River, Coastal and Estuarine Morphodynamics: RCEM2011

Morphodynamic responds of groyne fields to the lowering of crest level of the groynes in the Waal River, The Netherlands

Marcela María BUSNELLI, Filip SCHUURMAN
DHV Consultancy and Engineering, Department of River and Coastal engineering
Laan 1914 no 35, 3818 EX Amersfoort, the Netherlands

Arjan SIEBEN
Directorate General for Public Works and Water Management
Zuiderwagenplein 2, 8224 AD Lelystad, the Netherlands

Maarten VAN DER WAL
Deltares, Rotterdamseweg 185, 2629 HD Delft, the Netherlands

Huub HECTOR
Directorate General for Public Works and Water Management
Griffioenlaan 2, 3526 LA Utrecht, the Netherlands

ABSTRACT: The lowering of the crest of the groynes in the River Waal is one of the measures being applied in the Netherlands to reduce the water levels at high water conditions. A total of 750 groynes will be lowered lengthwise by 1 to 2 meters. An expected side-effect is sedimentation in the main channel, due to redistribution of the discharge in the cross-section. Also, the flow through the groyne fields will increase, so erosion in the groyne field is to be expected.

In order to get insight in the morphological developments after lowering the groynes, a pilot project has been conducted. It consisted of the lowering of the 70 groynes from April 2009 till September 2009. A monitoring program was implemented, including multi beam measurements of the groyne fields and the main channel. The measured groyne fields included river sections with and without lowered groynes. The measurements were carried out during a high water event, with a return period of once per year, in March 2010. Measurements of the bed levels for this high water event, were conducted at three moments: before the high water event, during the peak and after. The patterns of erosion and sedimentation in the groyne fields were analyzed and the effect of the lowering of the groynes on the morphology of the groyne field was quantified. This paper addresses the morphological developments of the groyne fields and near the head of the groynes.

The measurements show that between the initial situation and the discharge peak, erosion occurred in the groyne field in the first 40 m from the normal line towards the banks for both types of groyne fields. However, the amount of erosion in the groyne fields between lowered groynes, is twice as much as the erosion in the groyne field without lowering.

In the period after the peak discharge, in the first 25 m from the normal line towards the banks, sedimentation occurred in the groyne fields without lowering, and erosion in the groyne field with lowered groynes. Between 25 m and 50 m towards the banks, sedimentation occurred in both types of groyne fields, but the sedimentation in the groyne fields between lowered groynes was twice as much as in the groyne field between groynes without lowering.

Furthermore, the measurements show that the measured scour-holes near the groyne head, caused by local flow contraction and turbulence, are less deep for the lowered groynes. This is probably due to the

extension of the flow mixing layer over the lowered, submerged groynes. The lowered groynes are submerged for a longer period.

The new dynamic equilibrium situation has not yet been achieved. Further monitoring of the groyne fields will give additional insight and diminish the uncertainty regarding the morphodynamic responds.

1 INTRODUCTION

Because of the increasing peak discharge, the river Rhine geometry should be adapted in order to reduce the flood risk. Hence the river should accommodate a design discharge of 16,000 m^3/s at Lobith (on the Dutch-German border), which is an increase of design flow capacity by 1,000 m^3/s. In The Netherlands, this marks a new trend since the mid 1990's, when dikes were reinforced to anticipate increasing water levels. After two extreme flood events and with an increasing need to protect and reinforce river-nature developments, water management policies changed and from 1996, instead of raising the dikes, relandscaping flood plains is preferred to increase the river's discharge capacity. This means that the river is given more space in order to let it flow its natural way, instead of tightening the flow through higher dikes. The larger discharge capacity is being implemented within the framework of the project Room for the River Rhine Branches.

One of the measures of this frame work is lowering the groyne crests in the River Waal, one of the Rhine branches. Groynes are dams pointing at regular intervals from the banks in a direction perpendicular to the main flow. From 1850 on, they are constructed to normalize and fixate the main channel. By concentrating the flow at low discharge, the navigation channel is kept deep enough for the ships to pass. However, at high discharge, the groynes increase water levels and flood risk by blocking part of the flow.

Figure 1 illustrates the design of the lowered groynes. The groynes are lowered to the level OLR+1,2m, where OLR is the reference water level which corresponds with a 95% exceedance discharge of 1020 m^3/s at Lobith. This means that the crest of the groynes in the Waal River will be lowered by around 2 meters. The hydraulic effect of the lowering of the groynes is computed with a 2D hydrodynamic model which is the official instrument to evaluate the hydraulic effects of Room for the River Rhine Branches measures. The impact of groynes is simulated by additional energy losses computed from empirical weir coefficients (Busnelli et al, 2009). The computed decrease in water level, due to the lowering of the groynes in the Middle-Waal, is at maximum 12 cm for the design discharge (Figure 2).

After the lowering of the groynes, the groynes will be submerged at lower discharge than before lowering and, in case of submerged groynes, more discharge will flow trough the groyne fields, resulting in a reduction of discharge trough the main channel. This affects the flow velocity in the groyne fields and in the main channel (Figure 3). Hence, the lowering of the groynes will increase the flow capacity, but will affect the river morphology. The sediment transport capacity in the main channel will decrease, while the sediment transport capacity in the groyne fields will increase. An expected effect is deposition and consequently a raise of the river bed in the area of the lowered groynes.

Besides this, a reshape of the groyne field topography and a decrease of the scour hole depth near the groyne head are expected. The flow around the groyne head is complex and highly turbulent (Uijttewal 2001; Berg and Uijttewaal 2002; Yossef 2005). When the groynes are not submerged, a vortex will occur downstream of the groyne head, due to the detachment of the flow. This vortex causes the formation of a scour hole. When the groynes are submerged, the effect of the groynes on the local scour is reduced. Deeper holes will be created when the water level is just below the crest level of the groyne. Therefore, lower groynes would result in a decrease of scour hole depth.

