up in the laboratory, using a 10 m long and 0.8 m wide flume. The groyne in the flume was a vertical wall that extended halfway across the flume (from side wall to midpoint of the flume) and had a height of 5 cm. Flow experiments were carried out with the groyne being well-submerged.

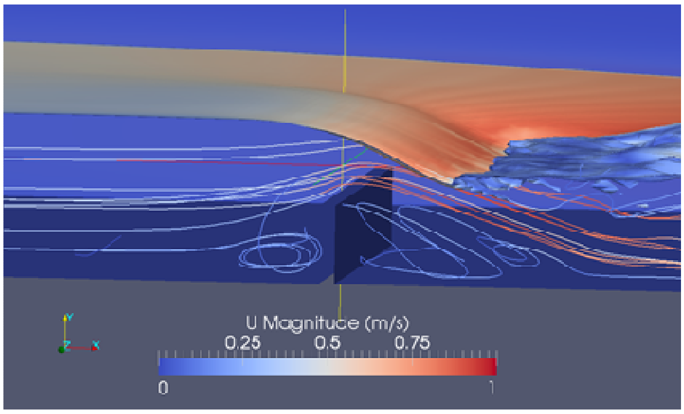

Figure 1: 3D simulation of the flow around a single groyne (snapshot showing the free water surface and streamlines).

For the purpose of reproducing these experiments numerically, we made use of the open-source package OpenFOAM (www.openfoam.com), using the interFoam flow solver in Large Eddy Simulations (LES) mode, using a spatial resolution of 0.25 cm in three dimensions. Under these modeling choices, the free water surfaces and the turbulent mixing motions in the wake of the groyne element were explicitly calculated. Figure 1 shows a snapshot of the simulated flow field, depicting the free water surface above the groyne element and also the streamlines demonstrating turbulent mixing near the groyne. Comparison between measured and simulated water surface profiles (Figure 2) and velocity profiles (Figure 3) show good agreement.

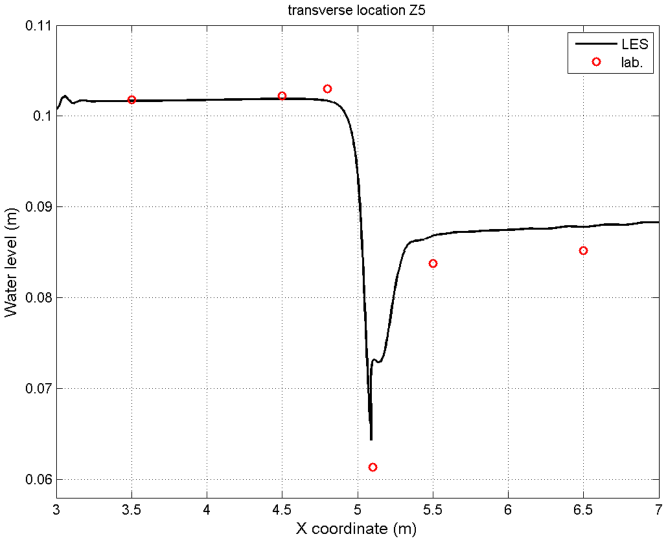

Figure 2: Measured and calculated mean water surface profiles along the center axis of the flume. The groyne is located at X= 5m.

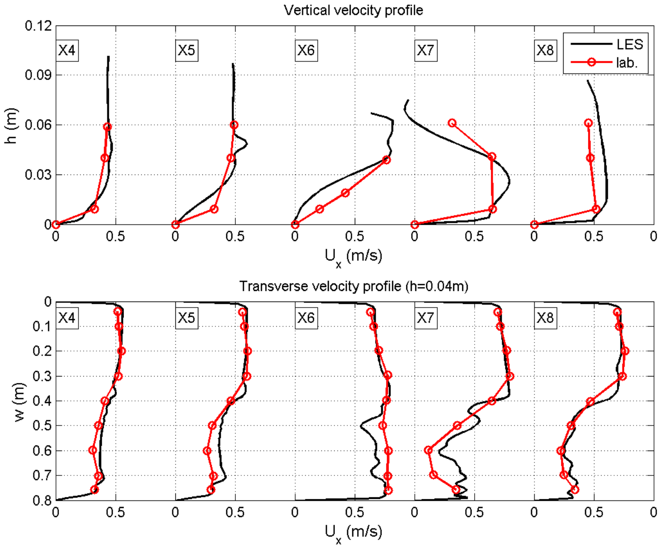

Figure 3: Measured and calculated mean velocity profiles at five streamwise locations (location X5 is just upstream of the groyne, X6 is just downstream). Top: vertical velocity profiles (over depth). Bottom: transverse velocity profiles (at 4 cm above the bed), The groyne extends from w=0 to w=0.4 m.

The next step is to extend our simulations to alternative groyne designs in order to gain insight into the corresponding hydrodynamic responses. We have investigated three groyne geometries:

1. WD_LESa (the reference case): a vertical wall with height 5 cm, following the geometry as used in the experiments of Azinfar and Kells (2011). See also Figures 1-3.
2. WD_LES_L: an L-shaped groyne, where the tip of the groyne is extended in streamwise direction. The length of this extension is equal

   to three times the height of the groyne, (i.e. extension of 15 cm, see Figure 4)

3. WD_LES_talud: a wedge-shaped groyne, with 1:3 side-slopes. The base of the downstream slope thus corresponds to the endpoint of the L-shaped groyne.

