

# Model experiments: Influence of floods on sediment deposits in rivers equipped with groynes

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**ABSTRACT:** Research of the behaviour of groyne structures during floods is topical. However, flood effects on sediment layers situated in groyne fields of large rivers are still not well understood. Sediment layers, often strongly polluted and restricted in their movement by groyne structures, represent a hazard for the river and its neighbouring floodplains during high discharge events. The erosion effects of floods on these sediment layers are focused on herein. A model of several groyne sections of a straight river stretch and its near floodplain – representative of the Rhine and Elbe Rivers – was built in a wide laboratory flume. The influence of flood discharges on sediment deposits in groyne fields was studied by evaluating the flow fields and the sediment transport in the main channel and floodplain of channels with groyne fields. The locations and geometries of the main flow structures and erosion patterns are identified. The experiments show that even during flood discharges the groyne fields act as dead water zones and minimal erosion occurs. Additionally, three different flow patterns are identified for the groyne. For emerged groynes a double-eddy pattern for normal winter discharges and a one-eddy pattern for a summer discharge are observed. Conversely, for submerged groynes, the flow at the water surface was mostly unidirectional. The results are discussed in relation to river pollution and biodiversity.

*Keywords: Hydraulic model; Groyne; Sediment; River; Flume.*

## 1 INTRODUCTIONS

### 1.1 Background

Large rivers in Europe, such as the Rhine and the Elbe Rivers, are strongly regulated in order to control floods, to guarantee navigation for ships during low water levels or to create new cultivable lands. Groynes are often used for these purposes. However, the suppression of meanders and the creation of a straighter river, combined with high pollution rates on the Rhine and the Elbe River, have negative consequences on their biodiversity (Boehme, 2006; Schwartz, 2006).

Nevertheless, as a consequence of setting up the International Commission for the Protection of the Rhine (IKSR) in 1965 and the Elbe (IKSE) in 1992 by the European Union, the water quality of these rivers has increased over the last decade and an expansion of indigenous species in the waters can be observed.

Groyne fields usually contain the same benthic species as meanders (Nakano and Nakamura, 2006), and are becoming increasingly important to fluvial biodiversity (Schwartz and Kozerski, 2004; Boehme, 2006).

As groyne fields also act as a substitute to natural dead water zones, fine, highly polluted sediments are deposited on the natural sand bed of the river and create an organic mud layer containing high concentrations of heavy metals (Schwartz and Kozerski, 2004). It is accepted that high discharges, as experienced during floods, remove this layer from the groyne fields, either through downstream migration or deposition of sediment on the floodplain (Ten Brinke et al., 2004). Displacement of the mud layer to the floodplains and to downstream groyne fields or even the main river channel, provides mobility of the pollution hazard. As a consequence, the IKSR and IKSE advice is to dredge polluted sediment layers.

As flood behaviours and sediment transport can hardly be predicted in such a complex structure, a physical model is the most appropriate way to simulate the displacement of the sediment layers in flood conditions.

### 1.2 Objectives and approach

For this study, the effects of a succession of seasonal discharges were observed using a groyne field laboratory model. The migration of sediment layers was analysed. Additionally, an evaluation of the hydrau-

lic behaviour of the groyne fields under several discharges is provided. For the experimental study a physical model was built in a wide flume. The effects of the flow on the floodplain deposits and on the groyne fields ecosystem are discussed.

## 2 EXPERIMENTAL SETUP

The flume used for the experiments (Figure 1) is 13-m-long and 2.44-m-wide. The slope of the flume is adjustable. The discharge and the velocity can also be adjusted. A 2D flow is ensured using a flow straightener. The flume floor is a concrete structure.



Figure 1. Wide flume used for the study. Downstream view. From left to right: floodplain, four groynes, main channel.

### 2.1 Model characteristics

The model built in the flume contained a floodplain, four groynes and the main channel (Figure 1 and Figure 2). The model was built of metal sheets. The roughness of the originally smooth metal sheets was increased by gluing coarse sand and fine gravel particles on to it. Individual groyne structures were 0.13-m high, 0.4-m wide and 1-m long. The width/length ratio for the groynes was equal to 0.4. This ratio was chosen to allow the formation of a double-eddy pattern (Uijttewaal et al., 2001) and is representative of a standard groyne field in the Elbe River (Sukhodolov et al., 2002).