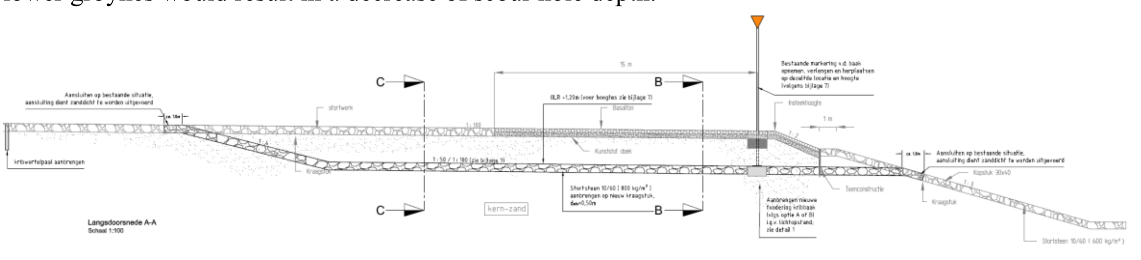


Figure 1 Design of lowering of the crest of the groynes (the right side is the river side)

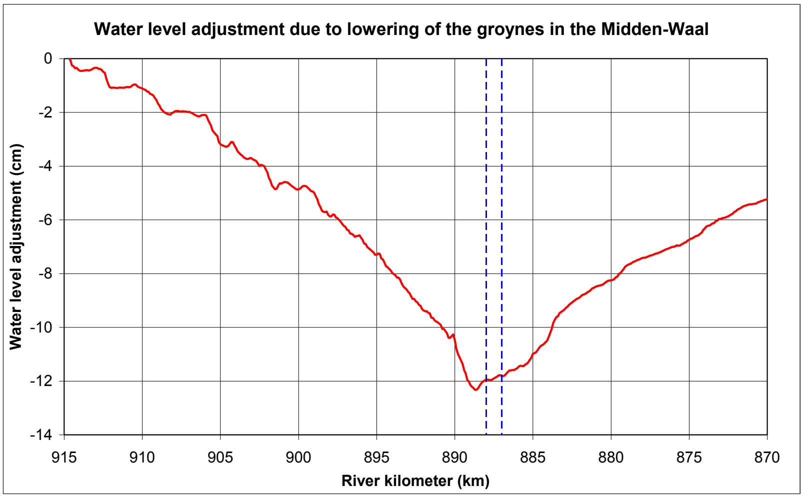


Figure 2 Effect of lowering of the groynes in the Midden-Waal on the water level at design discharge of 16,000 m³/s at Lobith

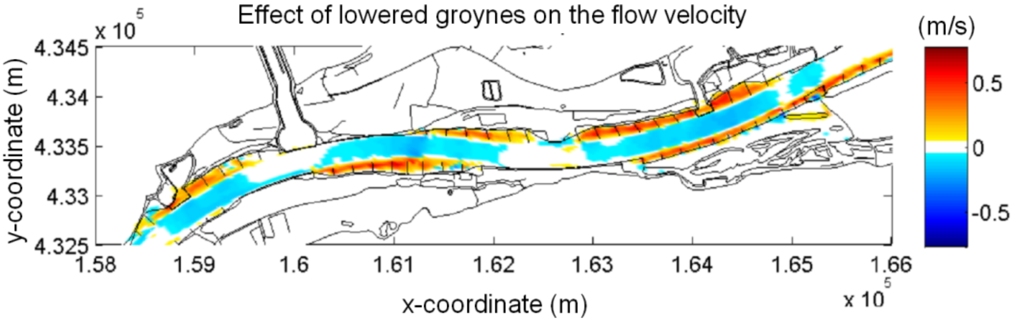


Figure 3 Effect of lowering of the groynes in the Midden-Waal on the flow velocity in the main channel and the groyne fields. Reduction of the velocity in blue, increase in red

The morphological developments in the groyne fields are determined by a combination of the flow conditions and the water movement induced by ships. Passing ships make waves and induce temporal suction of water from the groyne fields (Ten Brinke, 2003). Firstly, Ten Brinke (2003) concluded that the groyne fields along the Waal erode during average and low discharges. This erosion is mainly caused by the ship-induced water and sediment movement. A larger amount of erosion in the groyne fields along the south bank takes place due to the loaded ships in the upstream direction along this bank and largely unloaded ships along the north bank. Secondly, Ten Brinke (2003) stated that sufficiently high discharges lead to sedimentation of the groyne fields. A sufficiently high discharge has a return period of approximately 5 years. During this kind of high water the main channel will be eroded and sediment will be transported to the groyne fields. Thirdly, Ten Brinke (2003) concluded that the large-scale and long term morphological behavior of the groyne fields is dynamic. On a time scale of several years, erosion and sedimentation alternate: erosion during periods of low and average discharges and sedimentation during high waters. Over a period of several years, the total amount of erosion is equal to the total amount of deposition. This means that the long-term morphodynamics in the groyne fields have no influence on the sediment balance of the Waal.

In order to get insight in the morphological developments after lowering the groynes, a pilot project has been conducted. It consisted of the lowering of 70 groynes between km 887 and km 897 of the River Waal, from April 2009 till September 2009. A monitoring program was implemented to determine the morphological effects of the lowering of the groynes. The monitoring included multi-beam measurements of the groyne fields and the main channel. The measured groyne fields included river sections with and without lowered groynes.

When the groynes are not submerged, one or two horizontal eddies are present in the groyne fields. More than one horizontal eddy occurs in case of sufficient length of the groyne field and length of the groynes. Supercritical flow might occur when the groynes are submerged. Downstream of the groyne top, a vertical vortice might occur.

This paper describes the analysis of the morphological developments, erosion and sedimentation patterns in the groyne fields after the lowering of the crest of the groynes, based on the measurements of the first high water after the lowering of the groynes. This high water had a maximum discharge at Lobith of 5348 m^3/s and has a return period of about once per year. Two research questions are defined that will be answered by analyzing the processed data:

1. How will the local erosion near the groyne heads develop after the lowering of the crest of the groynes?
2. Where and how much erosion or sedimentation occurs in the groyne fields between lowered groyne crests, compared with the groyne fields between non-lowered groyne crests?

2 FIELD MEASUREMENTS

Two kind of data are used for this study: i) measurements of bottom levels in five groyne fields and ii) measurements of water levels and discharges at specified locations in the Waal. The measurements of the bottom levels are carried out especially for this project. Measurements of the water levels and discharges are regularly carried out in the Netherlands.