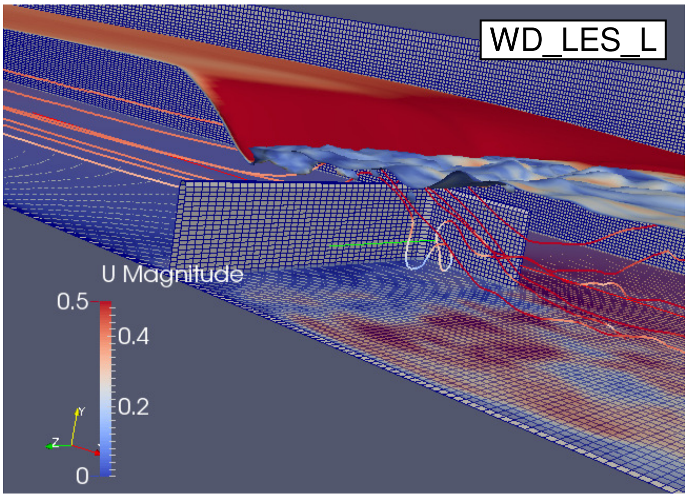

Figure 4: Simulated flow over the L-shaped groyne. For better visualization the vertical scale is stretched to twice the horizontal scale.

Figure 5 shows side-view snapshots of the streamwise velocity field over these three groyne geometries, using equal inflow conditions at the upstream boundary (i.e. equal discharge). The velocities are in the vertical plane that goes over the midpoint of the groynes. In this plane, the flow field hardly differs between the original groyne case (WD_LESa) and the L-shaped case (WD_LES_L). For the case of the wedge-shaped groyne (WD_LES_talud), the side slope approximately covers the space that was previously occupied by a flow recirculation zone. This recirculation zone is clearly marked in the other two cases by negative flow velocities.

The suppression of a recirculation zone in the wedge-shaped groyne manifests itself in a ~3% drop in upstream water levels as compared to the other two groyne geometries (see Figure 6). It thus appears that the groynes in the Rhine River (which have side slopes approximately 1:3) have been chosen quite appropriately to reduce flow resistance during flood flow conditions. Groynes with steeper side slopes, such as found in the Mississippi river, can thus be further optimized for minimal flood level impact.

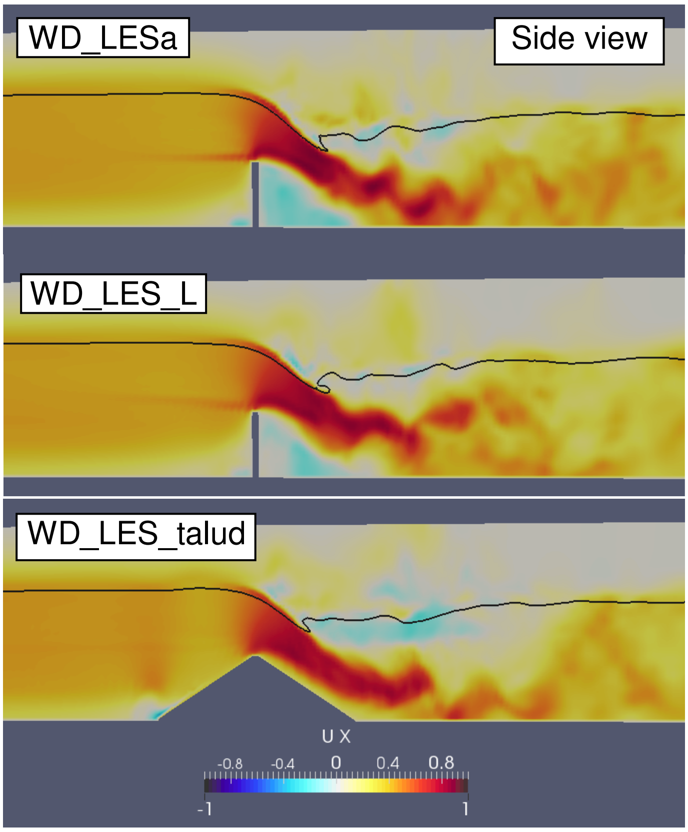

Figure 5: Snapshots of the streamwise velocity component (U_x) over the midpoint of the groyne for the three considered groyne geometries (flow from left to right). For better visualization, the vertical scale is stretched to twice the horizontal scale. The black line represents the water surface, above which also the air flow velocities are shown.