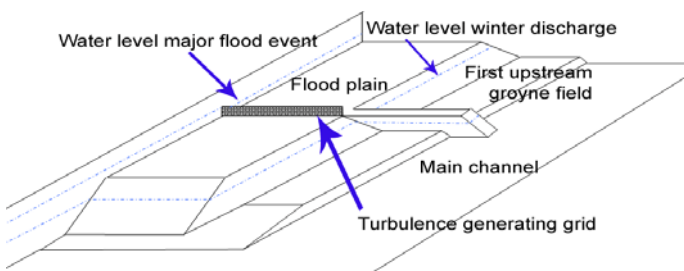


Figure 2. Schematic 3D partial view of the experimental groyne field. Flow is from bottom to top.

### 2.2 Scale effect considerations

In order to reproduce accurate surface roughness characteristics for both the main channel and the floodplain, fine gravel ( $d_{50}=3\text{-mm}$ ) and fine sand ( $d_{50}=0.27\text{-mm}$ ), respectively, were glued on the metal sheets. These sediments are ten times larger than the predominant sediments in the Elbe River and flow velocities in the model needed to be adapted. In order to represent typical flows of the Elbe and Rhine Rivers, the model was therefore exposed to the following four discharge conditions: a summer discharge (main channel velocity: 0.20-m/s), a major flood event (0.51-m/s), a seasonal flood event (0.42-m/s) and a winter discharge (0.33-m/s). Although effort was put into minimising scale effects, Reynolds numbers are orders of magnitudes larger in real rivers and results need to be interpreted carefully.

According to Bousmar et al. (2005), in model experiments the floodplain discharge is often too large compared to the main channel discharge of the model study and a mass transfer towards the main channel can occur along the flume. As the length of the model study was restricted by the flume length, a turbulence generating grid (Figure 2) was placed on the floodplain section of the model at the inlet end of the flume, thus allowing the discharge distribution to reach equilibrium through mass transfer between the floodplain and main channel. The increased turbulence and decreased flow velocity of the floodplain compared to the main channel also reflected the higher Manning coefficient for floodplains (Büttner et al. 2006).

### 2.3 Measurement techniques

3D flow velocities were measured using an ADV probe in the bulk flow during the experiments. The discharge in the flume was determined using an orifice plate in the supply pipe.

A bed profiler, which consists of an acoustic depth sounding probe mounted on a motorised carriage (Figure 3), was used to measure 11 continuous bed profiles within groynes two and three at the end of each measurement phase. The recording resolution was  $\Delta x=100\text{-mm}$  in the flow direction and  $\Delta y=1\text{-mm}$  across the groyne. As the position of the carriage was precisely known during these measurements, the 11 profiles can be used to plot a 3D representation of the groyne topographies.

A wide angle camera was used to record the flow fields. A dye injection system was implemented, which did not alter the hydraulic conditions, as the injection pipe is buried in the sediment layer. Discharge points, located every 5-cm along the injection pipe, allow dye injection across the entire groyne. Three different injection methods were used: single short injections, continuous injections and a series of injections at certain time intervals.

## 2.4 Experimental procedure

During initial testing, the fine sand was supplied to the system upstream of the model and allowed to settle in the main channel and the groyne field (Figure 3). These tests were run under summer discharge conditions for several days to allow for an accurate deposition of sediment on the model.

In order to study the effect of floods on sedimentation behaviour in the groyne field, a winter discharge (main channel velocity: 0.33-m/s; water depth: 0.1-m; emerged groyne structure) and a major flood event (main channel velocity: 0.51-m/s; water depth: 0.16-m; submerged groyne structure) were alternately applied to the model. The experiments were run for two phases of one week each. Initially the model was exposed to the winter discharge. After 23-hrs the discharge was adjusted to a major flood type event (for 20-hrs). After 43-hrs the discharge was again changed back to a winter discharge (for another 20-hrs). Finally, a second flood phase was applied to the model (21-hrs).

Additionally, the model was exposed to one single flood event for 63-hrs to study the changes of groyne field topographies for this single event.