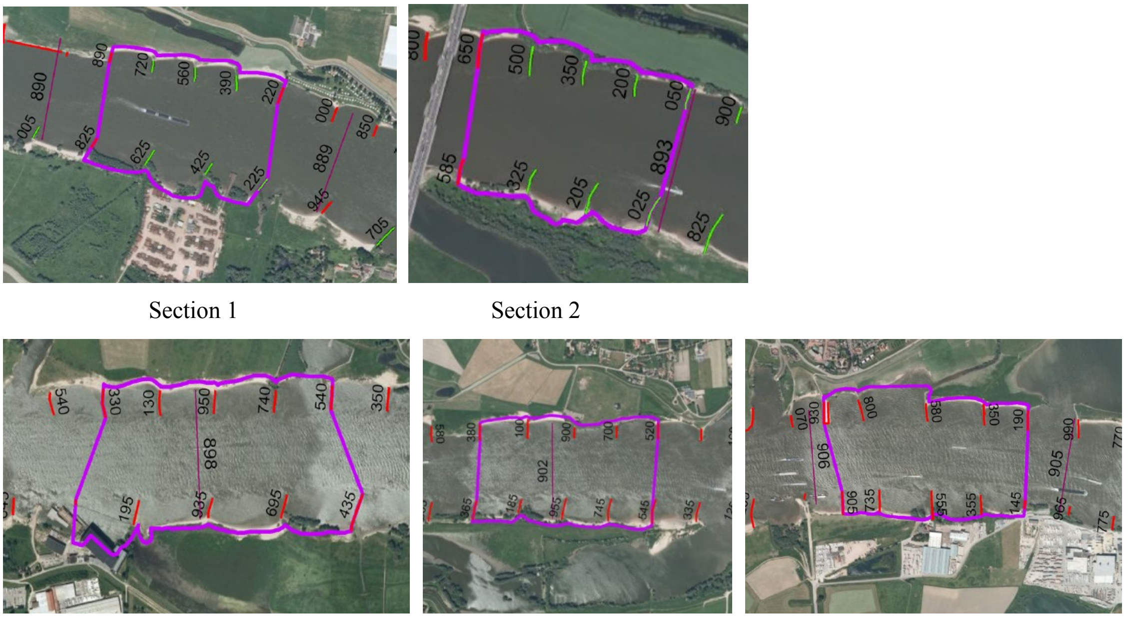
2.1 *Measured locations*

The groyne fields to be measured were specified in the monitoring program by Deltares (2009). To be able to compare the morphodynamics of the groyne fields with and without lowered groynes, three river sections, each containing 8 groyne fields with non-lowered groynes, and two river sections each containing 7 or 8 groyne fields with lowered groynes, were monitored. A total amount of 39 groyne fields were monitored and analysed (Figure 4a,b). The length of these river sections is approximately 800 m. The selected groyne fields meet the following criteria:

- Varying bend radius: the changes in the bottom levels after the lowering of its crests will be larger by varying bend radius. The location of the fairway in an outer bend is often near the groynes, so the ship waves will have a larger effect on the bottom developments.
- Varying flow direction: the floodplains in the Waal change the width strongly. During high water levels the water in some locations flows from the main channel towards the floodplains and in other locations back to the main channel. The flow direction over the groynes will therefore also change. A recirculation zone might occur near the bottom at the downstream site of an overflow groyne. Therefore the flow direction over a submerged groyne has an important effect on the morphology of the groyne fields.
- The length of two groynes opposite to each other should be more than the average length of 80 m. The reason for this is the assumption that long groynes have more morphodynamic effect than short groynes.
- The depth of the scour holes to two groynes opposite of each other should be more than the average scour hole depth. The reason for this is the expectation that the morphodynamic effect of the lowering of a groyne on the scour hole, is more in a deep scour hole.

2.2 *Measuring moments*

The Ministry of Public Works of the Netherlands carried out the first multi-beam measurements in the period between January 13th 2009 and April 3rd 2009. In this period, none of the groynes were lowered yet, so these measurements are used as reference and named T0. After the high discharge peak of March 3rd 2010, a second multi-beam measurement was conducted, named M1. The maximum discharge on March 3rd was 5348 m^3/s at Lobith and had a return period of about once per year. At the moment of the M1-measurement, a total of 70 groynes were already lowered within the period of August-November 2009. During the falling limb of this discharge peak, a third multi-beam measurement was conducted between March 11th and 13th 2010, named M2. The hydrograph is shown in Figure 5.



Section 1 Section 2

Section 3 Section 4 Section 5

Figure 4a Overview of the monitored river sections in the Waal River. Lowered groynes in green, non-lowered groynes in red. Purple indicates the measured section

Figure 4b Photo of the lowered groynes

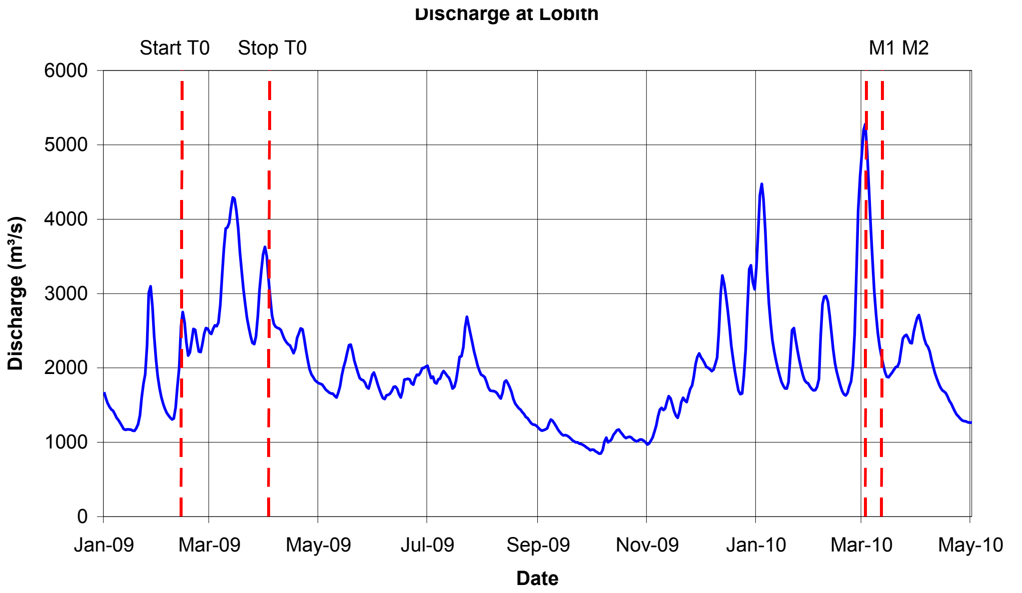


Figure 5 Hydrograph of the Rhine at Lobith

3 METHOD

The bottom levels measured by multi-beam were processed in GIS and Matlab. One part of the processing was the construction of maps, containing the bed level changes between the successive measuring moments. These maps are used to determine the spatial morphodynamics in the groyne fields and the effect of the lowering of the groynes on the scour holes.

