Deltares

Eindevaluatie pilot Langsdammen in de Waal

Morphology and maintenance

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Frontpage: Longitudinal training wall at Dreumel (photo by Frank Collas)

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Executive summary

General findings

River interventions such as the replacement of groynes by longitudinal training walls have morphological effects on different scales. Effects on the smallest scales occur almost immediately whereas effects on the largest scales manifest themselves only after decades. As discharges vary, morphological effects keep fluctuating even in the long term. Relevant scales for morphological effects of the longitudinal-training-wall pilot in the river Waal are the reach scale, the corridor scale, the cross-section scale and the depth scale. The present report evaluates effects on these scales in three steps. In the first step, expected effects are formulated based on established knowledge from previous experiences, theoretical assessments, and a numerical model study carried out before implementation of the pilot. The second step consists of analyzing hydro-morphological data from the monitoring programme of the pilot and simulating the hydro-morphological effects by a more refined numerical model than used before implementation. Conclusions are drawn in the third step, by balancing the results from data analysis and numerical modelling and by comparing these results with the expectations based on established knowledge. Additionally, experiences of *Rijkswaterstaat* with maintenance are reported as they are closely linked to the morphological developments in the river.

Data analysis and numerical simulations

The pilot of longitudinal training walls in the Waal included an extensive measurement programme with multibeam echosoundings, water level registrations and ADCP flow measurements. The resulting data were evaluated within the present final evaluation of the pilot. As the duration of the programme was relatively short, long-term effects could not be assessed. Yet initial developments towards a new long-term dynamic equilibrium could already be identified. In general, field measurements give a good insight in processes on smaller scales whereas numerical models give better insight in processes on a larger scale that are influenced by different factors. Both field data and numerical simulations have inaccuracies and shortcomings, which are minimized by applying them complementarily. Numerical results of morphological simulations are considered meaningful only in terms of differences with respect to a reference simulation, not in terms of absolute values, because of inaccuracies in schematization and calibration.

The hydro-morphological effects of the longitudinal training walls were assessed by comparing the situations before and after implementation. This comparison was problematic for the field data, because in the same period groynes were lowered upstream and downstream of the pilot and the Passewaaij side channel was realized. The pure effect of the training walls could be isolated more easily in the numerical simulations. Another limitation of the field data was that certain relevant conditions did not occur in the period of the measurement programme. Low discharges did occur during the 2018 drought, but no pronounced floods occurred. The numerical model could simulate flood conditions. Moreover, the numerical model simulated the morphological development over 20 years, thus spanning a longer time than the measurement programme.

Reach-scale effects

Reach-scale morphology concerns the development of the longitudinal bed profile several orders of magnitude greater than the width. The ongoing lowering or degradation of this profile in response to river training and sediment mining in the past poses currently one of the main challenges for river management. Theoretically, the narrowing and smoothing by longitudinal training walls and the diversion of sediment to auxiliary channels would enhance this degradation whereas the diversion of discharge through auxiliary channels would reduce or even reverse it. The latter effect was expected to be dominant, though not enough to fully stop the erosion trend. Accordingly, a response was expected in the main channel with slight erosion upstream of the pilot, significant sedimentation at inlets to auxiliary channels, slight sedimentation further downstream and significant erosion at the outlets of auxiliary channels. Observations and numerical simulations confirmed the sedimentation at the upstream end of each training wall, corresponding to a mean aggradation on the order of 10 cm. Flood events produced disturbances of this response on the order of decimetres that propagated at approximately 1 km/year. Observations and numerical simulations also confirmed the bed degradation at the downstream ends. As this response resulted primarily from discharge diversion, the inlet openings were important factors.

A reach-scale issue is the stability of the two-channel system that arises by the implementation of the training walls. This stability depends on the amount of sediment that enters the auxiliary channels at different discharges. No comprehensive observations on these amounts are available and numerical models still cannot reproduce these amounts reliably. However, the longitudinal bed profiles of the main channel and the auxiliary channel have not shown any signs of this instability. Significant sedimentation did occur in the auxiliary channels, but this was primarily due to the input of bank erosion products.

Corridor-scale effects

Effects on corridor scale regard exchanges between the main channel and the floodplains. The deposition of sand on floodplains is ecologically valuable for stream valley flora. The longitudinal training walls were not expected to cause any significant changes in sand deposition, although some ecologists had expressed concerns that the training walls would block sand fluxes to the floodplains. Field observations showed that sand deposits did develop on floodplains along the training walls, even in considerable quantities downstream of the pilot.

The removal of groynes was expected to expose the banks of the auxiliary channels to erosion, but no quantitative predictions of bank erosion had been made. Such predictions would have been uncertain due to factors such as bank composition heterogeneity, groyne leftovers, vegetation and wave penetration. Banklines retreated on the order of metres. This retreat amounted to 5 m between river kilometres 912.9 and 914. The initially fast bank erosion rates decreased over time.

Cross-section-scale effects

Morphological phenomena on cross-section scale regard bars and the profile of the navigation channel. The local aggradation of the river bed near the inlets can be seen as bars. No effects were observed on the overall pattern of bars in the main channel. Pairs of flow separation bars or eddy bars were expected to form in the upstream reaches of the auxiliary channels at Wamel and Ophemert. These bars did develop accordingly, as documented in particular for the channel at Ophemert.

Depth-scale effects

Morphological features that scale with water depth include underwater dunes, groyne flames and local scour holes. The longitudinal training walls have led to the disappearance of groyne flames that make the navigation channel shallower. The river has not scoured any local holes that could compromise the stability of the structure.

Rijkswaterstaat experiences with maintenance

Maintenance regards all technical activities to keep the structure and the navigation profile in place properly. Maintenance of the longitudinal training walls is carried out according to a performance contract. The corresponding activities consist of repairing damage to the training walls, clearing of vegetation, and dredging. The profiles of the training walls and the bearing soil underneath have not been deformed by any settling or sliding. Moreover, no significant scour holes have formed that could compromise the stability of the structure. As a result, no maintenance of structural aspects has been necessary. The poor accessibility of the training walls safeguarded them from vandalism. Interventions have only been necessary to repair damage from ship collisions. The costs of this repair turned out to be a multiple of the costs for repairing similar damage to groynes because the pilot structure has a granular build-up without geotextile.