The flow was stopped during measurement to avoid scouring when traversing the acoustic depth sounder. The flow velocity was gently decreased while keeping the same free surface water level in the model. After completing the measurements, the water was completely drained from the model to allow photographic recording of the groyne field topography. While draining the model, care was taken to avoid sediment movement. The above described discharge cycle results in topography measurements every 0, 23, 43, 63, and 84 hours.

The corresponding flow field patterns were also studied separately for the winter discharge (0.33-m/s) and the major flood event (0.51-m/s), as well as for a summer discharge (0.20-m/s) and a seasonal flood event (0.42-m/s). The additional flow discharges allowed us to study changes in flow field patterns more accurately.

Before dye experiments took place, the sediment layer was exposed to the studied discharge for 24hrs, in order to adjust to the flow conditions.

## 3 EXPERIMENTAL RESULTS

### 3.1 General remarks

Both main experimental phases revealed similar sedimentation and hydraulic behaviours. The relevance of the model observations and how feasible it is to describe a reproduction in the real river environment are discussed in the following sections for each separate groyne.

Behaviours in the vicinity of the furthest upstream groyne were influenced by the perturbations arising from the placement of the model itself. The placement of the model resulted in a reduction of the flow width just upstream of the model section, and therefore caused a more pronounced than usual erosion behaviour near the groyne. More than 75% of the initial sand volume was washed out during the experiment. Therefore, observations for this groyne cannot be used for any interpretation, which shows that a single-groyne field does not allow for the river flow to adapt to groyne structures. A significant part of the sand eroded from the first groyne was deposited on the floodplain near the second and third groynes (Figure 4).

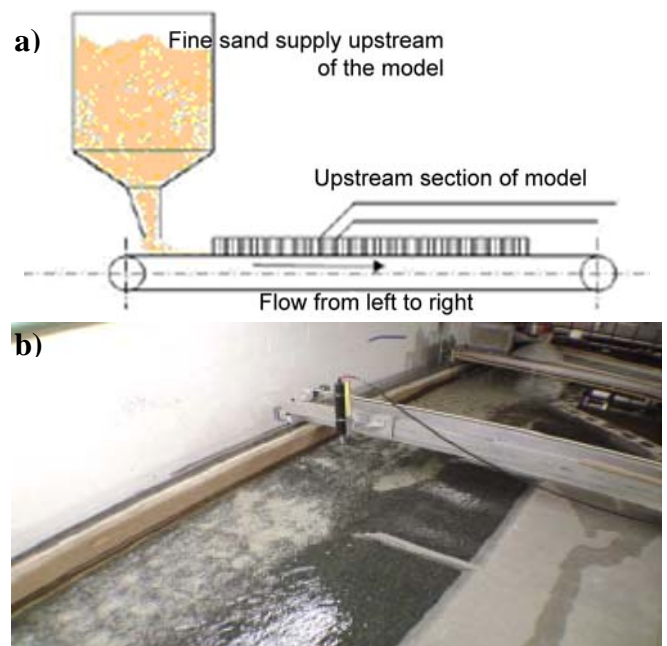


Figure 3. a) Schematic side view of initial sand supply to model. b) ADV on motorised carriage with upstream sand supply unit. Flow from top to bottom – floodplain on the right.

The second groyne featured a slight influence of the limited combined length of groynes one and two. A significant part of the sand eroded from the first groyne was deposited at the second groyne. However, observations show that the effects of the second groyne were quite similar to those of the third and fourth groynes. Downstream of the first groyne, similar deposition features were observed as for the following groynes. At the second groyne, an overall deposition of sand occurred, as a significant amount of sediment from the first groyne was deposited at the second groyne (Figure 4).

Observations for the third groyne showed that it represents well the typical sedimentation as well as hydraulic behaviours. The flow field in the main channel adapted to the existence of the groynes. The observations for the third groyne are discussed in more detail in Section 3.2, as it provides representative information.



The fourth groyne was influenced by the end of the model, although the sedimentation pattern is similar to those for the second and third groynes.



Figure 4. Top view of groynes two to four. Flow is from bottom to top. Main channel on the right and floodplain on the left.

### 3.2 Representative groyne

The third groyne is used as the representative groyne in order to discuss sedimentation issues as well as hydraulic behaviours in groyne fields. The third groyne was less influenced by the upstream and downstream ends of the model. The observations

were similar for both experiments. The global hydraulic flow pattern in this groyne resembles the in-situ tracer studies of Kozerski et al. (2006) for the Elbe River.

