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Numerical modelling approaches for flow near groynes - comparison with experiments

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Abstract: Groynes are used for river training and providing navigation depth. Groynes add resistance, increasing the water level, which can be hazardous during floods. To reduce groyne resistance, different optimizations of the groyne geometry are considered. Often, numerical modelling is applied to assess the effects of such measures. Therefore, we investigate the performance of several numerical models in representing the flow over groynes, by comparing to laboratory measurements. Low- and high-resolution, two- and three-dimensional, as well as hydrostatic and non-hydrostatic computations are considered. Using a coarse-grid, two-dimensional model, with subgrid weir-losses for representing the groynes, the discharge over the groynes is strongly over-estimated. Better agreement is obtained using the non-hydrostatic, three-dimensional model. Due to the over-prediction of the discharge over the groynes also the effect of groyne modification is over-estimated. Therefore, coarse-grid, two-dimensional simulations, with the present subgrid weir-loss formulation, may not be appropriate for modelling the flow over (modified) groynes.

1 Introduction

Groynes are used in rivers mostly for bank protection and maintaining sufficient depth for shipping (van der Wal, Akkerman & Stam et al. (2006)). However, at high water conditions, the groynes raise the water level due to increased total flow resistance. The effect of possible measures, such as lowering or streamlining (reduction of the downstream groyne slope) of groynes, to reduce the groyne resistance in submerged conditions, has become an important research topic (Bloemberg (2001); van Broekhoven (2007); Huthoff et al. (2013); Kruijt (2013); Platzek et al. (2018); Ambagts (2019)). A number of pilot projects have been realized (e.g. in the Waal River between the cities of Beuningen and Gorinchem), to investigate the (long-term) effect on the flow and morphodynamics in the river. However, these effects (both hydro- and morphodynamically), still remain unquantified up to date.

Historically, most of the research on hydraulic structures was concentrated on weir flow (e. g. Villemonte (1947); Bloemberg (2001); Ali (2013)). Therefore, also most laboratory data concerns the flow over weirs, either in perfect or imperfect (drowned) condition. The aim of these works mostly concerns the establishment of weir relations, between the upstream water level (or energy head) and the discharge over the weir. A constitutional relation can then be derived for the energy loss over a weir, e.g. Villemonte (1947); Sieben (2011).

However, groynes are fundamentally different as the flow can pass both over and around the groyne (for submerged conditions). How much of the discharge flows over the groyne and how much flows around depends on several factors: groyne geometry (length, crest height, upstream/downstream slope, groyne tip shape, roughness), submergence ratio, groyne field geometry (longitudinal/lateral slope), discharge, bottom roughness, etc. All these factors influence the total flow resistance due to a submerged groyne. For this purpose, it is considerably more difficult to establish a quantification of the energy loss for a groyne, based on a weir-like or bottom friction formulation.

Most experimental investigations on groynes consider simplified obstacles, e.g. plates or blocks (McCoy, Weber & Constantinescu (2008); Azinfar (2010)), or permeable structures (e.g. Mahmoud, El-raheem & Tominaga (2014)). Other works concern reach-scale river cases, with measurements (e.g. Jia, Xu & Wang (2009)). However, from these latter investigations it is difficult to deduce dependency relations between the different aforementioned parameters (e.g. submergence ratio, groyne geometry, groyne field geometry), due to the limited control of the flow conditions. Sukhodolov (2014) set up a groyne experiment in a small river reach and made interesting observations on the flow patterns around groynes. He concluded that the main resistance contribution due to groynes comes from the increase in velocity in the main channel due to the local reduction of the flow cross-section. Other investigations in a laboratory flume with groynes, under controlled conditions were performed by Uijttewaal, Lehmann & van Mazijk (2001); Uijttewaal (2005); Yossef (2005). These works focused mostly on horizontal flow patterns and emerged groynes. To the knowledge of the authors, the largest scale laboratory experiments, which consider both emerged and submerged groynes were performed at the Bundesanstalt für Wasserbau (BAW), where a 62,5 m long flume, with 40 groynes was tested for several discharges, see Hüsener, Faulhaber & Baron (2012); Baron & Patzwahl (2013); Faulhaber & Hentschel (2020).