The coarse riprap of longitudinal training walls renders vegetation clearance more difficult. The contractor has ceased this activity. The training walls have nonetheless remained free of vegetation because the river washed vegetation away during floods. About 30 000 m^3 of material has been dredged from the auxiliary channels in 2018. This concerned mainly bank erosion products.

Answers to specific questions of *Rijkswaterstaat*

What dredging effort is expected based on the modelled development of the main and auxiliary channels? What are the differences in frequency and amount of dredging compared to other sections of the Waal River? What are the consequences of varying the inlets regarding dredging?

Measured field data do not allow a firm conclusion, but numerical simulation results before implementation and in the framework of the present final evaluation suggest that dredging efforts do not undergo significant changes. Differences and consequences appear negligible.

What is the vegetation development on the longitudinal training walls? What is the required management and maintenance as caused by the previously mentioned changes in vegetation development? How does this relate to the maintenance and management of groynes?

Vegetation has been observed to grow at lower discharges and to be washed away during floods on both the longitudinal training walls and the groynes. Vegetation on training walls was generally less dense than vegetation on groynes. Moreover, the same vegetation biomass on training walls produces less flow resistance than vegetation on groynes because its configuration is aligned with the flow rather than perpendicular to the flow.

What is the influence of the inlet openings regarding bed level changes?

At equal average sill crest elevations, no influence could be found of the shape of inlets on the amount of sediment entering the auxiliary channels. Sustained differences in sill crest elevation, however, were found to significantly affect main-channel morphology through changes in the flow field. Closed inlets maintained the bed degradation whereas open inlets reduced or even reversed bed degradation.

What are the upstream and downstream effects of the longitudinal training walls for a particular opening of the inlets?

The field data and the numerical simulations showed local aggradation at the upstream end of the Wamel training wall and local degradation at the downstream end of the Ophemert training wall, in accordance with expectations. The field data did not provide information on large-scale changes on a long term. The simulation results suggest that significant large-scale changes in bed elevation will occur neither upstream nor downstream. From a theoretical point of view, however, a few centimetres of aggradation or reduced degradation is expected upstream of the pilot.

Which morphodynamic trends in bed elevation have been measured and are expected to occur?

Data from multibeam echosoundings suggest that the rate of bed degradation has decreased, in accordance with the results of numerical simulations and theoretical expectations. This means that the effect of diverting part of the discharge through auxiliary channels dominates over the effect of a narrower main channel. Local aggradation occurred at the inlet and local degradation at the outlet. ADCP velocity measurements suggest a slight increase in flow velocity at water levels below the crest of the training walls and a decrease at water levels above the crest. This corresponds to increases and decreases in sediment transport capacity and hence to erosion and sedimentation or decreased erosion. The echosoundings indicate that the decrease in transport capacity dominated.

Which morphodynamic trends have been observed along the river banks?

The banks of the auxiliary channel have experienced significant erosion but erosion rates have gradually decreased. The bank between river kilometres 912.9 and 914 retreated by 5 m. The volume of 30 000 m^3 of material dredged from the auxiliary channel in 2018 resulted mainly from bank erosion.

Which signs of morphological development can be derived from stage-discharge relationships?

The data suggest that, for the same discharge, water levels have lowered after implementation of the longitudinal training walls. This reflects the enlarged space of the auxiliary channels and hence does not form a contradiction with the aggradation of the river bed in the main channel. The effect on water levels, however, cannot be ascribed to the system of training walls and auxiliary channels alone. The period of the pilot coincided with the lowering of groynes upstream and downstream, as well as with the opening of the side channel at Passewaaij. Moreover, the data scatter is so large that no strong conclusions on systematic changes in stage-discharge relationships can be drawn.

How is the discharge partitioned between the auxiliary channel and the main channel?

Field data indicate that the discharge through the auxiliary channels varies between 5% and 25% of the total discharge. For a larger total discharge, a larger proportion is transported through the auxiliary channels.

Contents

Preface

Het riviersysteem van de Rijn, met daarin alle Nederlandse Rijntakken, kent problemen met onder meer hoogwaterveiligheid, insnijding van de zomerbedbodem, daling van laagwaterstanden en grondwaterstanden, de kwaliteit van het rivierecosysteem, en het gebruik van de rivier als vaarweg. De laatste decennia wordt onderkend dat de sectorale aanpak niet efficiënt is. De beleidsdirecties van het ministerie van Infrastructuur en Waterstaat hebben de wens uitgesproken voor een meer innovatieve systeem- en gebiedsgerichte aanpak, met integrale aandacht voor alle probleemvelden tegelijk. Deze integrale aanpak beoogt de som van alle problemen te reduceren in plaats van slechts de problemen van een beperkt aantal sectoren.

Voor deze integrale aanpak heeft Rijkswaterstaat Oost-Nederland een idee gelanceerd onder de werknaam WaalSamen. Dit is een plan voor herinrichting van het zomerbed in de gehele Waal. De herinrichting wijzigt het principe van het bestaande normalisatiesysteem door het zomerbed te verdelen in twee parallelle stroomgeulen, gescheiden door een langsdam. Om de eigenschappen van deze systeemwijziging in de praktijk te beproeven is over een lengte van tien kilometer de pilot Langsdammen uitgevoerd. Het doel daarvan is een proof of concept, om meer zekerheid te verkrijgen over de integrale werking en de potenties van een dergelijke systeemwijziging.

Voor de pilot werd het Waaltraject Wamel-Ophemert (km 911.5-921.5) bij Tiel gekozen. Om redenen van efficiëntie werd de pilot tegelijk uitgevoerd met Fase III van het project Kribverlaging Waal van het programma Ruimte voor de Rivier. Hiervoor leverde Rijkswaterstaat Oost-Nederland op 30 juni 2011 de producten van een SNIP-3-besluit op aan de Programmadirectie Ruimte voor de Rivier van Rijkswaterstaat, inclusief een omwisselbesluit om geplande kribverlaging te vervangen door langsdammen. De Staatssecretaris van Verkeer en Waterstaat bekrachtigde dit eind 2011. De langsdammen tussen Wamel en Ophemert werden vervolgens in de periode van augustus 2014 tot maart 2016 gerealiseerd.

