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River scale model of a training dam using lightweight granulates

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Abstract

Replacing existing river groynes with longitudinal training dams is considered as a promising flood mitigation measure in the main Dutch rivers, which can also serve to guarantee navigability during low flows and to create conditions favourable for ecological development. Whereas the bed response in the streamwise uniform part of a river trained by a longitudinal dam can be readily predicted, the bed response at the transition zones is unclear. In the present study, we investigate the local morphological effects resulting at the intake section of a longitudinal training dam, where the flow is distributed over the main channel and a side channel in between the dam and the river shore. A sediment recirculating model with a nearly undistorted geometry with respect to the prototype was setup. Lightweight polystyrene granulates were used as a surrogate for sediment, to properly scale the Shields parameter without compromising Froude scaling, and reach dynamical similarity. A laser scanner allowed collecting high-resolution bed elevation data. Results obtained under typical low flow and high flow conditions show a general deepening of the bed in the area adjacent to the training dam, in response to narrowing of the main channel. Scour at an upstream river groyne embedded in the model showed a scour hole which was deeper than realistic. Throughout the entire domain, bedforms developed featuring geometrical properties that reproduced the prototype conditions appropriately. Based on a comparison with characteristics from the River Waal, regarded as the prototype without a longitudinal dam, lightweight sediments were considered to be a proper choice for this study, in which bedload is the main sediment transport mode. The main conclusion regards the absence of significant morphodynamic developments at the intake section, both during the high flow experiment and during the low flow experiment, which can be attributed to the alignment of the dam with the local streamlines.
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1. Introduction

Longitudinal training dams (Fig. 1) serve to constrict the flow in the navigable part of the river during low water conditions, while preserving a high cross-sectional area, and therefore a high channel conveyance during high water conditions. In The Netherlands, replacement of a series of river groynes (also referred to as spur-dikes, or wing dams) by a longitudinal dam is considered to be a promising flood mitigation measure. Next to the benefits related both to low flows and peak water levels, training dams are expected to exert a favourable influence on ecological conditions near the riverbanks, where flow velocity will decrease and the effect of ship waves will diminish.

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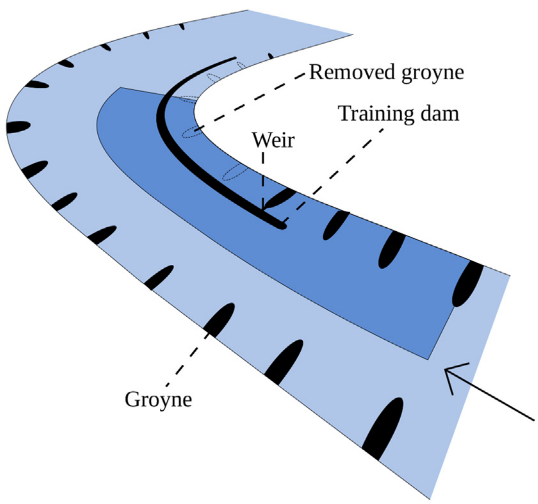

Fig. 1. Sketch of the prototype. Dark area corresponds to the area included in the physical scale model.

The riverbed can locally aggrade or degrade due to the three-dimensional flow patterns around the training dam, especially at the upstream head of the dam. Flow impinging on the head and separation of the flow may induce local scouring and sedimentation, which may lead to undermining of the structure or to impediment of navigation, respectively. In the present contribution, we focus on local morphological effects in response to flow velocity patterns in the surroundings of a longitudinal training dam, based on experiments with a physical scale model with a moveable bed.