The numerical modelling of groynes is challenging, in particular in submerged conditions, due to the three-dimensional flow character (re-circulations) and turbulent exchange between the main channel and the groyne field. Depending on the chosen grid resolution, groynes can be included in numerical river models using two approaches. On a fine mesh, groynes can be resolved in the bed topography, as e.g. in Patzwahl, Jankowski & Lege (2008). On the other hand, on a coarse mesh, groynes need to be represented as subgrid energy losses in cells or on cell-edges. This latter approach is mostly applied in two-dimensional models. The groyne losses can either be computed based on weir formulations or based on (bottom) roughness considerations. For large river systems, such as the Dutch Rhine delta, computational power often limits the application of high-resolution models and modellers often need to resort to such subgrid parameterizations for including energy losses due to submerged groynes. However, an important engineering question that has been posed in the past decades is:

Can groynes be modified to reduce their contribution to flow resistance at high water, e.g. through groyne lowering or streamlining?

This involves an expensive measure, where several thousands of groynes over hundreds of kilometers would have to be altered individually. Therefore, there is a need to investigate numerically, whether such measures are worth the effort. This requires appropriate numerical models, which are able to adequately represent the flow resistance due to (submerged) groynes. Is this also possible with relatively coarse depth-averaged (2D) models?

The primary aim of this work is, therefore, to find the most appropriate way for incorporating submerged groynes in a numerical model: capturing the resistance effect and local flow patterns near the groynes. In future research, , also the effect on morphodynamics could be included. A secondary aim is to be able to quantify the effect of groyne modifications.

To be able to choose an appropriate numerical model, we need data for verification. This paper is therefore structured as follows. In section 2, we describe high-quality measurements from a groyne flume at the BAW, which we use for comparison with a series of numerical experiments. In section 3, we then describe the different two- and three-dimensional (3D), coarse- and fine-grid numerical experiments we performed and in section 4, we present the results, including an assessment of the effect of groyne modifications. We end with a discussion (section 5) and draw conclusions on the consequences of this work (section 6).

2 Measurement Data

The BAW measurements from Hüsener, Faulhaber & Baron (2012); Baron and Patzwahl (2013); Ambagts (2019) involve a straight flume with length L = 62.5 m, width W = 2.5 m, containing 40 (8 cm high) groynes, see Figure 1. In the flume an elaborate measurement campaign was executed, involving geometrical configurations with and without groynes, with different groyne field aspect ratios, with an embankment (filled-up groyne fields), and with scour holes near groynes, see Faulhaber & Hentschel (2020) for a complete overview.

The free-surface level and surface flow velocities were measured using a highly-accurate 3D Particle-Tracking Velocimetry (PTV) technique (Henning, Sahrhage & Hentschel (2007)). Additionally, a number of vertical profiles were measured both in the main flume direction (providing x - z transects) and in lateral direction (providing y - z transects). These lateral profiles were measured for several groye sections and through several groyne fields.

The BAW measurements encompassed both emerged and submerged groyne conditions. In the present work we focus on the submerged situation, with total water depths of approximately 12 cm (called *H120*) and 16 cm (called *H160*), with corresponding submergence ratios are S = 1.5 and S = 2, respectively. The high quality of data and the bandwidth of considered flow depths yields the BAW groyne flume a very suitable test case for testing numerical models.

3 Numerical Modelling

At BAW, the modelling systems TELEMAC (Hervouet (2007)) and UnTRIM (Casulli & Walters (2000)) were compared to the BAW groyne flume data, using 2D and 3D computations, comparing a hydrostatic and non-hydrostatic pressure approach, different advection schemes, turbulence models, different (fine) grid resolutions, bottom friction and wall roughness values, see Baron and Patzwahl (2013). The main conclusions of this work were: 1) for emerged groynes, mostly 2D horizontal flow patterns emerge, which can be adequately captured by selecting an appropriate momentum advection scheme; 2) for submerged groynes, flow patterns are 3D and the vertical recirculation is only captured with a non-hydrostatic pressure solver. Agreement with the measurements was largely determined by the turbulence model.