Voor, tijdens en na de aanleg van de langsdammen is een uitgebreid monitorings- en onderzoeksprogramma uitgevoerd door de partners van de samenwerkingsovereenkomst “WaalSamen”. Dit programma is afgesloten met een integrale eindevaluatie, onderverdeeld in 12 inhoudelijke deelprojecten die worden aangeduid met “WP” (werkpakket). Voor u ligt het deelrapport van WP10 over het onderdeel van de evaluatie van het tweegeulensysteem met langsdammen dat gericht is op morfologie en onderhoud. De deelrapporten vormen de ondergrond van het hoofdrapport, maar de inzichten en conclusies zijn bij het opstellen van dat hoofdrapport integraler beschouwd, verder geëvolueerd en verduidelijkt. Waar dat mogelijk tot verschillen heeft geleid, zijn de conclusies van het hoofdrapport leidend.

1 Introduction

The Waal River is characterized by long-term (decadal) and large-scale (on the order of kilometres) degradation (Sloff, 2019). Degradation is harmful as several river functions are hampered. For instance, degradation exposes the foundation of structures and lowers the groundwater level, challenging farming in the surroundings (Galay, 1983). Additional particular problems for the Dutch river system include navigational bottlenecks created at fixed layers, such as that at Nijmegen, as well as the exposure of cables and tubes crossing the river (Berkhof *et al.*, 2018). The substitution of a groyne field by longitudinal training walls is said to contribute to decreasing river-bed degradation.

The construction of longitudinal training walls instantly changes the hydrodynamic field (e.g., flow velocity and flow depth patterns) along the intervention area, as well as upstream of it. These changes cause an impact on the river functions on the short term. The changes in the hydrodynamic properties induce aggradation and degradation patterns, as well as changes in the grain size distribution of the bed surface. While hydrodynamic changes are instantly felt, morphodynamic changes take place on a longer timescale (decades and centuries). Eventually, the long-term impact of the implementation of longitudinal training walls may be opposite to the short-term impact.

The main objective of this report is to assess the morphodynamic impact due to the construction of longitudinal training walls. First, we present the expected impact of the construction of the longitudinal training walls. The expectations are partly based on a theoretical analysis that also serves to highlight the variables that control the morphodynamic behaviour of the system.

Second, we assess the impact of the longitudinal training walls by means of data analysis. A large data set of field measurements collected by *Rijkswaterstaat* throughout the years before and after construction of the longitudinal training walls has been analysed by several researchers as well as by a specific work package within this project (WP0). The time since construction is relatively short with respect to the timescale associated to morphodynamic changes. Nevertheless, we review the results and compare these to the expectations.

The analytical study is limited by the simplifying assumptions that are needed for tackling the problem. The analysis of the field data is limited by the fact that the effect of the construction of the longitudinal training walls cannot be isolated from several other interventions, changes, and natural variability in conditions. For these reasons, thirdly, we use results from a numerical model to quantify the isolated effect of implementing longitudinal training walls along the Waal River.

None of the two methods assessing the impact of the implementation of longitudinal training walls (i.e., data analysis and numerical model) is superior to the other and we find that the combination of the two methods provides the best impression of the morphodynamic impact.

The analysis is complete with an overview of the experiences of operation and management by *Rijkswaterstaat*. This analysis not only focuses on past experiences, but also shows the important points to be considered in similar future projects.

2 Objective and research questions

The objective of this project is to gain understanding about the morphodynamic impact of the implementation of the longitudinal training wallsin the Waal River as well as the consequences for management and maintenance.

The following main research questions is posed:

- What is the influence of the longitudinal training walls on the management and maintenance conducted by *Rijkswaterstaat*?

The research questions that derive from the objective are:

1. What dredging effort is expected based on the modelled development of the main and auxiliary channels?
2. What are the differences in frequency and amount of dredging compared to other sections of the Waal River?
3. What are the consequences of varying the inlets regarding dredging?
4. What is the vegetation development in the longitudinal training walls?
5. What is the required management and maintenance as caused by the previously mentioned changes in vegetation development?
6. How does this relate to the maintenance and management of groynes?
7. What is the influence of the inlet openings regarding bed level changes?
8. What are the upstream and downstream effects of the longitudinal training walls for a particular opening of the inlets?
9. Which morphodynamic trends in bed elevation have been measured and are expected to occur?
10. Which morphodynamic trends have been observed along the river banks?
11. Which signs of morphological development can be derived from stage-discharge relationships?
12. How is the discharge partitioned between the auxiliary channel and the main channel?

In answering the research questions, in Section 3 the effects of an idealized longitudinal training wall are studied. In Section 4 measured data are interpreted and discussed. In Section 5 the results of a morphodynamic numerical model are shown. Finally, in Section 6 the experience by *Rijkswaterstaat* regarding management of the longitudinal training walls is treated.

3 Expected morphological effects based on established knowledge

3.1 Introduction

One obvious effect of constructing a longitudinal training wall is that the main channel width is reduced with respect to a situation with groynes. This effect is clearly visible under low-flow conditions, when flow is restricted to the main channel only and the auxiliary channel (*oevergeul*), and the floodplains are not inundated. A second effect is the transfer of water from the main channel to the auxiliary channel. Under flood conditions, when summer levees (*zomerdijk*) are submerged, substituting groynes (perpendicular to the main flow direction) with a longitudinal training wall (parallel to the main flow direction) decreases the overall friction experienced by the flow. Furthermore, the construction of a longitudinal training wall has an impact on the sediment transport in the main channel.

In this section, the expectations: (1) based on theory (Section 3.2), (2) regarding bar formation and bank erosion in the auxiliary channel (Section 3.3), (3) regarding sediment control (Section 3.4), and (4) previous numerical exercises (Section 3.5) are discussed.

3.2 Expectations based on theory

3.2.1 Assumptions for idealized one-dimensional channel

We assess the short-term and long-term morphodynamic response expected to occur in an idealized one-dimensional channel initially under equilibrium conditions subject to: (1) a reduction of the width of the main channel (Section 3.2.2), (2) a water extraction (Section 3.2.3), (3) a reduction of the overall flow resistance (Section 3.2.4), and (4) a sediment extraction (Section 3.2.5).