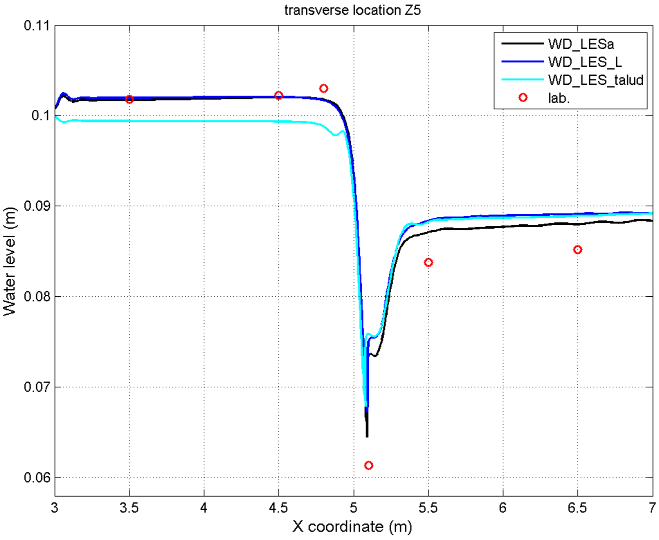

Figure 6: Water level surfaces near the groyne for the three groyne geometries (flow from left to right). The groyne is located at X = 5 m.

Using gentler side-slopes than 1:3 may further reduce the impact of groynes on flood levels, but such modifications require more building material and thus increase construction costs. Also, the groyne may become unsuitable for breaking up of ice-cover and may lead to a weakened ability to stimulate scouring of the main channel. To illustrate potential impact on bed scouring the velocity magnitudes near the bed are shown in Figure 7. It appears that in the free-flowing zone past the groyne the reference case (WD_LESa) produces highest flow velocities near the bed. This case therefore seems most effective in maintaining a deep (self-scouring) main channel. However, for this case also large patches of high velocities are found next to and downstream of the groyne, which likely lead to large localized scour holes. In contrast, the L-shaped groyne guides flow more gently past the groyne, which appears to reduce the strength of turbulent mixing, and associated scouring, just downstream of the groyne.

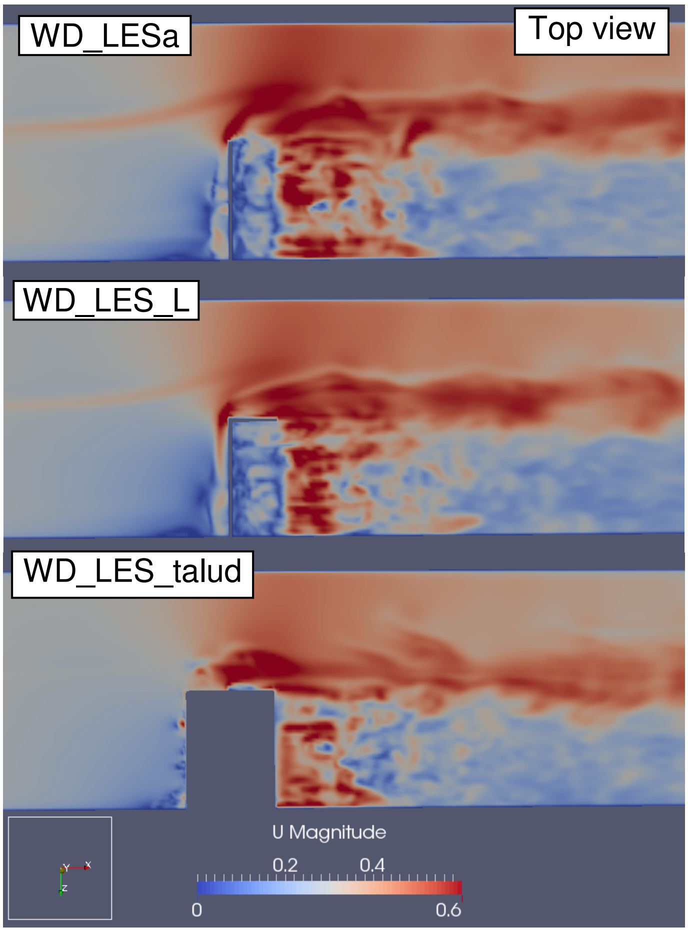

Figure 7: Snapshots of the simulated velocity magnitude at a small distance of 2,5mm above the bed of the flume (top view, flow from left to right).

The considered cases in this study were modeled after conditions that have been accurately measured in a small-scale laboratory setting (case WD_LESa). It shows that for these conditions the flow could be well-reproduced allowing further investigations of important steering parameters in the design for hydro- and morphodynamics impacts. The next step is to up-scale the modeling approach in order to make more detailed recommendations on suitable geometries for groynes and other river training structures (e.g. longitudinal dams, chevrons, etc.) under for full-scale field conditions. For validation of such studies it is important that more detailed field data, such as for example those presented in Jamieson et al (2011), become available.

5 CONCLUSION

Traditional and innovative training structures were discussed with respect to their intended impacts and their multi-functional potential. Nowadays, when uses of river systems are increasingly under pressure to meet ecological, economical and safety goals, it is unavoidable to consider these different goals in the design phase of river engineering works. Modern techniques such as 3D flow simulations are useful supplements to the more traditional laboratory and field flow studies and allow us to better understand hydrodynamic cause-and-effect relationships. These modeling efforts are particularly useful in identifying design modifications, or design steering parameters, that are effective in suppressing or amplifying hydrodynamic and/or morphodynamics impacts.

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