Several studies (e.g. Ettema and Muste, 2004; Kuhnle et al., 1999, 2002; Yossef and de Vriend, 2010) have analysed the effect of groynes on flow patterns and bed morphology. For example, Ettema and Muste (2004) have systematically analysed the influence of several scaling ratios on geometrical descriptors of scour occurring behind a groyne. Similar studies on the effect of training dams are scarce (Westrich, 1988). The complex three-dimensional character of the flow around river training works renders numerical modelling a daunting task, which is why a laboratory approach is still being adopted, despite it being labour intensive. Physical-scale models with movable beds primarily rely on scaling of the Shields parameter, which is the non-dimensional bed shear stress quantifying the mobility of the sediment. Because sediment properties cannot easily be manipulated, dynamic similarity of the flow is not always achieved. Ettema and Muste (2004) show that scaling based on shear stress leads to a much higher Froude number in the model, which significantly influences the resulting morphology. A way of circumventing this is to use lightweight sediments that magnify the mobility. Despite potential drawbacks of lightweight sediments related to buoyancy, the angle of repose, skin friction and bed-form shapes (Frostick et al., 2011), the use of low-density surrogates for sediment may be considered one of the few options to achieve dynamical similarity of both sediment transport and the basic characteristics of the mean flow in a physical scale model.

In this study, we employ lightweight sediments to study the local morphological response to flow variation at the upstream intake of a longitudinal training dam, where flow divided over the main channel and a side channel in between the dam and the river shore. In Section 2,we analyse the most relevant parameters using dimensional analysis. In Section 3 we describe the design of the experiments and in Section 4 we present the results. These results, and the suitability of polystyrene granulates for this type of study, are discussed in Section 5 and main conclusions are drawn in Section 6.

2. Dimensional analysis

We determine a set of dimensionless parameters characterizing the main processes in the flume by dimensional analysis. The following variables characterize flow, sediment transport and morphology:

$$L,\ W,\ d,\ D_{50},\ \rho_w,\ \rho_s,\ \rho_s-\rho_w,\ \nu,\ s,\ g,\ C \text{ and } U,$$

which represent a characteristic length, width and depth (m), median particle diameter (m), density of water (kg m^{-3}), difference between sediment density and water density (kg m^{-3}), kinematic viscosity (m^2 s^{-1}), surface tension (kg s^{-2}), gravitational acceleration (m s^{-2}), the Chézy friction parameter (m$^{0.5}$ s^{-1}) and a characteristic velocity (m s^{-1}). We reduce this set of variables to a set of non-dimensional variables through dimensional analysis:

$$L_*,\ W_*,\ D_{50*},\ \Delta,\ Re,\ We,\ Fr,\ S_0,$$

in which:

$$L_*=L/d,\ W_*=W/d,\ D_{50*}=D_{50}/d,\ \Delta=(\rho_s-\rho_w)/\rho_w,$$
$$Re=Ud/\nu,\ We=\rho_w U^2 d/\sigma,\ Fr=U/(gd)0.5,\ S_0=U^2/\left(C^2 d\right)$$

The first three terms can be used to achieve geometric similarity. The other terms need to be equal in the model and in the prototype to achieve dynamic similarity. The submerged density of the sediment (Δ) represents the ratio of gravity and buoyancy (lift), the Reynolds number (*Re*) the ratio between inertia and viscosity, the Weber number (*We*) the ratio between inertia and surface tension, the Froude number (*Fr*) the ratio between inertia and gravity, and the equilibrium slope (S_0) is the balance between gravity and drag.

From this set, we can obtain the dimensionless particle number D_* (van Rijn, 1984a), the shields parameter θ (Engelund and Hansen, 1967), and the interaction parameter γ defined as (Struiksma et al., 1985):

$$D_*=\Delta^{1/3}Re^{2/3}Fr^{-2/3}D_{50*}=D_{50}(\Delta g/v^2)1/3,$$
$$\theta=S_0(D_{50*}\Delta)^{-1}=U_2/(C^2\Delta D_{50}),$$
$$\gamma=2\left(\Delta D_{50*}S_0^3\right)^{-1}(W_*/Fr)^2=2(UgW^2)/\left(C^3d^2(\Delta D_{50})^{0.5}\right)$$

The dimensionless particle number represents the relation between the combined effect of gravity and buoyancy, and viscosity. Based on this parameter, it is possible to predict the bed-form regime (van Rijn, 1984b). The Shields parameter

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expresses the ratio between drag, buoyancy and gravity acting on the particle. It describes the mobility of the sediment on the bed. The interaction parameter can be used to quantify the spatial lag between streamline curvature and bed response. These parameters form the basis for the experimental design and the interpretation of the experimental results.