The short-term effect is analysed by studying the hydrodynamic effect of each intervention assuming that no changes occur to the river bed, as the timescale of morphodynamic changes is larger than the timescale of changes associated to the flow. Initial changes in the hydrodynamic field induce changes in the sediment transport field which eventually cause changes in bed elevation. The long-term effect is studied by assuming that the river reaches a new equilibrium state a long time after the intervention takes place. Under this condition, the flow equations reduce to the normal flow equation (i.e., Chézy equation) which, when combined with a sediment transport relation (in our case, Engelund and Hansen (1967)), yield a set of equations for the equilibrium bed slope and flow depth. Jansen *et al.* (1979) explain the methodology in detail and in Appendix A a reflection on the limitations of the theoretical assessment is provided.

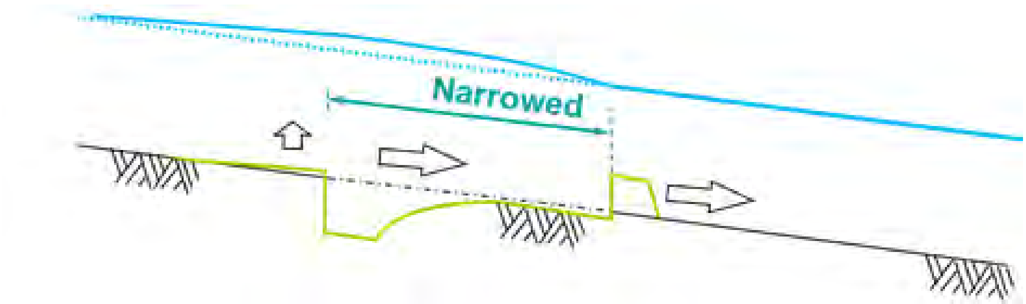

Figure 1 Short-term effect of narrowing the main channel.

3.2.2 Effects of main-channel narrowing

We consider a channel initially under equilibrium and subject to a constant discharge under subcritical conditions (i.e., the Froude number is below 1). The bed slope and the flow depth are constant along the channel. The channel is assumed of type M (i.e., the bed slope is milder than the non-dimensional friction coefficient (see e.g., Chow (1959)). Reducing the channel width along a section of the channel causes an increase in the normal flow depth in the section where the intervention takes place. This induces the formation of an M2 backwater curve in the narrowed section and an M1 backwater curve in the section upstream of the narrowed section (Figure 1). The water level increases everywhere upstream from the downstream end of the intervention. The maximum water-level increase occurs at the upstream end of the intervention. Assuming that the intervention is sufficiently long such that the normal flow depth is found at the upstream end of the intervention, the maximum water level increase is equal to the difference between normal flow depths. Assuming a total discharge equal to 1825 m^3/s (at which the water level is at the crest of the longitudinal training walls along the Waal), a non-dimensional friction coefficient equal to 0.004 (which is equal to a Chézy friction value equal to 50 $m^{1/2}/s$), a bed slope equal to 1×10^{-4}, an initial width equal to 290 m, and a width reduction of 30 m, the maximum increase in water level is equal to 0.41 m. The exact values representing the Waal River are not relevant given the simplifying assumptions. The important point is the order of magnitude of the effect of the intervention.

Figure 2 Long-term effect of narrowing the main channel.

The initial morphodynamic response due to the backwater curves is aggradation upstream of the narrowed section and degradation in the narrowed section. The aggradation rate is largest close to the upstream end of the intervention and the degradation rate is largest close to the downstream end of the intervention. At the upstream (downstream) end of the intervention, a degradational (aggradational) wave forms. After a long time, once a new equilibrium state is reached, the bed slope along the narrowed section of the river is milder than initially and the flow depth larger than initially (Figure 2). Upstream and downstream of the intervention, the bed slope and flow depth remain as they were initially. This causes that, downstream of the intervention, the water level and bed level are equal to the initial state while degradation is found everywhere upstream from the downstream end of the intervention (Figure 1). Maximum degradation occurs at the upstream end of the intervention. To estimate the order of magnitude of the expected maximum degradation, we compute the equilibrium bed slope after the intervention by assuming an annual sediment load equal to 200 000 m^3 (Frings *et al.*, 2019) of sediment with density equal to 2650 kg/m^3 with characteristic grain size equal to 1 mm. Rather than considering the initial bed slope equal to 1×10^{-4}, for a fair comparison we consider the initial bed slope to be under equilibrium given the sediment load. This yields initial and final bed slopes equal to 4.0×10^{-5} and 3.9×10^{-5}. Considering a length of the intervention equal to 10 km, the maximum degradation is found by adding the difference in normal flow depth under the new equilibrium configuration to the length of the intervention multiplied by the difference in bed slopes. This results in a maximum degradation equal to 0.69 m. Note that, due to the limited extension of the intervention, the effect is mainly due to the change in normal flow depth. Upstream from the intervention, degradation is limited to 0.02 m.

3.2.3 Effects of water extraction from main channel

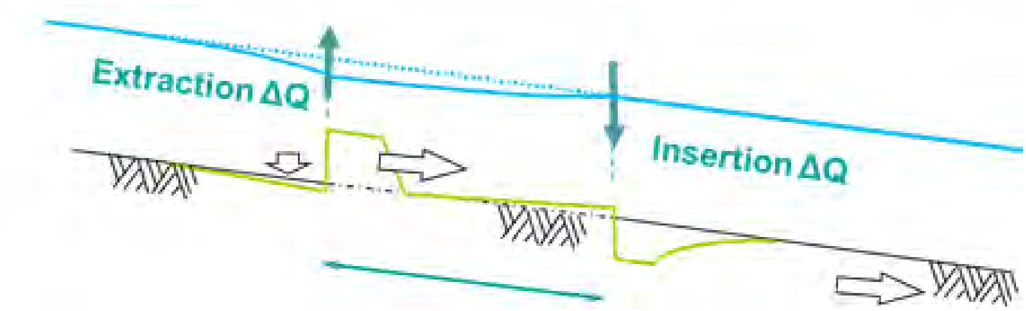

Figure 3 Short-term effect of extracting water from the main channel.