#### 3.2.1 Sedimentation

The variation of the global quantity of sediment in the groyne after alternating exposure to winter and flood discharge can be neglected (Figure 5b,c). Overall, slightly more sediment was deposited, than was eroded, at the third groyne .

When initially exposed to the winter discharge, the groyne quickly adapted to a stable condition, after major erosion took place in some areas during the early stage (Figure 5a). During the flood event the groyne continued to accumulate sediments in the lower velocity areas (Figure 5b). Even after the long simulation of a major flood event, and the following winter discharge, roughly 70% of the groyne topography was not altered significantly (Figure 5c). Therefore, the model reflects a relatively stable groyne even when exposed to high discharges.

Two main erosion zones were observed. The larger zone was located around 20-cm downstream of the upstream groyne structure. Its width along the groyne was very regular, until the scouring increased due to a secondary eddy near the floodplain. The second erosion zone was located upstream of the following groyne structure. From other research it is known that this zone contains high velocities (due to reduction of the section) and the core of the mixing layer.

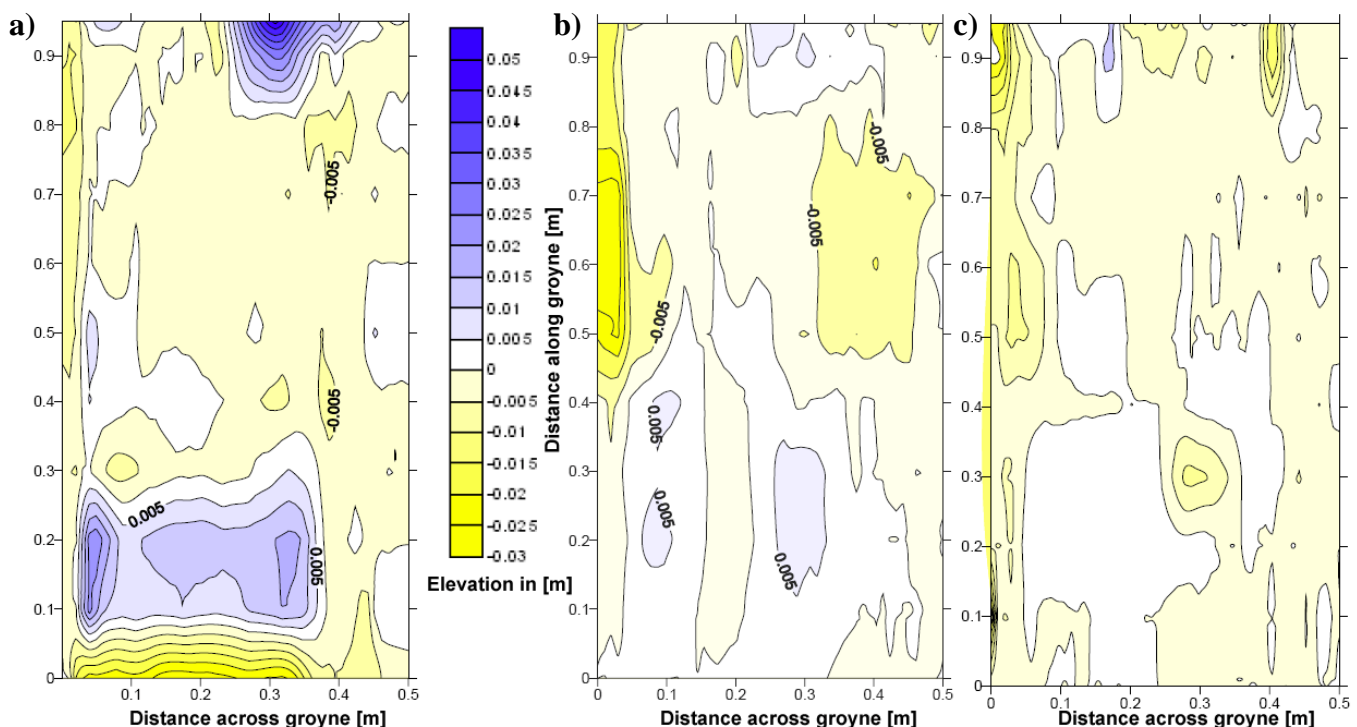


Figure 5. Relative bed elevation variations for the third groyne – a)  $t=0$ -hrs to 23-hrs, b)  $t=23$ -hrs to 43-hrs, c)  $t=43$ -hrs to 63-hrs. Blue indicates erosion and yellow deposition of sand. Flow from bottom to top. Floodplain left and main channel right.