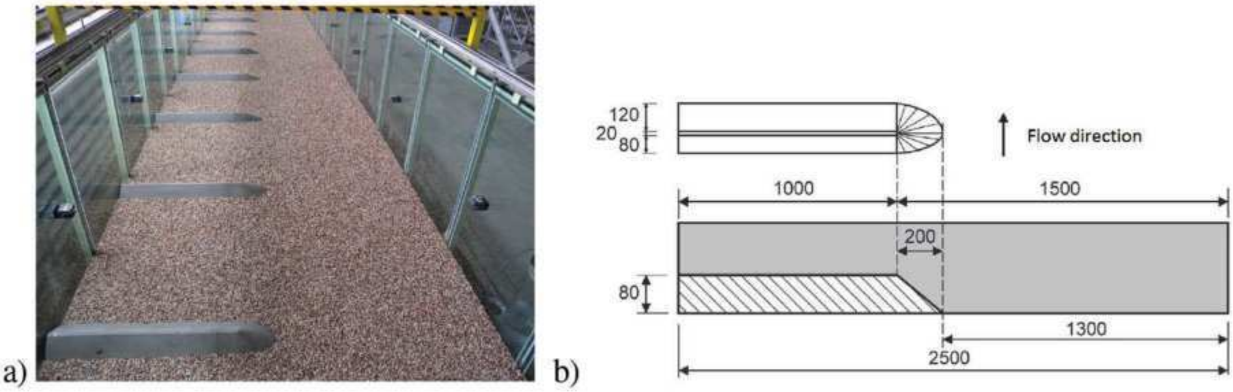

Figure 1: The BAW groyne flume: a) The (empty) groyne flume; b) groyne and cross-section dimensions.

In this work we perform the same experiments using the modelling system Delft3D (Deltares (2014)). As in the comparison at BAW, we also compared 2D and 3D modelling approaches, different grid resolutions, hydrostatic and non-hydrostatic modelling, and to a lesser extent, the role of the advection scheme and the chosen turbulence model. What is different in the present work, is the comparison with a relatively coarse grid with additional subgrid weir-like losses for incorporating the resistance due to groynes. Summarizing, the following configurations were investigated:

1. 2D coarse grid with subgrid weir formulation for groyne losses
2. 2D fine grid with groynes resolved in the topography
3. 3D fine grid, hydrostatic
4. 3D fine grid, non-hydrostatic

The first configuration was run on the grid with $\Delta x = \Delta y = 0{,}25$ m, where the groynes are included as subgrid-weir losses (based on a combined energy-loss formulation of Vermaas (1987) and Carnot expansion losses). Configurations 2–4 are simulated on a finer grid with $\Delta x = \Delta y = 0{,}05$ m, which is still coarse, with respect to the groyne dimensions, but the groyne are resolved in the topography. All computations in Delft3D were performed using the *Delft3D-Flooding* scheme (Stelling & Duinmeijer (2003)), for momentum advection. This scheme was chosen for its conservation properties for the flow over strongly variable topography.

We consider both water levels (backwater effect) and flow distributions, for the two aforementioned discharge conditions (both with submerged groynes). We also simulate the flume with lowered and with streamlined groynes and inspect the effect on the water levels. For these latter simulations, no measurement data is available, yielding the comparison mostly qualitative. More details on the numerical model set-up can be found in Ambagts (2019).