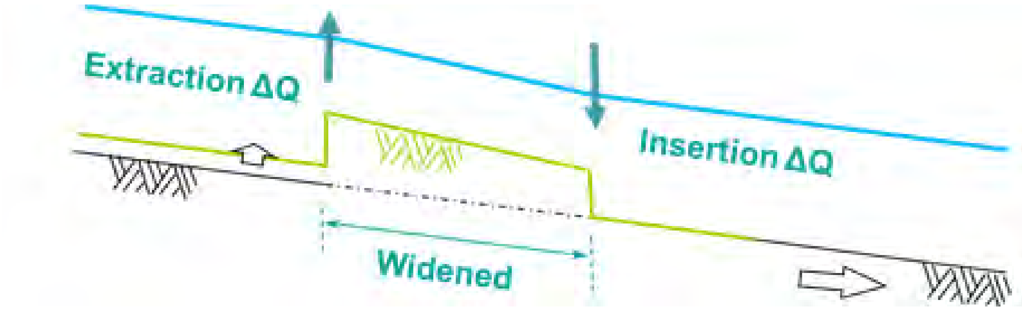

Figure 4 Long-term effect of extracting water from the main channel.

We consider the same situation as before but, rather than a reduction in flow width, we consider the effect of reducing the discharge along a limited section of the river. The effect is opposite to the case of a reduction in flow width. Lowering the discharge causes a reduction of the normal flow depth along the intervened river section. This induces the formation of an M1 backwater curve in the intervened river section and an M2 backwater curve upstream of it (Figure 3). In the short term, the water level lowers everywhere upstream from the downstream end of the intervention. The maximum lowering is found at the upstream end of the intervention. Considering a sufficiently long intervention, and a water extraction equal to 15% of the total discharge, the maximum lowering of the water level is equal to 0.56 m. The aggradation and degradation pattern is opposite to the one due to river narrowing. Aggradation occurs along the intervened section and degradation is found upstream of it. An aggradation wave is formed at the upstream end of the intervention and a degradational wave forms at the downstream end of it. Under the new equilibrium condition, aggradation occurs in the intervened section and upstream of it (Figure 4). Given the values of the parameters used above, the maximum aggradation is found at the upstream end of the intervention and equals 1.18 m. Upstream from the intervention, aggradation is uniform and equal to 0.07 m.

3.2.4 Effects of lower resistance

The short-term morphodynamic response to a lowering of friction is equivalent to a decrease in discharge, as in both cases the normal flow depth of the intervened section decreases. Considering a 5% reduction in the non-dimensional friction coefficient, the maximum water-level lowering is equal to 0.09 m and the same pattern of aggradation and degradation is found as for the previous case. However, the long-term morphodynamic consequences of a friction lowering are different than for the case of a discharge lowering. A friction lowering causes a milder equilibrium bed slope, which causes degradation. In our case, the maximum degradation amounts to 0.02 m. Interestingly, the equilibrium flow depth is equal to the initial flow depth. Thus, degradation in the upstream reach is also equal to 0.02 m.

3.2.5 Effects of sediment extraction from main channel

A sediment extraction and subsequent input further downstream has no morphodynamic effect in the short term. This can be understood from the fact that neither extracting nor adding sediment has an impact on the hydrodynamic field. In the long term, the river stretch where the sediment load has been reduced, experiences a decrease of the bed slope and degradation. Assuming that, for instance, 20% of the load is transported along the auxiliary channel, causes a maximum degradation equal to 0.39 m. Upstream from the intervention, the bed experiences degradation of 0.05 m.

3.2.6 Combined effect

By analysing the effect of each of the components of a longitudinal training wall individually, we have observed that some components cause aggradation in the short term, while some others cause degradation. Similarly, the long-term behaviour of, for instance, a water extraction, is opposite to the effect of a river narrowing. Thus, the overall morphodynamic effect depends on the ratios between each of the components. The combined effect of all components yields short-term lowering of the water level by 0.28 m, a maximum aggradation along the intervened section equal to 0.20 m, and degradation upstream of the intervention of 0.03 m. Nevertheless, the balance between overall aggradation and degradation is delicate and depends on crucial (and difficult to measure) parameters such as the sediment load that is transferred to the auxiliary channel.

For gaining insight into this respect, we study the long-term combined effect of a change in river width and a change in the discharge distribution (Figure 5). For the case in which the width is reduced by approximately 10%, a discharge reduction below 10% causes degradation, while aggradation is observed for a larger water extraction. Figure 6 shows the combined effect of a water and a sediment extraction. From these figures one observes the delicate balance between overall degradation and aggradation in the long term, keeping in mind that the short-term effect may be opposite.

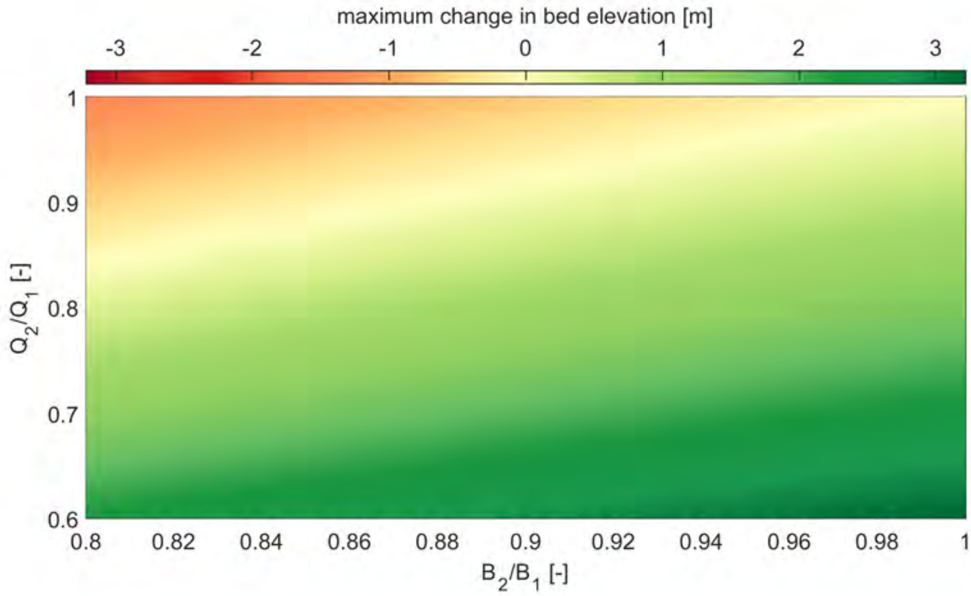

Figure 5 Maximum change in bed elevation for a given change in discharge (Q) and width (B) of the main channel. Subscript 1 refers to the situation before the intervention and subscript 2 to the situation after the intervention.