3. Experimental setup

3.1. Prototype

The prototype at bankfull conditions consists of a 260 m wide, mildly curved section of the river Waal, The Netherlands. The training dam is a longitudinal construction that will be placed at the inner side of the bend, 30 m further into the river with respect to the head of the groynes, as indicated schematically in Fig. 1. The dam has a planned length between 3000 m and 5000 m, depending on the length of the bend. All groynes behind the training dam will be removed, except for the first one the flow encounters after the intake section, which is lowered. Between the single groyne that remains in the side channel and the training dam, a fixed weir controls the intake of water behind the dam (Fig. 1). The cross-profile of the prototype training dam is trapezoidal, with lateral side-slopes of 0.33, and a 2 m wide upper base.

At the planned section, the sediment has a D_{50} of 1.2 mm and a D_{90} of 2.0 mm. The sediment transport consists predominantly of bedload. According to Sieben (2007), scour holes caused by groynes in areas with limited exposure to waves from shipping typically have a depth of 2.7 m below the average river depth, and the distance from the head of the groyne to the deepest point in the scour is about 120 m at inner banks. The inclination angle between the orientation of the scour and the centreline is around 38°. These values were determined by fitting a 2D function to time-averaged bed elevations from the River Waal. The average flow velocity in the prototype is typically 1 m s^{-1}. The mean depth is about 4 m at low stage, and 8 m at high stage with a corresponding discharge of 1250 m^3 s^{-1} and 4600 m^3 s^{-1}, respectively. These two contrasting hydraulic conditions, representing low flow and high flow conditions, are the basis for the experimental setup.

3.2. Scaling and model setup

Since the main purpose of the model is to study the morphological effects around the intake of the training dam, the upstream area is projected onto a straight flume in the Kraijenhoff van de Leur Laboratory for Water and Sediment Dynamics at Wageningen University (Fig. 2). The flume has a width of 2.6 m and a length of 12.6 m. To minimize boundary effects, we extended the model domain upstream, to include two upstream groynes, and in the downstream direction with the same distance (Fig. 2). The main difference with the prototype is the absence of the mild curvature, and the spacing between the upstream groynes. The spacing between the groynes was somewhat distorted to be able to include two groynes before the training dam, which will allow the flow to adapt to the presence of upstream groynes.

Fig. 2. The model domain extends from halfway the groyne length up to halfway the fairway. It includes two upstream groynes, to properly reproduce the flow pattern reaching the head of the training dam. Water is flowing from top to bottom.

In the lateral direction, the model extends from halfway the groynes until halfway the fairway. The modelled area is 156 m wide and 756 m long in the prototype. We used a geometric scaling factor $n_L = 60$. Since bedload is the main mode of sediment transport, and the main driver of morphological changes of the bed, we scaled the hydraulic conditions primarily based on the Shields parameter.

To properly scale bedload sediment transport according to the Shields parameter, retaining a reasonable scale relation with respect to the Froude number, polystyrene granulates were used for which $\rho_s = 1055$ kg/m^3, $D_{50} = 2.1$ mm and $D_{90} = 2.9$ mm, so that $D_* = 16$. Since the Chézy coefficient cannot be determined a priori, we measured the water surface slope to determine the Chézy coefficient during the experiments, and we adjusted the imposed discharge until we obtained an appropriate value of the Shields parameter. The final optimized results are as listed in Table 1. The largest compromises were made to D_{50*}, Δ, Re, We, which differ between the model and the prototype.