The model was calibrated in two steps. First, the bottom friction coefficient was chosen based on runs with an empty flume (configuration without groynes, called *V00*), for which the BAW also performed measurements. This step resulted in a Nikuradse roughness height k_s = 7.5 mm for the 2D model and k_s = 10.0 mm for the 3D model. Next, the model was calibrated for the horizontal eddy viscosity using the flume with the 40 groynes (called *V01*). This calibration was done for the H120 case, with a water depth in the main channel of approximately 12 cm. The results were compared with the measurements, for the agreement with the shear zone width and strength. Based on computations with a horizontal viscosity ν_H in the range 1.0×10^{-4} – 5.0×10^{-3} m^2/s, a spatially-constant value of $\nu_H = 1.0 \times 10^{-3}$ m^2/s was chosen. One could argue that the fine-grid 2D model would require a higher bed (turbulent) viscosity coefficient to counter the reduced numerical diffusion for the finer grid. This was not yet investigated. The results shown in section 4, indeed show a reduced flow resistance for the fine grid computations, compared to the coarse-grid computations.

4 Results

In this section, we compare the numerical modelling results obtained with Delft3D, for the H120 and the H160 cases (both with submerged groynes), with the data from the BAW experiment. The focus is on the H160 case (with the water depth of 16 cm), corresponding to the high-water scenario, with submergence ratio of the groynes S = 2. We also compare the different modelling approaches and grid resolutions, considering both water levels, velocities and discharge distributions, in 2DH (horizontal) and in 3D. More elaborate considerations can be found in Ambagts (2019).

4.1 Water levels

Figure 2a shows a longitudinal slice of the water level through the groyne fields (for y = 2.25 m), for the discharges providing flow depths of 10 cm (H100), 12 cm (H120), 16 cm (H160) and 20 cm (H200). It can be seen that the fine-grid 2D model considerably underestimates the water level set-up due the groynes, in particular for the higher discharges. Contrarily, both the coarse 2D model (with subgrid weir losses) and the 3D non-hydrostatic model perform better, but still underestimate the water levels. The hydrostatic results have not been included, as they are very similar to the non-hydrostatic results. For the H160 and H200 cases, the water levels of the hydrostatic run are slightly lower than the non-hydrostatic water levels. For the lower discharges, the fine-grid 2D model provides similar or better agreement with the measured water levels than the coarse 2D model. It can be concluded that the fine 2D model is more sensitive to the discharge (and submergence level). The finer grid will generally have lower numerical viscosity than the coarse grid. For the higher discharges, the (horizontal) velocity gradients are higher and for the coarse-grid model – with higher