The 2D maps are further processed in order to be able to characterized the groyne fields between lowered and non-lowered groynes, by relating the morphodynamics to the lateral position with respect to the normal line (the imaginary line trough the groyne heads). Each monitored groyne field is divided into subsections (strips). Each strip has a width of 4 meters in lateral direction and covers the entire length of the groyne field. The 2D maps show that material from the lowered groynes is dumped along the downstream side of the lowered groynes. This artificial disturbance is removed from the data by excluding a zone of 30 m around the groynes axis. The value of 30 m is an estimation based on the 2D maps. The extent of the vertical vortices downstream of the groynes, caused by the dead zone, is in the order of 15 m, approximately 7-8 times the groyne height. Per strip, the total volume and total area of erosion/sedimentation were computed.

4 MORPHODYNAMICS OF THE SCOUR HOLES

The depth of the scour holes in section 1 (lowered groynes) and in section 5 (non-lowered groynes) are shown in Figure 6. For both types of groynes, the scour hole depths in M1 are shallower than in the T0. Nevertheless, these profiles show a clear difference in scour hole depth between the lowered and the non-lowered groynes. The scour holes near the non-lowered groynes were filled by on average 50 cm, while scour holes near the lowered groynes were filled up by around 140 cm (Table 1).

The average depth of the local holes before the lowering of the crest of the groynes is about 3 m with respect to the surrounding bottom levels. According to the formula of Hoffmans & Verheij (1997) and Suzuki et al. (1987), this depth corresponds with a discharge of around 3000 m^3/s at Lobith. This discharge is approximately in agreement with the discharge where the non-lowered groynes are just submerged. The scour holes have achieved a dynamic equilibrium before the lowering of the groynes, which was disturbed after the lowering of the groynes. The scour holes after the lowering of the groynes are not yet in equilibrium. The lowered groynes are submerged at a discharge of about 1600 m^3/s by Lobith. In the new equilibrium situation the depth of the scour holes will be around 2 m (Table 2), which is about 1 m less than for the non-lowered groynes. This is just an estimate since the formula is not yet sufficiently validated.

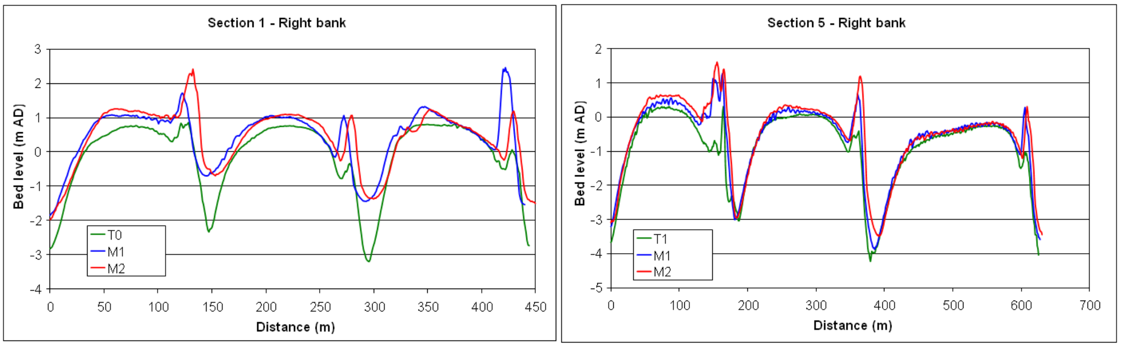


Figure 6 Depth of the scour holes in river section 1 (left) and 5 (right) before lowering of the groynes (T0), after lowering of the groynes during peak discharge (M1) and during falling discharge (M2)

Table 1 Average filling of the scour holes in the period between the measurements

Period	Lowered groynes (cm)	non-lowered groynes (cm)
T0 - M1	137	50
M1 - M2	4	0

Table 2 Predicted scour depth using Hoffmans & Verheij (1997) and Suzuki et al. (1987)

Water depth (m)	Discharge at Lobith (m^3/s)	Equilibrium depth (m)	Reduced equilibrium depth (m)
4	900	5,17	1,63
5	1300	6,46	2,03
6	1900	7,75	2,44
7	2550	9,03	2,85
8	3350	10,32	3,25

The measurements show that the scour holes are partially filled up after the lowering of the crest of the groynes. However, it is not clear what the effect of the lowering is on the location of the scour holes. The deepest points of the scour holes have shifted in both groynes by about 3 m in the direction of the normal lines (the imaginary line through the groyne heads). The distance between the deepest points of the scour holes and the head of the groynes erosion, has remained unchanged.

5 MORPHODYNAMICS OF THE GROYNE FIELDS

5.1 *Analysis of 2D morphodynamics*

For every measured section two maps were made, illustrating the bottom level differences (between T0 and M1 and between M1 and M2). Figure 7 shows an example of the difference between T0 and M1 for measured section 1. The red color in this figure indicates erosion and the blue color sedimentation. This figure shows that, firstly, there is significant sedimentation downstream of the lowered groynes (sections 1 and 2). This is caused by the construction works and is therefore not considered in the analyses of the data. Secondly, downstream of the groyne heads the scour holes partially fill up. The scour holes have shifted during high water. Thirdly, sedimentation takes place in the transition of the groyne field to the main channel, so along the normal line. This sedimentation is local and does not extend to the navigation channel.