At the start of the experiments, the flume features a flat bed. A sediment recirculation system was used to ensure an input rate of sediment similar to the rate of transport in the flume (Fig. 3). The sediment is trapped at the downstream end of the flume in a settling basin. At the bottom of this basin, a mixture of water and sediment is pumped to the upstream end of the flume, while the majority of the clear water discharge leaves the flume over the spillway at the end of the flume. The incoming water-sediment mixture is distributed over the width of the flume using a diffusor. Since the sediment used is nearly uniform, no partial transport is expected (Parker and Wilcock, 1993). A laminator ensures suppression of turbulence at the inflow of water into the flume.

During the low flow experiments, the water surface remains below the top of the groynes and the training dam. A small

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Table 1
Scaling of Dimensionless parameters for low and high water situation.

Variable	Low flow experiment			High flow experiment		
	Prototype	Model	Scale	Prototype	Model	Scale
L_*	136	82	1.66	95	57	1.66
W_*	28	28	1	19.5	19.5	1
D_{50*}	2.17e-4	228e-4	9.5e-3	2.17e-4	228e-4	9.5e-3
Δ	1.65	0.055	30	1.65	0.055	30
Re	4,165,000	12,300	326	6e6	18,500	324
We	74,600	28	2639	107,500	41	2629
Fr	0.14	0.16	0.86	0.11	0.13	0.86
S_0	8.9e-5	13.8e-5	0.64	6.2e-5	9.6e-5	0.64
θ	0.25	0.11	2.26	0.25	0.11	2.26
D_*	25	16	1.54	25	16	1.54
γ	3.84	2.95	1.30	1.85	1.41	1.31

portion of the total discharge is directed to the side channel. A separate pump was placed near the outlet of the side-channel, to obtain control over the discharge through the side channel. For each model run, we performed several scans of the bed elevation (15 during low flow and 16 during high flow), to estimate the mean bed surface topography and the superimposed variability related to bed form dynamics.

The flume is equipped with an electromagnetic flow meter to monitor discharge. Water levels were recorded with a magnetostrictive linear position sensor. To determine the surface level slope accurately, we measured the water level difference with a differential pressure transmitter, which was connected to a set of Pitot tubes. Bed levels were probed with a laser distance sensor. The laser sensor was operated during still water conditions, to avoid inaccuracy due to a rough water surface. We accounted for diffraction errors during post processing of the scanned bed levels, following the approach of Visconti et al. (2012). Outliers and small errors in the probed bed elevation were filtered out and bed elevations were interpolated to a common grid with a two-dimensional loess filter with a span of ca. 6 cm^2 (Cleveland et al., 1988).

We quantified dune characteristics to compare these with the prototype conditions. We performed this analysis in the fairway region where bedforms were observed (this region is indicated by the dashed lines in Figs. 4 and 5). We first filtered out large-scale variations with a two-dimensional loess filter with a span of ca. 4 m^2. Afterwards maxima and minima are detected along the longitudinal direction, and dune dimensions are determined following an approach similar to van der Mark et al. (2008).

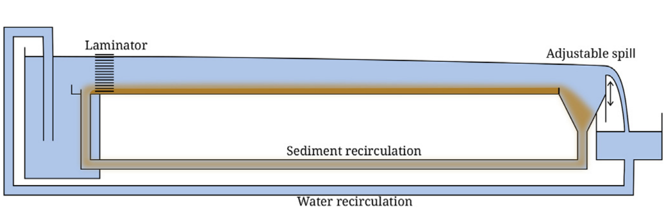

Fig. 3. The flume is equipped with a sediment recirculation system. The laminator suppresses excessive turbulence caused by the inflow of water in the flume.