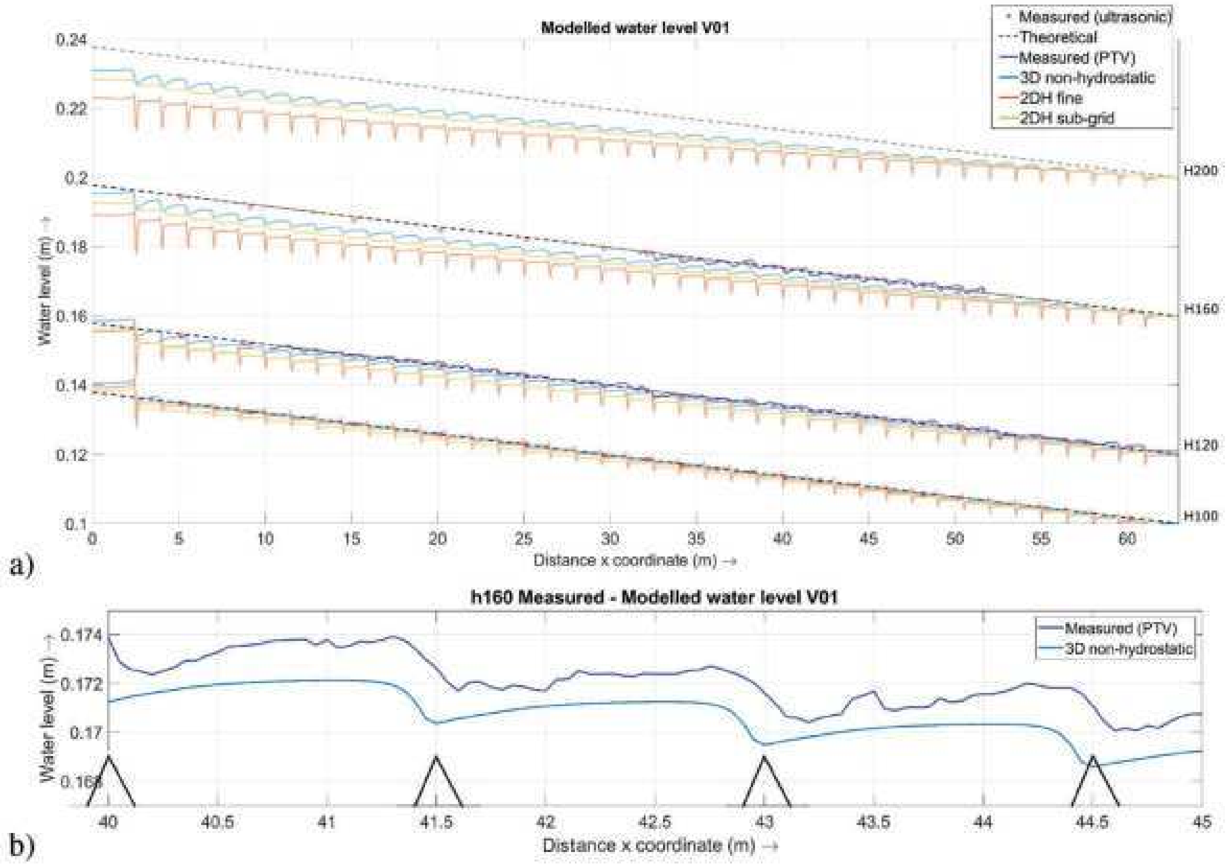

Figure 2: Comparison of measured and computed water levels at $y = 2.25$ m: a) full flume length for the four cases H100, H120, H160 and H200 for the coarse and fine 2D models and the non-hydrostatic model; b) detailed view of the measurement and the 3D non-hydrostatic run for the section $40 < x < 45$ m.

numerical viscosity – this results in more numerical mixing and a larger backwater effect, similar to what was found in Platzek et al. (2018). In the detailed plot of Figure 2b, it can be seen that – despite an underestimation of the water levels – the general variation of the water level in the groyne field and the energy loss over the groyne is nicely captured by the 3D non-hydrostatic model.

4.2 Discharge distribution

Both for the measurements and the numerical simulations, the discharge distribution was inspected. Two sections were defined: the main channel section for $0.0 < y < 1.5$ m and the groyne field section for $1.5 < y < 2.5$ m. To be able to perform a fair comparison with the coarse-grid model with subgrid weirs, the groyne tip is considered a part of the main channel. Table 1 shows the discharge distribution (in % of the total discharge) for both the measurements and the numerical simulations, for the H160 case. In the measurements, 85 % of the discharge flows through the main channel (of which 7 % over the groyne tip, or through the shear zone) and only 15 % flow over the groynes. It can be seen that all model configurations overestimate the discharge over the groynes. In particular, the (coarse) 2D runs shows an over-prediction of the discharge over the groyne by 87 %, compared to an over-estimation of only 9 % for the 3D non-hydrostatic model.

Table 1: Discharge distribution through main channel and over the groynes and differences with measurements. All numbers given in % of the total discharge.

	Main channel		Groyne field	
Model configuration	Discharge	Difference with measurement	Discharge	Difference with measurement
Measurements	85*	N/A	15	N/A
2DH coarse	72	-15	28	+87
2DH fine	77	-9	23	+51
3D hydrostatic	82	-4	18	+21
3D non-hydrostatic	83	-2	17	+9

* of which 7 % through the mixing zone.

Additionally, the flow velocity distribution in the wake of the groyne was investigated, to see how this varies along the groyne. In Figure 3, the flow velocity just above the bed is shown, where it can be seen that along approximately 3/4 of the groyne length, the velocity distribution does not change significantly. This indicates that - at least for the present geometrical set-up and flow conditions - the groyne behaves like a weir for approximately 3/4 of its length, from the groyne foot towards the groyne tip.