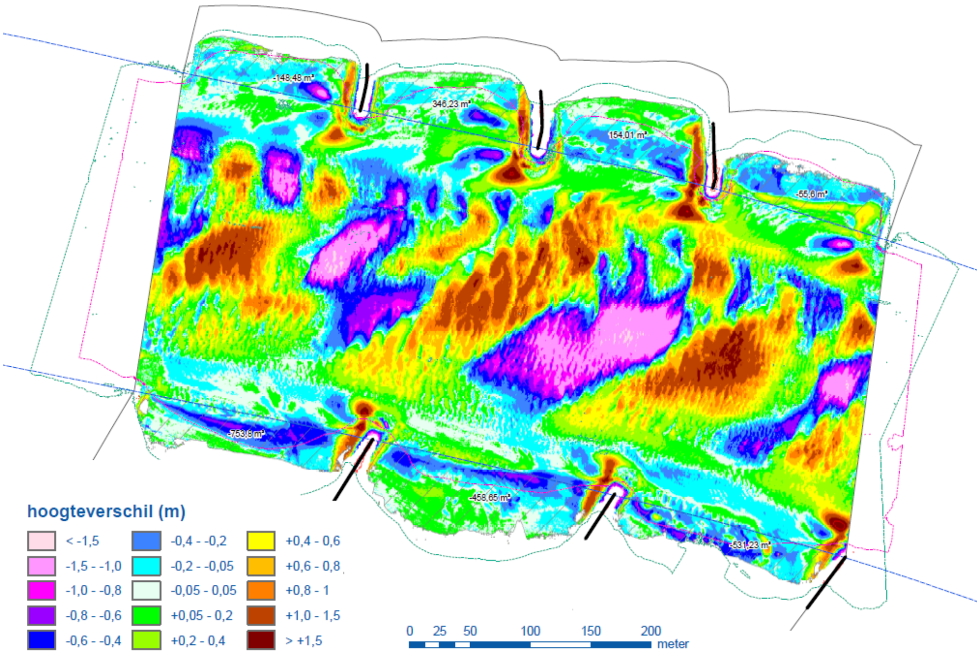


Figure 7 Bed level change in river section 1 between T0 and M1

5.2 *Analysis of erosion and sedimentation volume per strip per groyne field*

The total volume of erosion/sedimentation per strip is determined between the measurements T0 and M1 and between M1 and M2. This erosion/sedimentation is illustrated in two ways: in function of the distance to the groyne head and in function of the bottom level in the middle of the groyne field. Figure 8 illustrates the results for the bottom level differences between T0 and M1 for section 1. The vertical axis is the distance to the normal line. Positive values show in the direction to the main channel and the negative values in the direction to the bank. The length of the bars indicates the amount of erosion (negative values) or sedimentation (positive values) that took place. The values of erosion/sedimentation are summarized in Tables 3 and 4.

The graphs show that between 0 m and +50 m mainly sedimentation took place. Between 0 m and -40 m, mainly erosion took place. Further in the direction to the bank mainly sedimentation took place. Besides this, the erosion/sedimentation around the normal line is generally low. The erosion/sedimentation between M2 and M1 is lower than between M1 and T0. This is related to the period between the measurements.

5.3 *Analysis of the percentage area of erosion/sedimentation*

For every strip the percentage of the area that is subjected to erosion or sedimentation has been determined. These percentages are shown in Figure 9 between T0 and M1 for section 1. From these graphs can be concluded that between 0 m and +50 m, in the direction of the main channel mainly sedimentation took place and the percentage of area sedimentation is the largest. Additionally, between 0 m and -40 m, in the direction of the banks mainly erosion took place and the percentage of area erosion is the largest. Further in the direction of the bank mainly sedimentation took place. The transition between the percentage of erosion and sedimentation (around the -40 m line) is in general sharper in the groyne field between lowered groynes.

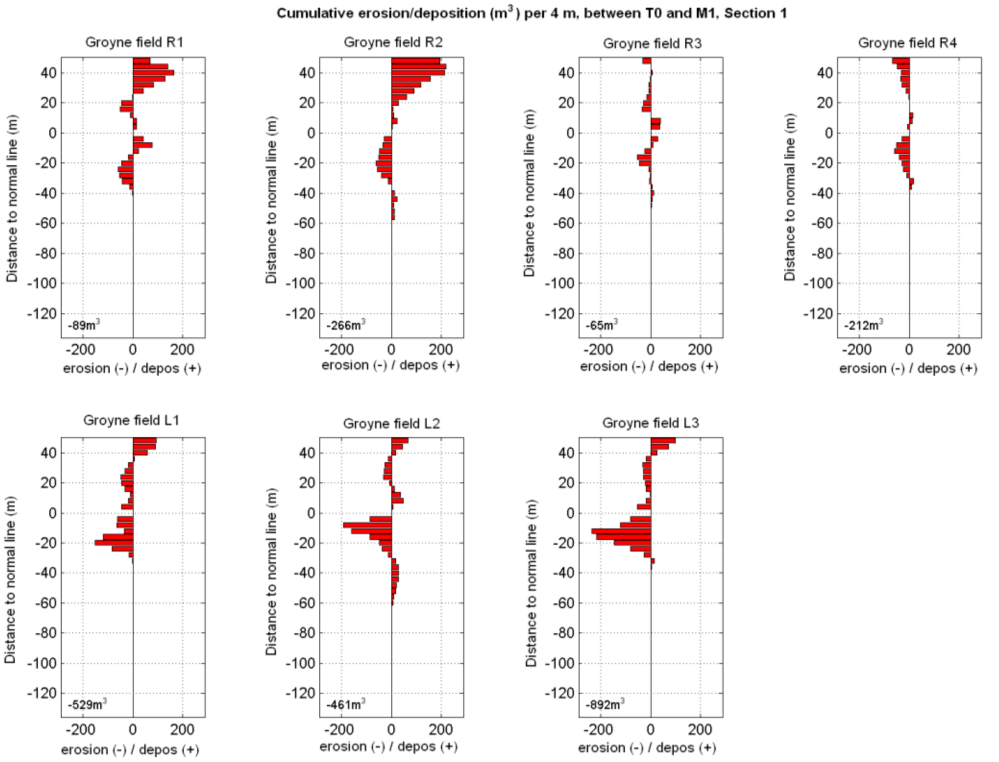


Figure 8 Total volume of erosion and deposition in the groyne fields of section 1