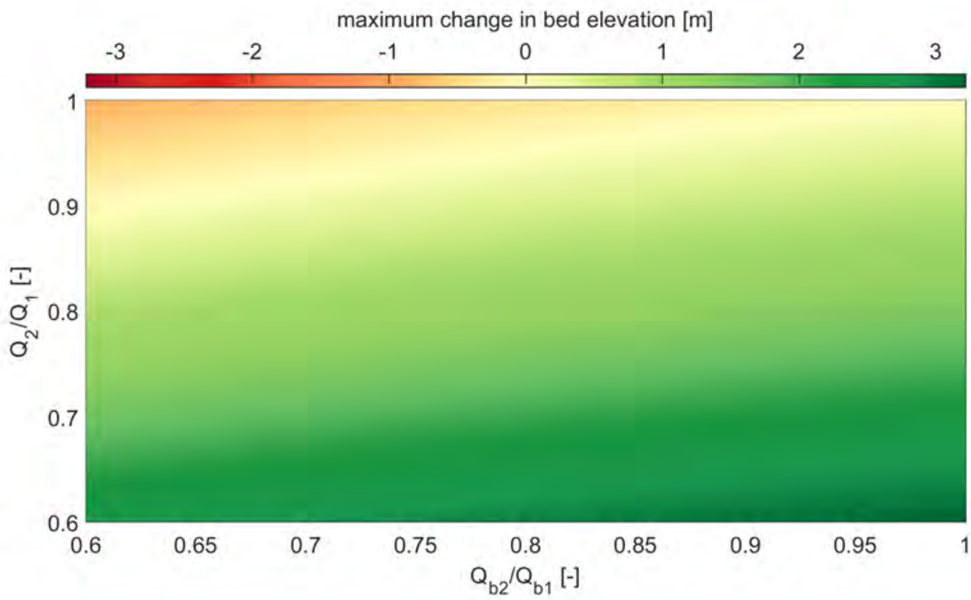

Figure 6 Maximum change in bed elevation for a given change in discharge (Q) and sediment discharge (Q_b) of the main channel. Subscript 1 refers to the situation before the intervention and subscript 2 to the situation after the intervention.

3.3 Expected bar formation and bank erosion in auxiliary channel

The overall development of the auxiliary channel is hard to predict as it depends sensitively on the amount of sediment passing over the entrance sill. The bed topography in the channel was expected to develop a pattern of eddy bars forming at a cross-section scale (Alvarez *et al.*, 2017; Crosato and Mosselman, 2020) (also known as separation bars (Schmidt, 1990)) due to flow separation, as indicated in Figure 7. The banks were expected to erode after removal of the groynes, but no quantitative predictions had been made beforehand.

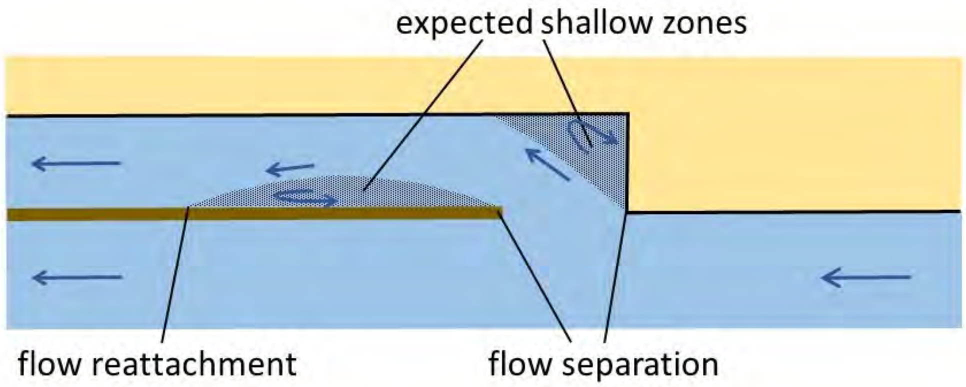

Figure 7 Expected pattern of eddy bars in auxiliary channel.

3.4 Expectations regarding sediment control

Rijkswaterstaat expects that the dredging effort in the main and auxiliary channel as well as the long-term bed degradation can be controlled by varying the inlet openings of the longitudinal training walls. *Rijkswaterstaat* expects that the sediment partitioning can be influenced with the adjustable openings, with a possibly favourable effect on the bed level and the water level of the main channel.

The construction of the longitudinal training walls is expected to cause aggradation at the inlets considering them as a water extraction (Section 3.2, Figure 3). In the long term, a step would develop from a theoretical perspective (Figure 4). The flow variability in combination with the short length between inlet and outlet will most probably make the step difficult to identify. On the one hand-side, aggradation would cause an increase in dredging effort. On the other hand, while increasing the bed level, the flow should concentrate in the main channel during low flow thanks to the longitudinal training wall, hence maintaining enough depth for navigation.