4.3 Effect of groyne modifications

The situation with lowered or streamlined groynes was only simulated with the 2D coarse-grid model (with subgrid weir losses) and the 3D non-hydrostatic model. A comparison of the effect of these measures (for the different discharges) on the upstream water levels can be found in Figure 4 for the whole spectrum of submerged discharges. First, it can be seen that groyne streamlining has a considerably smaller effect on the water levels than groyne lowering. Furthermore, the figure shows that the coarse-grid 2D model results in a much larger effect of the groyne modifications. This may be attributed to the erroneously over-predicted discharge over the groynes. It could be stated that the groyne modification acts on too large a portion of the actual discharge.

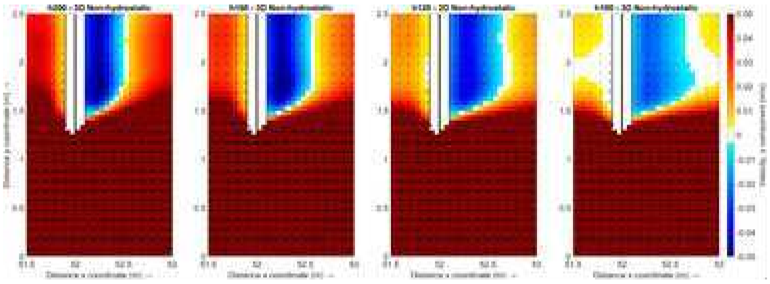

Figure 3: Flow velocity in x-direction (colours) and flow vectors just above the bed for the 3D non-hydrostatic run around the groyne at x = 52 m.

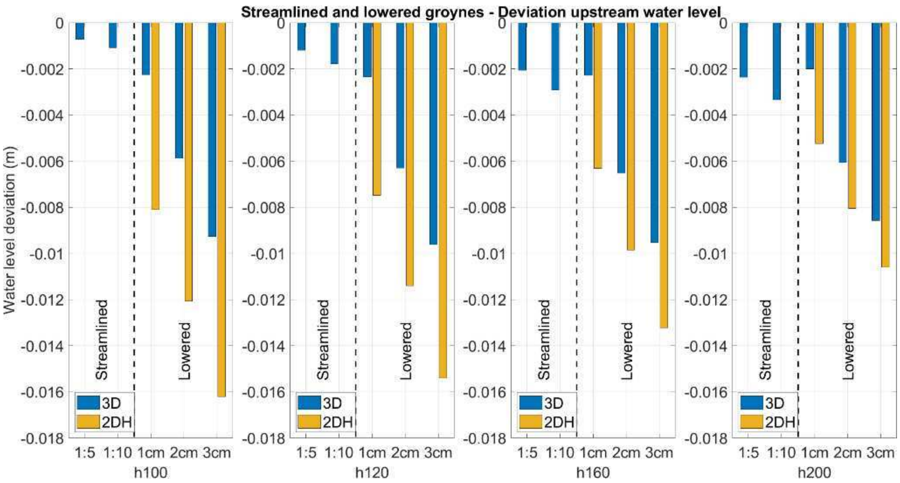

Figure 4. Comparison of the effect of lowering or streamlining of groynes on the upstream water level for the different discharges. Both the 2D coarse-grid results and the 3D non-hydrostatic results are shown.

Based on the 2D coarse-grid results, an engineer may decide that it is worth the effort and expenses to lower and/or streamline the groynes, to reduce water levels. However, based on the 3D non-hydrostatic results, the engineer might judge differently. This shows that the way in which groynes are represented in numerical models, can greatly influence a costly engineering decision.