Table 3 Total erosion and sedimentation per groyne field between T0 and M1

Section	river bank	Total erosion/sedimentation in groyne fields T0-M1 (m^3)			
		Groyne field 1	Groyne field 2	Groyne field 3	Groyne field 4
Section 1	Right bank	-89*	-266	-65	-212**
	Left bank	-529	-461	-892	-
Section 2	Right bank	-273	-54	-207	12**
	Left bank	-490	-700	-255**	-
Section 3	Right bank	190	154	-328	0
	Left bank	161	480	554	0
Section 4	Right bank	-311	40	-134	-160
	Left bank	-112	-261	-105	-83
Section 5	Right bank	-220	-266	-246	-126
	Left bank	-50	-6	-479	-67

* Groyne at upstream side is not lowered
** Groyne at downstream side is not lowered

Table 4 Total erosion and sedimentation per groyne field between M1 and M2

Section	river bank	Total erosion/sedimentation in groyne fields M1-M2 (m^3]			
		Groyne field 1	Groyne field 2	Groyne field 3	Groyne field 4
Section 1	Right bank	54*	-11	-3	-3
	Left bank	2	-61	-36	-
Section 2	Right bank	2	-37	-6	-14**
	Left bank	-20	-40	-85**	-
Section 3	Right bank	-2	-12	67	-31
	Left bank	43	45	47	108
Section 4	Right bank	23	17	56	-18
	Left bank	-13	-20	117	72
Section 5	Right bank	59	59	98	4
	Left bank	3	73	133	46

* Groyne at upstream side is not lowered
** Groyne at downstream side is not lowered

5.4 *Analysis of average erosion/sedimentation*

The groyne fields are divided in strips van 4 m. Per strip the average erosion/sedimentation [m] is also determined between the measurements T0 and M1 and between M1 and M2. The results are illustrated in Figure 10 for section 1 between T0 and M1. The locations where erosion and sedimentation took place are the same as described in the analysis of the volumes of erosion sedimentation.

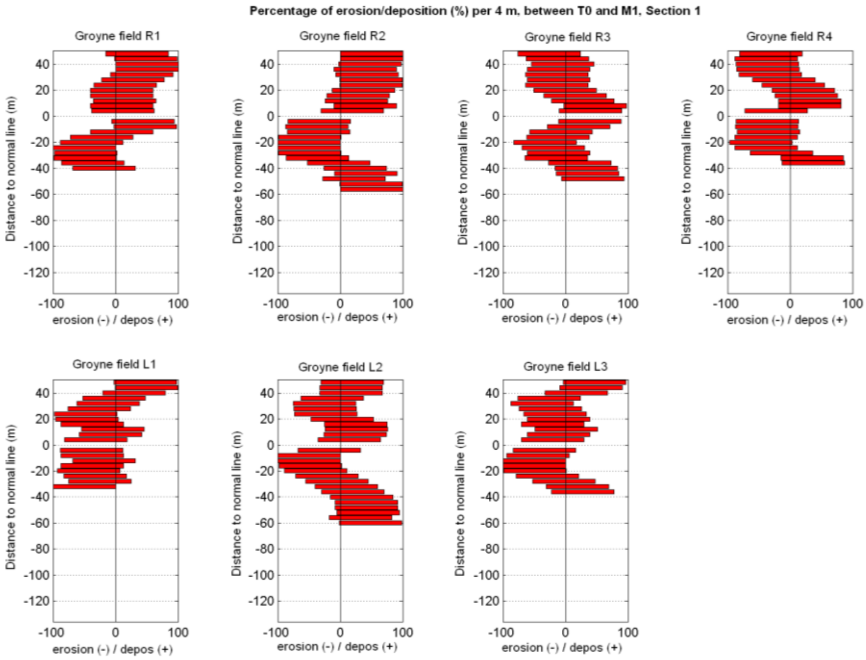


Figure 9 Percentages of areas of erosion and deposition in the groyne fields of section 1

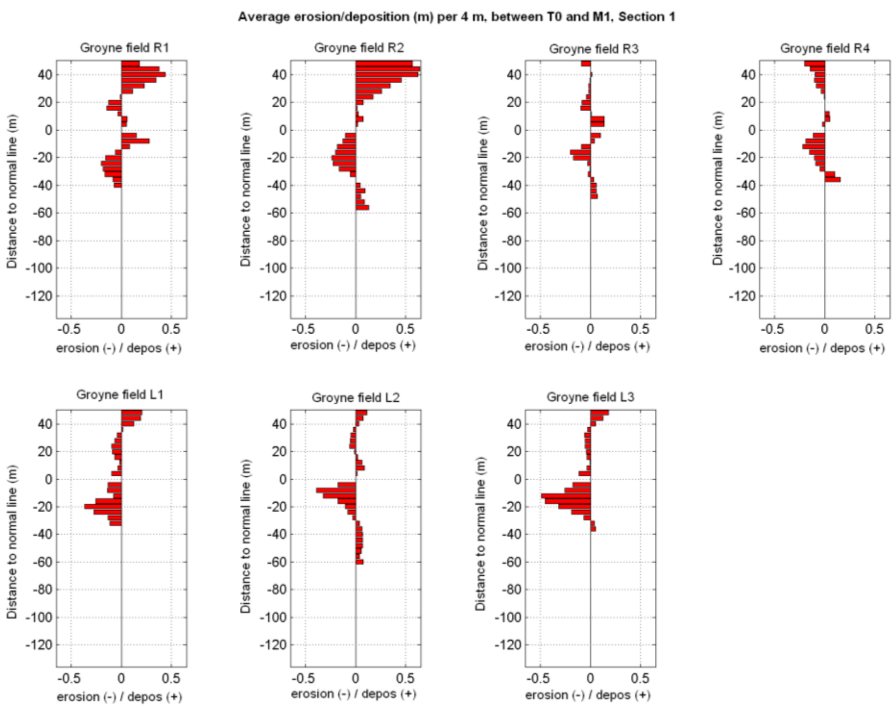


Figure 10 Average amount bed level change due to erosion and deposition in the groyne fields of section 1

5.5 *Comparison between lowered and non-lowered groynes T0-M1*

In the above analyses, the groyne fields were considered separately. In section 1 and 2 the crest of the groynes were lowered, in section 3, 4 and 5 they were not lowered. In order to get insight in the differences in erosion and sedimentation patterns of groyne fields between lowered and non-lowered groynes, the results of the lowered groynes (sections 1 and 2) and the non-lowered groynes (sections 3, 4 and 5) were added.