Deposition zones were observed in large parts of the groyne. The deposition was slightly more pronounced in some areas than in others. The main deposition area was immediately downstream of the first groyne structure, utilising the quasi dead water zone created by the obstacle. Other deposition areas were observed near the centre of the groyne and along the floodplain.

As no additional sand was supplied during the main experiment, the observed newly deposited sand at the groyne was eroded upstream. For natural river environments it can be concluded that during flood events a large amount of upstream sediment, transported with the water flow, is deposited in dead water zones.

The results for the extended single flood event are shown in Figure 7. The variations of groyne topography are minimal between Figure 7a and Figure 7c, indicating that even during flood discharges the groynes act as dead water zones and minimal erosion occurs.

### 3.2.2 Flow field pattern

#### 3.2.2.1 Normal discharge

Two different discharges were tested with groynes, which protruded above the water surface (termed “emerged groynes”): a summer discharge, characterized by very low flow velocities (0.2-m/s) in the bulk flow and a low water level near the groynes, and a medium discharge (0.33-m/s), simulating a winter discharge. The results agree with observations of previous studies at similar groyne fields (Uijtewaal et al., 2001; Kozerski et al., 2006).

The characteristic hydraulic pattern for the winter discharge is represented in Figure 6. The currents in the groyne follow a double-eddy pattern. A major part of the field is occupied by the main eddy. Low to very low velocities are observed in this eddy, as a single revolution within a winter medium discharge takes 50-sec. The centre of the eddy acts as a dead water zone.

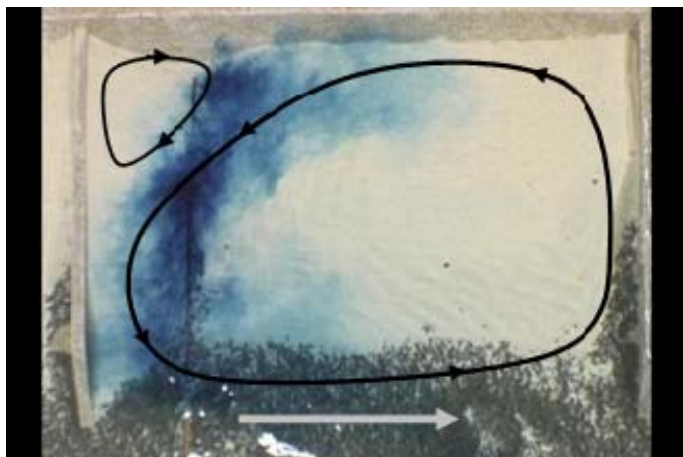


Figure 6. Flow field for winter discharge. Main eddy and secondary eddy. Flow is from left to right.

A secondary eddy is caused by spatial restrictions for the backflow of the main eddy through the upstream groyne structure and the embankment. The size, stability and flow velocity of the secondary eddy strongly depend on the discharge and on the water depth at the groyne. The secondary eddy was not observed or was unstable during tests for the summer discharge. For this case, the velocities in the area formerly occupied by the secondary eddy are low enough to change this zone into a dead water zone. The flow field structures did not change significantly across the water depth, except close to the sand bed due to bed friction. Independent injections of dye across different water depths showed the same flow field pattern, as described above.

#### 3.2.2.2 Flood discharge

The hydraulic pattern observed for submerged groynes during flood was different from that observed for emerged groynes. For a major flood event, the observed secondary eddy during normal discharge disappeared and a straight upstream-to-downstream current dominated the flow over the whole groyne (Figure 8).

For submerged groynes, the water flows over the groynes and dye injections show that, initially, multiple unstable eddies are formed just downstream of the groyne structure. This allows the flow to erode sediment, as shown in Figures 5 and 7. At a point about 25% along the groyne, the eddies do not exist anymore and dye visualisation shows a stable unidirectional flow at low velocity (0.1-m/s as compared to 0.5-m/s in the main channel). This allows for deposition of sediment along most of the length of the groyne. The more pronounced erosion near the main channel is due to the higher flow velocity in this area.