5 Discussion

This study was motivated by the ongoing discussion in the Netherlands (and in Germany), on the effectiveness of changing groyne design, by lowering, streamlining, removal and/or replacement with longitudinal training walls over large river stretches. Coarse-grid 2D models play an important role in assessing the effects of these measures. We aim to build knowledge about the performance of such 2D models in capturing the relevant processes of the flow near groynes. For this purpose, a two-step comparison was made: we compared both coarse-grid 2D and fine-grid 3D numerical results to laboratory experiments and additionally we assessed the performance of the coarse 2D model versus the finer 3D model.

In the present 2D coarse-grid model setup, the groynes have been included in the coarse-grid model as subgrid losses, based on the work of Vermaas (1987) and Carnot expansion losses. In this way, the model is sensitive to the chosen grid size with respect to the actual length of the groynes. Sieben (2011) investigated a large data set for the flow over weirs and constructed a formulation based on Villemonte (1947), which can handle different groyne geometries (e.g. upstream and downstream slopes). Using such a formulation, it may be possible to improve the 2D coarse-grid model results.

For the 3D fine-grid model, a number of options need to be investigated for their effects on the results. First, the horizontal and vertical grid resolution may have considerable influence on the flow resistance and the local flow patterns (recirculation) near the groyn. Second, the non-hydrostatic pressure computation may be further improved. Third, a different horizontal viscosity or a possible turbulence model (e.g. the Delft3D-HLES model, see Uittenbogaard & Van Vossen (2003)) may be worth consideration.

In real high-water situations, a portion of the discharge flows over the flood plains. This means in reality a smaller fraction of the discharge (that flows over the flood plains. This means in reality a smaller fraction of the discharge (that flows through the groyne field) is affected by the groynes. The laboratory set-up in the BAW experiment does not include flood plains. This results in an overestimation of the effectiveness of modification to groynes in this research.

The present experiments were performed on the scale of the laboratory experiment. It remains to be verified if the present results can be transferred to an actual river scale. Therefore a comparison between the 2D sub-grid and 3D model on an up-scaled case with more realistic dimensions and geometry (e.g. shallow groyne fields, moderate groyne slopes) is needed, Finally, to quantitatively assess the effects of streamlining or lowering of groynes, data from physical experiments where the geometry is varied are necessary.

6 Conclusions

Based on a comparison between laboratory measurements in a flume with groynes, we investigated which numerical modelling approach is best suitable for modelling submerged groynes. It can be concluded that all investigated configurations (2D coarse grid with subgrid weir losses, 2D fine grid, 3D hydrostatic and 3D non-hydrostatic) underestimate the groyne losses and overestimate the amount of discharge over the groynes. The 3D models (21 % and 9 % overestimation of the discharge, respectively) outperform the 2D models (87 % and 51 % overestimation, respectively) and the non-hydrostatic model (9 % overestimation) provides better agreement with the measurements than the hydrostatic model (21 % overestimation). The 2D computations on a coarse grid with subgrid groyne losses provide better agreement with the measured water levels than the fine-grid 2D runs. However, when considering the discharge distribution, the fine-grid 2D model shows better agreement. It can not be concluded which of the two 2D approaches is more suitable. For modelling groynes using a 3D non-hydrostatic model, the horizontal and vertical grid resolution need to be sufficient for capturing the local pressure and acceleration effect.

An interesting secondary conclusion (for the present geometry configuration) is that approximately 3/4 of the groyne length 'behaves' like a weir, i.e. that the flow over that section of the groyne is predominantly 2DV and the losses due to the groyne resemble those of a weir. This can help in developing parametrizations for groyne losses based on weir formulations in coarse 2D models.

The present work has some implications on the applicability of coarse 2D models in highwater conditions and for evaluating modifications to the groyne design (groyne lowering and streamlining). Due to the over-prediction of the discharge over the groynes, the effectiveness of measures of groyne lowering is overestimated when using 2DH (subgrid weir-loss) models. This implies that 3D modelling of a subsection of the reach in 3D is necessary.

Finally, research involving a more realistic laboratory set-up, e.g. with shallow groyne fields, less steep groynes, and including food plains, is recommended, Additionally, such a situation should then both be modelled at laboratory and prototype scale, using both 2D and 3 D simulations.

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