Furthermore, a characteristic profile of the bottom level of the groyne field between lowered and non-lowered groynes, was determined as the average bottom level with respect to the average water level per strip of 4 m. Figure 11 shows the characteristic profiles, the volumes of erosion/sedimentation, the average erosion/sedimentation and the percentage area of erosion/sedimentation.

These figures show that from the normal line in the direction to the main channel (0 m to +50 m) sedimentation took place by the groyne fields between lowered groynes (about 8 cm). In the groyne fields between non lowered groyne erosion took place (about 10 cm). In the first 40 m from the normal line in the direction to the banks (0 m up to -40 m) erosion took place in both lowered and non-lowered groynes. The total erosion in the lowered groynes is twice as much as the erosion in the non-lowered groynes. Between 40 m and 70 m from the normal line in the direction of the banks (-40 m to -70 m) sedimentation took place in both the lowered and non-lowered groynes. The sedimentation in the lowered groynes is larger than in the non-lowered groynes. When the erosion/sedimentation per groyne field is added, it is concluded that the groyne fields are eroded. This erosion amounts to 4 cm for the lowered groynes and 1 cm for the non-lowered groynes in a 1 year period.

We also distinguished the left and right banks. Figure 12 shows the average erosion/sedimentation at the left and right banks for the lowered and non-lowered groynes. The erosion is larger at the left bank than at the right bank. This can be explained by the impact of the loaded ships in the upstream direction (from Rotterdan to Duisburg) on the groyne fields at the left banks. This is in agreement with Ten Brinke (2003).

5.6 *Comparison between lowered and non-lowered groynes M1-M2*

In the period between M1 and M2, from the normal line in the direction to the main channel (0 m to +50 m) both erosion (close by the normal line) and sedimentation (from 30 m) took place. There is erosion in the groyne fields between lowered groynes (about 8 cm). In the groyne fields between non-lowered groynes erosion took place (about 10 cm). There is not much difference between the lowered and the non lowered groynes. In the first 25 m from the normal line in the direction to the banks (0 m up to -25 m) erosion took place in the groyne fields with lowered groynes, while sedimentation occurred in the non-lowered groynes. Between 25 m and 50 m from the normal line in the direction of the banks (-25 m to -50 m) sedimentation took place in the groyne fields with both the lowered and non-lowered groynes. The sedimentation near the lowered groynes is about twice as much as near the non-lowered groynes.

7 CONCLUSIONS

It is expected that the groyne fields will erode in the long-term due to the lowering of the crests of the groynes. This is caused by the increased frequency of submergence of the lowered groynes and the increase in flow velocity within the groyne fields. From the analysis of the multi-beam measurements, an impression of this erosion trend was made for the first year after the lowering. Beside this, the effect of the lowering on the scour holes around the groyne heads has also been described and quantified.

It has to be realized that the crests of the groynes were lowered just a few months before the measurements were carried out. The dynamic morphological equilibrium is not yet achieved in the lowered groynes. Furthermore, the analysis is based on the measurements of one high water with a return period of about once per year. The monitoring will be continued and more high water situations will be measured.