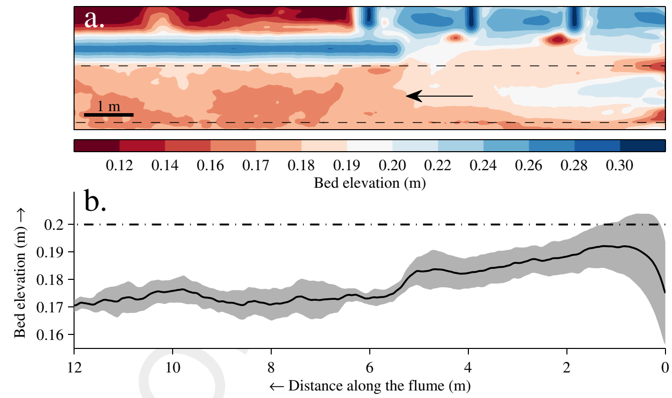

Fig. 4. Top view of averaged bed elevation for the low water experiment (a); Side view of bed elevations averaged over the dashed area in the upper panel (b). The grey area in (b) corresponds to the bed elevation plus and minus one standard deviation. The dash-dotted line indicates the initial bed-level.

4. Results

4.1. Low flow experiment

During the low-flow experiment, local effects are found near the groynes and between the training dam and the side wall of the flume (Fig. 4a). The areas between the groynes aggrade, while next to the groyne heads erosion creates large scour holes. Despite the low discharge, which is unlikely to cause the scour holes in the prototype, the depth of the scour-holes is very similar to the corresponding prototype depth, i.e. 2.5 m in the model compared to 2.7 in the prototype (Sieben, 2007). This suggests an overestimation of the scour depth, while the distance to the point of highest depth is about half the corresponding distance in the prototype. The angle the scours form with the centreline is similar to the angle in the prototype scours. Due to constriction of the flow caused by the training dam, the streamlines are curved near the head of the dam. Flow separation and shedding of vortices, appear to exert only a limited morphological impact on the region adjacent to the dam, much smaller than the impacts of river groynes. On

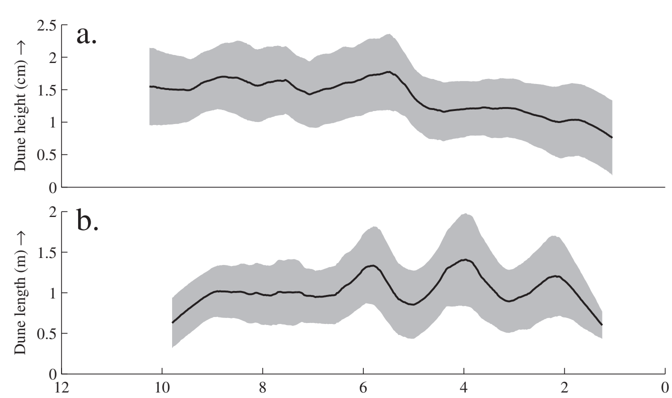

Fig. 5. Dune height (a) and length (b) for the low water experiment. Dune height increases along the training dam. Dune length peaks near the groynes and at the head of the training dam.

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the riverbank side of the training dam, erosion creates a small channel, which follows the shape of the dam, connecting the head of the dam with the downstream weir.

General degradation of the bed occurs in the region next to the training dam (Fig. 4b). The constriction of the flow causes an increase in transport capacity, resulting in increased sediment transport. The associated degradation of the bed is considered a positive effect of the training dam, since it increases the depth of the fairway. The increase in depth next to the dam is about 3 cm in the model, which corresponds to 1.8 m in the prototype.

In response to the increased water depth, dune heights increase in the section next to the training dam (Fig. 5a), as dune heights scale with the water depth (van Rijn, 1984b). Dune lengths are on average 1 m, but show peaks nearly exceeding 2 m in the areas facing the groynes and the head of the training dam (Fig. 5b). In the region next to the training dam, the dune height is 1.5 cm, which corresponds to a prototype height of 90 cm. Before the training dam, the dune height is ca. 1.0 cm, corresponding to 60 cm in the prototype. This is quite close to typical values reported for Dutch rivers, which are in the range of 20–50 cm (van Rijn, 1984b). Dune length fluctuates around 1 m, which corresponds to 60 m dunes in the prototype, which seems to be slightly overestimated. Nevertheless, the friction factor (C) found in the model compares well with values found in the prototype, as the scaling ratio for C is 1.07. Dune lengths peak near the tips of the groynes and near the head of the training dam (Fig. 5b).