However, as Figure 8 shows, minor traces of the double-eddy pattern, as observed for the emerged groyne case can still be identified. Near the upstream groyne head, a back current following the lateral direction diverted water from the field to the bulk flow.

The transition study (seasonal flood event with main channel velocity of 0.42-m/s) emphasised the progressive transition from double-eddy pattern to unidirectional downstream flow. The main eddy observed for the emerged groyne case slowly weakened, and the secondary eddy simultaneously gained strength. Consequently, an equilibrium between the downstream flow over the groyne structure and the upstream current of the main eddy resulted in an unstable dead water zone. Deeper water layers are governed by the double-eddy pattern, whereas layers close to the water surface adjust to the unidirectional flow observed for the submerged groyne flood event.



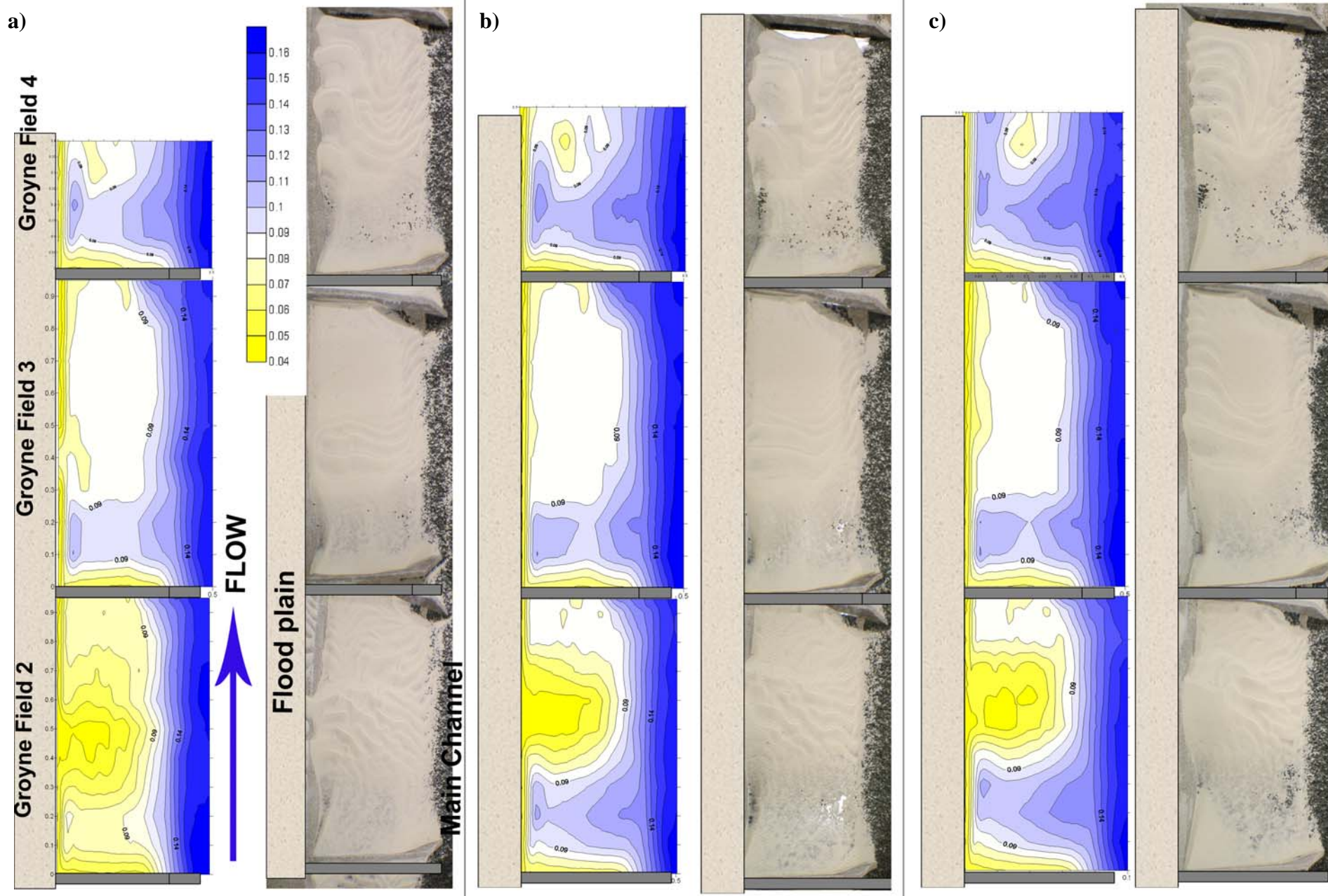


Figure 7. Change of bed elevations (cm) during prolonged flood period for groynes two to four. Blue indicates erosion and yellow deposition of sand. a) t=0-hrs to 17-hrs, b) t=17-hrs to 41-hrs, c) t=41-hrs to 63-hrs. Reference point is 5-cm above floodplain, with numbers indicating distance away from reference point.

### 3.2.3 Floodplain interaction

No direct flow between the groyne and the floodplain could be observed for submerged groyne studies, with the exception of the first upstream groyne. Here the initially overloaded groyne caused a diversion of the flow towards the floodplain and resulted in the deposition of eroded sand from the overloaded groyne on the floodplain (Figure 4).

## 4 FURTHER OBSERVATIONS AND DISCUSSION

### 4.1 Sedimentation

The experiments reveal the areas which are eroded during floods (Figure 5 and 7). The flow fields that cause this erosion are revealed by dye experiments.

A local reduction of the flow width upstream of the head of the first groyne is responsible for the deep, but spatially restricted, erosion in the first groyne. Observations reveal that the erosion is controlled by the following three components:

- Pronounced erosion downstream of a groyne structure, caused by the turbulent flow field.