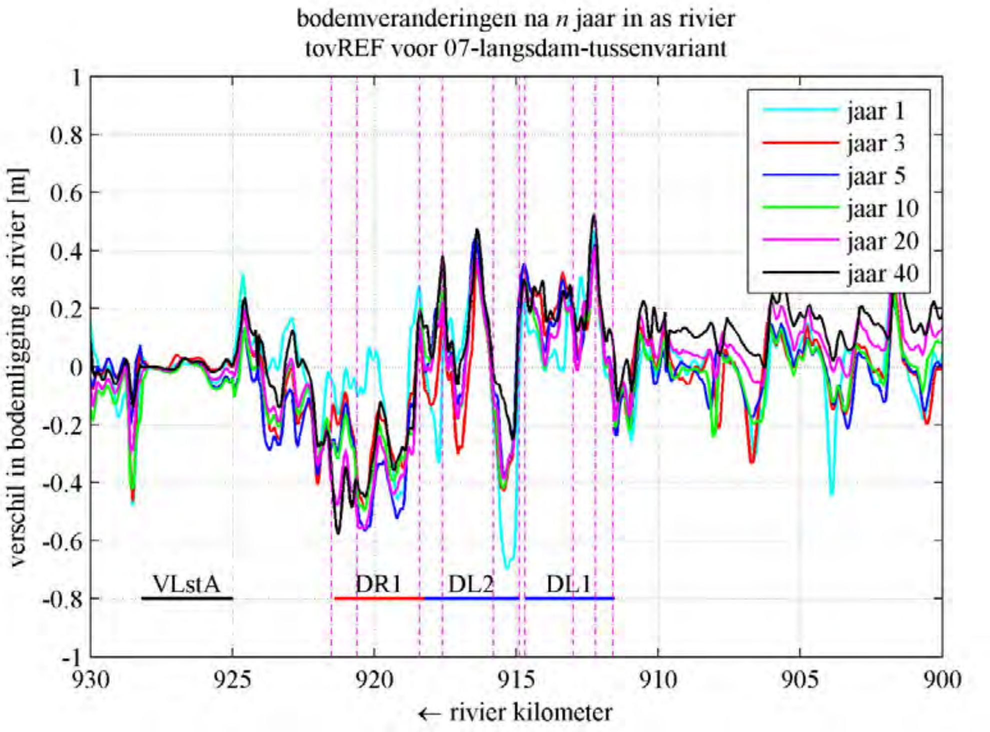

Figure 8 Bed level changes along the river axis of the improved longitudinal training walls design compared to the reference case without intervention. Figure from Huthoff *et al.* (2011).

3.5 Expectations based on numerical simulations

Huthoff *et al.* (2011) conducted a numerical study of the effects of the construction of the longitudinal training walls along the Waal River. To this end, they used WAQUA for hydrodynamic purposes on the Waal branch of the *Rijntakken* schematization available at that time and Delft3D for morphodynamic purposes using the Waal branch of the DVR schematization (Van Vuren *et al.*, 2006). They studied the effect of an original design and an improved design (*tussenvariant*). Only the improved design was successful in achieving similar results as those obtained due to groynes lowering.

The main outcome of the study regarding hydrodynamics was that the implementation of the longitudinal training walls achieved a lower water level than with the lowering of groynes. With regards to morphodynamic processes, comparison of simulation results with open inlets and closed inlets over the full length showed that these have a strong effect on bed elevation changes in the main channel. Open inlets let to a higher bed level than the reference scenario without intervention and opposite for closed inlets.

The bed elevation changes along the river axis agree in general with the expected results based on theory due to an extraction of water from the main channel (Section 3.2.3). The bed level increases compared to the reference along the longitudinal training walls and degradation is found at the inlets and outlets. Slight degradation was found at Ophemert, which is not the effect one would expect from a water extraction (Figure 8). We explain this erosion from the geometry in the model schematization to be such that the effect of narrowing (Section 3.2.2) is larger than the effect of water extraction from the main channel (Section 3.2.3).

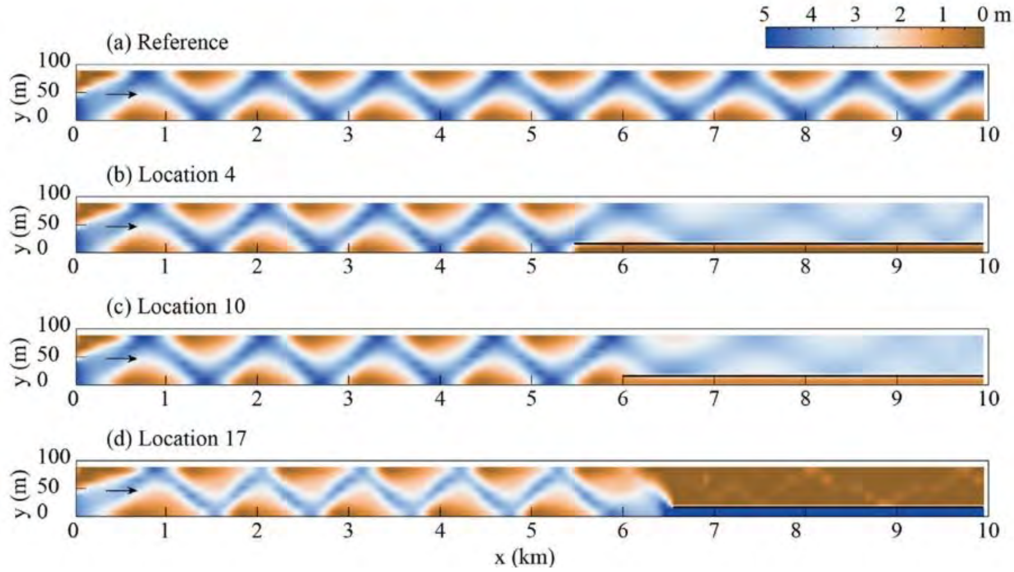

Figure 9 Water depth after 100 years of morphodynamic development in: (a) reference case without training wall, (b) training wall starting at the upstream part of a bar: the side channel closes and bars in the main channel tend to disappear for a distance, (c) training wall starting at the downstream part of a bar close to the crest: both channels remain open, (d) training wall starting at downstream part of the bar close to the pool: the side channel deepens and the main channel is closed. Figure and caption (adapted) from Le *et al.* (2018a).

Their study does not include development in the auxiliary channels. Hence, the costs of management and dredging are only due to main channel development. Moreover, there are no sills and the inlets. In general, they recommend to further research the morphodynamic effect of the longitudinal training walls.

Numerical simulation by Berkhof *et al.* (2018) showed that the longitudinal training walls would help in reducing the ongoing degradation of the longitudinal bed profile, but that the longitudinal training walls would not be sufficient to bring this degradation to a full stop.