4.2. High flow experiment

During high flow, the bed strongly scours at the groynes, especially near the head of the first groyne, where separation occurs (Fig. 6a). The scour hole at the first groyne is overestimated, compared to the prototype, i.e. 3.6 m in the model compared to 2.7 m in the prototype (Sieben, 2007). The deepest point, however, is closer to the groyne than in prototype conditions. The scour extends from the groyne head toward the fairway, extending up the scour near the head of the training dam. Scouring at the second groyne is much smaller, and similar to the scouring observed during low water. Sedimentation occurs between the groynes, upstream of the groyne heads. Near the side wall of the flume, the bed is eroded. This pattern indicates conditions that are more dynamic during high water, compared to the low water condition. There are no local effects present near the head of the training dam, on the fairway side. A vortex street commencing at the head of the training dam remains close to the dam, and therefore does not induce scouring, since the excess stress is exerted on the concrete slope of the dam. The streamlining of the training dam minimizes local scouring near the head of the dam. At the bank side of the training dam, strong scouring occurs due to the strong inflow into the side channel over the weir.

Deepening of the main channel section along the training dam is strongest near the head of the dam (Fig. 6b). It is not clear whether the excessive scouring near the first groyne is also affecting the region near the training dam. The reduced scouring toward the end of the flume is attributed to the higher water level, overtopping the training dam, which allows for exchange of momentum in the fairway section with the region behind the training dam, decelerating the flow. In the upstream section of the flume, sedimentation is observed in the fairway. This causes the flow to concentrate right before the first groyne. This convergence of the flow in front of the first groyne might be causing the excessive scouring. The average scour depth next to the training dam is about 1.5 cm, corresponding to 0.9 m in the prototype.

In the high flow experiment, dune heights increase almost linearly along the flume (Fig. 7magnetostrictive) from ca. 1 cm up to almost 3 cm corresponding to 0.6 m and 1.8 m for the prototype, respectively. This shows that the dunes are still in a stage of development. The heights, however, are within the expected range for the prototype (typically 30–85 cm). The dune lengths remain constant, around 1 m. This corresponds to 60 m in the prototype and is close to values typically found in the prototype under these flow conditions (about 58 m).

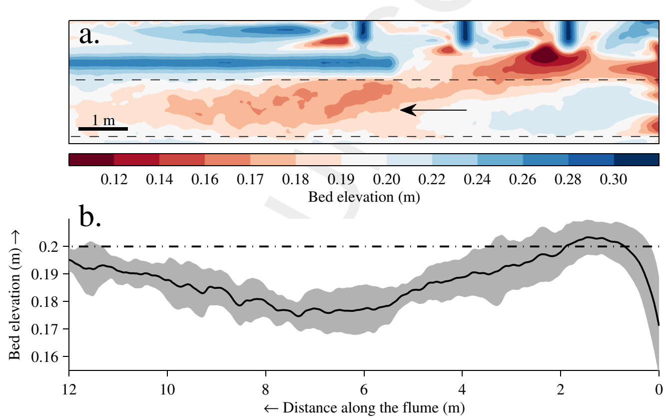

Fig. 6. Top view of average bed level for the high water experiment at end of the model run (a); and side view of the bed elevations, averaged over the area indicated in panel a by the dashed line (b). The gray area in b corresponds to the bed elevation plus or minus one standard deviation. The dash-dotted line indicates the initial bed-level.