- Erosion near the main channel, due to an acceleration of the flow from the main channel to the floodplain, caused by the main eddy. This process was apparent for all tested discharges.
- Erosion near the floodplain, due to the double-eddy pattern. The influence of the main eddy is less important near the floodplain and the extent of erosion depends on the secondary eddy.

### 4.2 Flow field pattern

The average flow velocity in the main channel has only a minor influence on the flow pattern under

normal discharges. However, the water depth near the groyne plays a significant role in the flow pattern. The shallowest depth (summer discharge) results in a disappearance of the secondary eddy, with the flow circulating around a unique eddy. The winter discharge allows the formation of a double-eddy pattern. Whereas during a flood event, the flow is regulated in the field, resulting in a unidirectional flow, because only the lower layers of water are influenced by the remaining eddies' effects.

A shallow depth and consequently slower flow velocities allow a greater deposition of sediment. The instability of the secondary eddy is observed during summer discharge conditions, when the momentum of the entering water is too low to create the secondary eddy.

### 4.3 Pollution and biodiversity issues

The study has revealed two different spatial scales for the hazard induced by polluted sediment layers in groyne fields. An internal pollution of the groyne field exists, transporting polluted sediments from one groyne to the next one. This presents a problem in case of removal of the pollutants from around only some of the groynes, because the polluted sediment layer can be readily re-deposited near 'clean' groynes.

The floodplain-groyne field interaction is only observed when the flow is perturbed by an obstacle, such as the initial excess sediment at the first groyne. The observations can be compared to sediment movement on the inner side of river bends, where during floods deposits are transferred to the neighbouring floodplains.

As the sediment transport takes place between groynes, a partial treatment (dredging only in some fields) is not a sustainable solution.