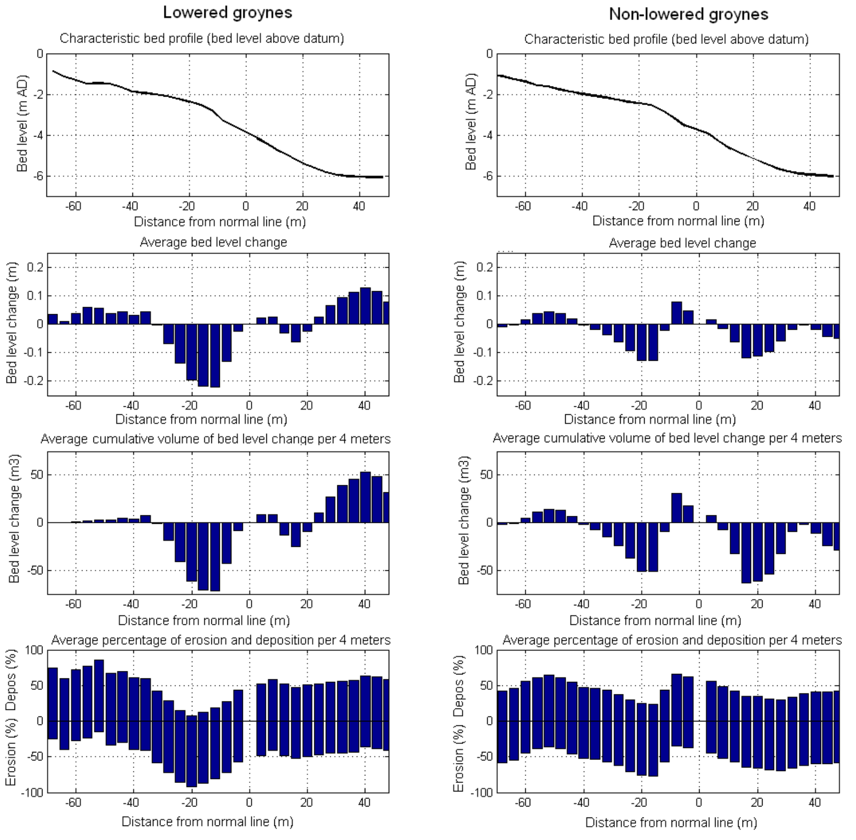


Figure 11 Morphological adjustment between T0 and M1 in the groyne fields

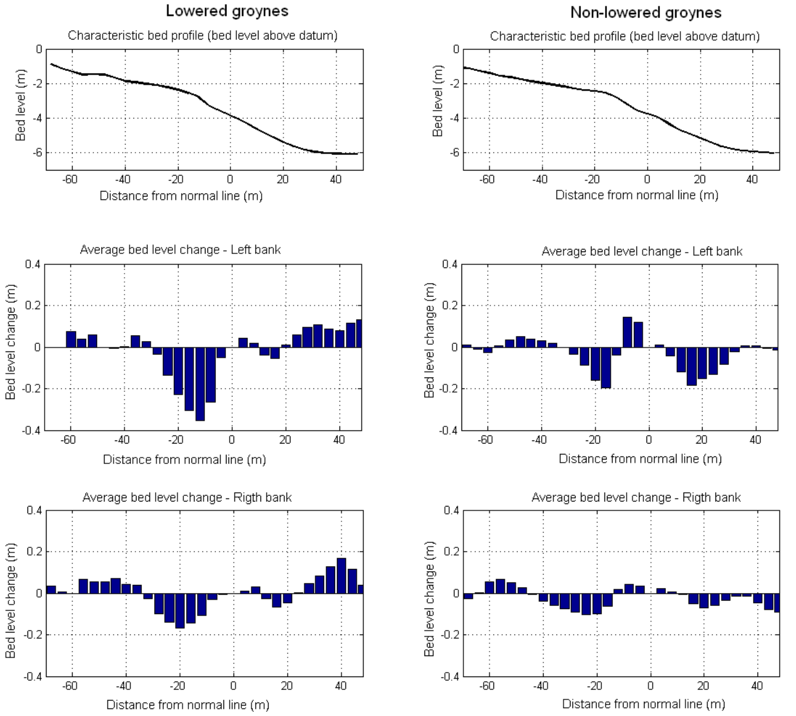


Figure 12 Morphological adjustment between T0 en M1 in the groyne fields at the left side of the river and the right side of the river

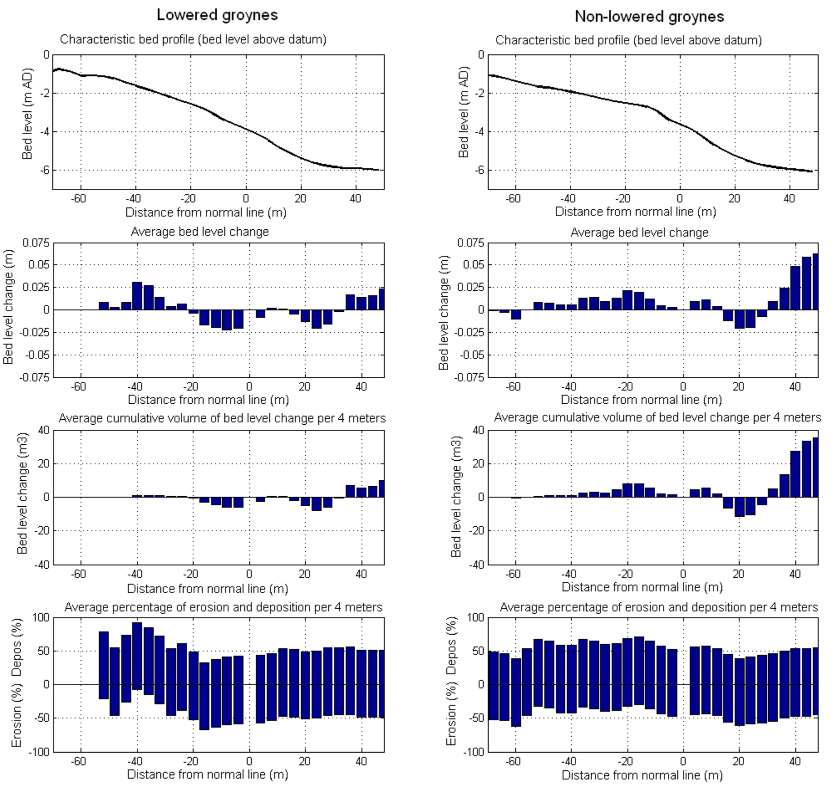


Figure 13 Morphological adjustment between M1 and M2 in the groyne fields

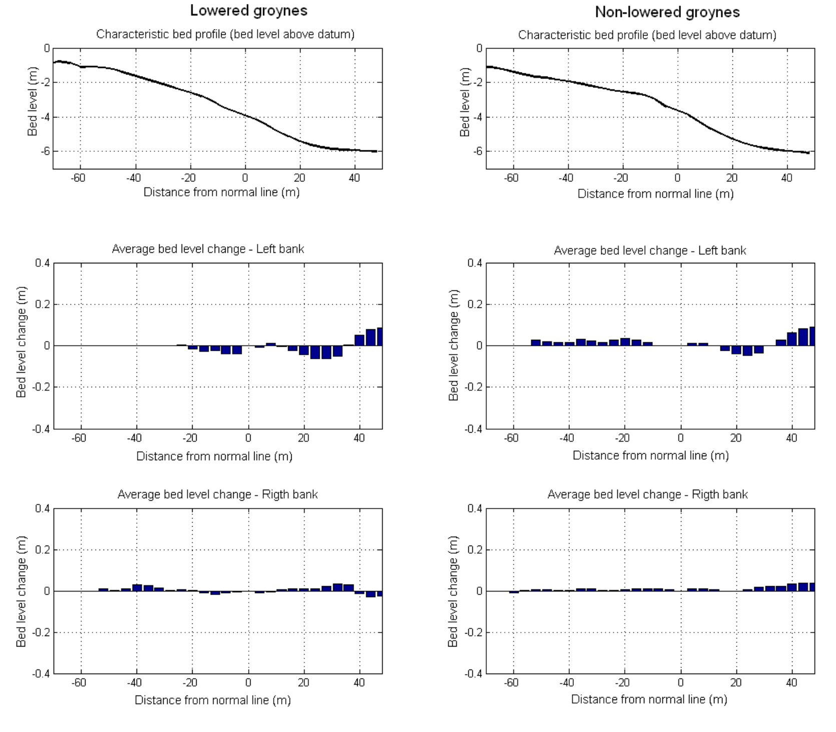


Figure 14 Morphological adjustment between M1 en M2 in the groyne fields at the left side of the river and the right side of the river

7 ACKNOWLEDGEMENTS

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