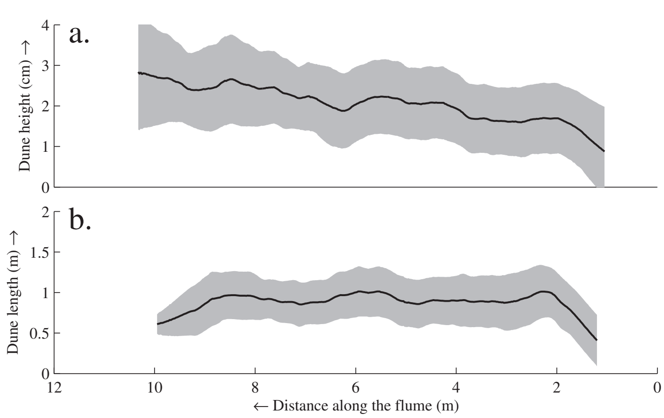

Fig. 7. Dune height (a) and length (b) during the high flow experiment. Dune heights increase from the beginning to the end of the flume. Dune lengths remain relatively constant.

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5. Discussion

The model results obtained in the present study provide qualitative insight into the local morphological effects at the intake section of a training dam. The reasonable dimensions of the bedforms and the proper reproduction of the roughness factor suggest that the morphological behaviour is, at least in a qualitative manner, properly reproduced. The compromised scaling of several of the dimensionless numbers leads to unavoidable scaling effects in the model results. This affects the results, and especially the magnitude of scouring and deposition. Exact scouring depth and amounts of erosion and deposition are not considered reliable enough to directly infer their corresponding prototype values. The location and occurrence of scouring and deposition is expected to be well reproduced. The origin of the peaks in dune lengths near the head of the groynes and the head of the dam is unclear. Complementary velocity data could shed light on the underlying processes.

The Shields parameter in the model was slightly overestimated, resulting in a degree of mobility of the granulates, which was somewhat too high. Morphological changes in the flume are therefore likely to be overestimated as well. The strong scouring at the first groyne during high flow and the slightly overestimated dune length during low flow can be related to this excessive mobility. The overestimated mobility reduces the time-scale for morphological development, limiting the chance that a longer duration of the experiments would yield different results. The excessive depth of the scour holes in front of the groynes, whether or not related to sediment mobility, indicates that the model exaggerates the morphological response to perturbations. In the closed circuit, the additional erosion in the scour holes implies additional sedimentation someplace else in the model, considering the quantity of material in suspension to remain unchanged. The exaggeration of erosion and deposition in the model, in turn, suggests that the absence of a local bed development around the intake section can be considered realistic. Based on the results, we do not expect the development of areas of deposition that may cause impediment for navigation.

The buoyancy (or submerged density) of the sediment is overestimated by 30 times. Once the sediment is entrained in suspension, it will remain in suspension for a much longer period, resulting in higher suspended sediment concentrations (Hughes, 1993). The use of polystyrene sediment in physical scale models is therefore not recommended to reproduce those processes for which suspended sediment plays an important role. Useful results are expected for processes dominated by bedload transport. In the model, the side channel behind the training dam captured a portion of the sediment in suspension, both in the low-flow experiment and in the high flow experiment. The import of sediment in the side channel is not considered reliable.

6. Conclusion

Based on results from high-flow and low-flow experiments in a physical scale model, the local morphological developments in the direct surroundings of the intake section of a longitudinal training dam are expected to be limited. No depositional areas are to be expected which could possibly cause impediment for navigation. Although scale effects may be present in the model, this conclusion can be underpinned with two considerations. Firstly, the dunes that developed in the polystyrene granulates were similar to the prototype, especially regarding dune height, and the deepening of the fairway in response to width reduction agreed with expectations. Secondly, the mobility of the granulates in the model was too high, which resulted in scour holes in front of a groyne that were too deep. As a consequence, the model may be expected to exaggerate the morphological response to perturbations of the flow, such that the absence of depositional areas can be considered realistic.

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