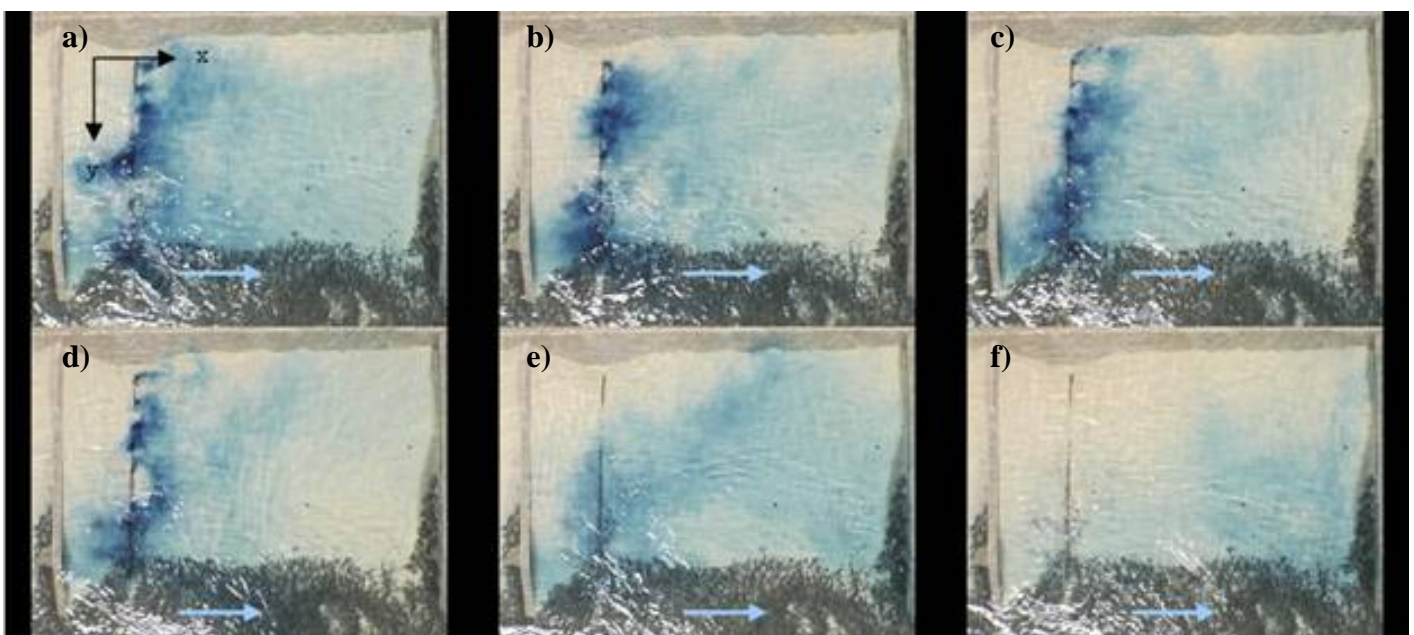


Figure 8. Flow field during major flood event. a)  $t=0$ , b)  $t=1$ -sec, c)  $t=2$ -sec, d)  $t=3$ -sec, e)  $t=6$ -sec, f)  $t=11$ -sec. Flow from left to right.

It is known that groyne fields with similar geometric ratios (permitting double-eddy pattern, rather than only a single eddy) provide habitats for various species and therefore stimulate river biodiversity. According to Grift et al. (2003), groyne beaches offer a refuge to juvenile fishes, whereas eroded areas provide a habitat for adult fish. Although our study showed the existence of the double-eddy pattern, the tests also revealed limited erosion during major flood events. As a consequence, it is planned to undertake studies with a V-shape groyne design, permitting a faster circulation of water in the middle of the groyne. This will allow better mixing of water and therefore distribution of sediment in order to provide healthier habitats.

The inability of the flow to remove most of the sediment from the groynes, even during flood events, requires human intervention. Otherwise, it is likely that once sediment layers are polluted, the amount of polluted sediment at neighbouring groynes will increase over time

## 5 CONCLUSION

The present experimental study was conducted in order to evaluate the influence of flood discharges on groyne field environments. The results are discussed in relation to pollution and biodiversity issues.

The study confirms that groynes act basically as dead water zones, even during floods. Only the areas directly influenced by the groyne structures are subjected to increased scouring, the rest of the field exhibiting flow velocities low enough to permit deposition under all tested discharge conditions.

Three characteristic flow patterns are observed at the groynes, a one-eddy pattern for a summer discharge, a double-eddy pattern for a winter discharge and unidirectional flow during a flood event. The study also showed that transitional flow patterns are observed during seasonal flood events.

The experiments show that the scouring process quickly attained equilibrium conditions during a prolonged flood event, and did not allow for a complete removal of sediments from the groynes, even during major floods.

## 6 ACKNOWLEDGEMENTS

R. Gasset would like to acknowledge the Department of Civil and Environmental Engineering at The University of Auckland, enabling him to undertake this study in Auckland. Furthermore the authors want to thank S. Reynaud for providing information about scale effects and adjustment in mobile bed experiments, and the technical staff, Geoff Kirby and Jim Luo of The University of Auckland.

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