Le *et al.* (2018b,a) studied the stability of alternate bar patterns subject to construction of a longitudinal training walls. Laboratory experiments showed that the system is inherently unstable. Worded differently, after construction of a longitudinal training wall, either the main channel or the auxiliary channel silts up, while the other eventually transports all the sediment and water. Numerical simulations show a stabilizing effect by natural changes in the relation governing the distribution of sediment over the main channel and the auxiliary channel. Le and coauthors found that the main parameter controlling whether the auxiliary channel silts up is the position of the upstream end of the longitudinal training wall with respect to the crest of a bar in the same side as the auxiliary channel. If the start of the longitudinal training wall is on the upstream side of the crest, the auxiliary channel silts up, while it attracts flow otherwise (Figure 9).

According to the analysis of the bed elevation conducted by De Ruijsscher *et al.* (2020a), the upstream end of longitudinal training walls at Wamel and Dreumel are upstream from the bar crest while it is downstream from the crest for the one at Ophemert. Thus, in an idealized scenario one may expect siltation at Wamel and Dreumel and degradation at Ophemert according to Le *et al.* (2018b,a). While this is correct for the first two, the auxiliary channel at Ophemert experiences aggradation, contrary to the expected results by Le and coauthors.

As we have seen in the theoretical analysis, a key aspect for determining siltation or degradation of a bifurcating system is the distribution of water with respect to sediment. Together with the fact that bank erosion is not accounted for by the studies conducted by Le *et al.* (2018b,a), the local three-dimensional effects that determine the sediment partitioning in the specific case of a sill such as the one constructed in the Waal have been neglected. More importantly, the auxiliary channels in the Waal River are not in-stream, as the experiments and simulations by Le and coauthors but are next to the original main channel.

4 Analysis of measured data

4.1 Introduction

In this section we analyse measured data of bed elevation, bank erosion, grain size, water elevation, water discharge, and dredging with the intention to understand the morphodynamic effects induced by the construction of the longitudinal training walls. Ideally, a long time-series of measurements along a sufficiently long non-intervened river stretch would exist, that could be used to derive the representative situation before the construction of the longitudinal training walls. Note that, given the dynamic nature of the river due to, for instance, unsteady flow, data right after the construction of the longitudinal training walls are not sufficient to characterize the situation before intervention. A similarly long time-series of measurements would ideally be available after intervening in the river by constructing the longitudinal training walls only. If other interventions take place at the same time, it is not straightforward to isolate the effect of the longitudinal training walls from other sources of morphodynamic change.

The situation we face in the study area is far from being ideal. One key component is that interventions such as lowering of the floodplains, the removal of hydraulic obstacles, or the setting back of levees have been taking place uninterruptedly since the start of the Room for the River programme. This inhibits the existence of a clear reference situation prior to intervention. The intervention with a larger potential impact is the lowering of groynes (*kribverlaging*) that took place at the same time as the construction of the longitudinal training walls both downstream and upstream of the study area (Figure 10). The lowered groynes downstream of the project area create a relative drawdown of flood levels (when groynes are submerged) and induce a possible additional backwater influence upstream, interfering with the processes that occur at and due to the longitudinal training walls. Similarly, the morphological impact (erosion wave) of the upstream lowered groynes will pass through the longitudinal training walls' section as well.

A second point of attention is that the contractor was allowed to extract sediment for the construction of the longitudinal training walls. The amount of sediment that was extracted, as well as the exact locations and times, is unclear. Van Weerdenburg (2018) roughly estimates the sediment extracted to be 550 000 m^3, which is on the order of magnitude of the annual sediment load of the Waal (Frings *et al.*, 2019). Certainly, such an intervention has a significant impact on the short-term morphodynamic development.

Figure 10 Groynes lowered.

4.2 Bed elevation

The study area is characterized by long-term (decadal) and large-scale (tens of kilometres) degradation of approximately 1 cm/year (Sloff, 2019) due to past interventions such as the construction of groynes and sediment extraction. These temporal and spatial scales are the largest and longest to consider. The following spatial scale of interest corresponds with the longitudinal training walls, which extend over approximately 10 km. Bar length are on the order of one or two kilometres. Finally, dune length is on the order of hundreds of metres. All these scales are captured in the biweekly multibeam echosounding of the river bed. These data are processed by *Rijkswaterstaat* and delivered with a 1 m by 1 m resolution.

For the sake of filtering the length scales above and below the scale of interest (i.e., the scale that contains information about changes due to the construction of the longitudinal training walls), Van Denderen *et al.* (2020) use the wavelet technique to filter the data between 2005 and 2019 (Figure 11).

They focus on the dynamics of the main channel, as the side channel is not as extensively measured as the main channel. For filtering, they make use of a Morlet wavelet. In comparison to other ways of filtering data such as the common moving mean (also known as sliding window), the wavelet analysis allows selecting a particular frequency rather than filtering everything below a threshold frequency.

The effect of large floods, such as the one in 2011, is visible in the filtered data. A perturbation appears with a wavelength of approximately 1 km that propagates at an approximate celerity of 1 km/year. The perturbation diffuses with time and reappears in the next high-water event. The perturbation is forced by the geometry, as for every high-water event it appears at the same location.

The data filtering prevents us to analyse an important difference between longitudinal training walls and groyne fields. As groynes are an obstacle perpendicular to the flow, they cause three-dimensional features that create a local pattern on a depth scale (Wright and Crosato, 2011) in the bed usually referred to as “groyne flames”. While the mean bed elevation is unaffected by the flames, these pose a challenge for maintenance. Longitudinal training walls create local three-dimensional effects at the upstream and downstream ends only, possibly decreasing maintenance costs.

After the construction of the longitudinal training walls, aggradation of several decimetres is observed right downstream of each of the upstream ends of the longitudinal training walls at the river kilometres (RKM) approximately equal to 912, 916, and 919.5. This is the expected behaviour if one considers that the main effect right after the construction is that which is equivalent to a water extraction (Section 3.2.3). At the confluences of the auxiliary channels with the main channel, degradation is observed. This is also expected considering the intervention as a water extraction. Degradation at the downstream end of the study area is larger than downstream from the first and second longitudinal training walls. This is logical, given that downstream of the first and second longitudinal training walls, there is still a channel that diverts part of the flow, while downstream from the last longitudinal training wall, all flow is transported by the main channel.

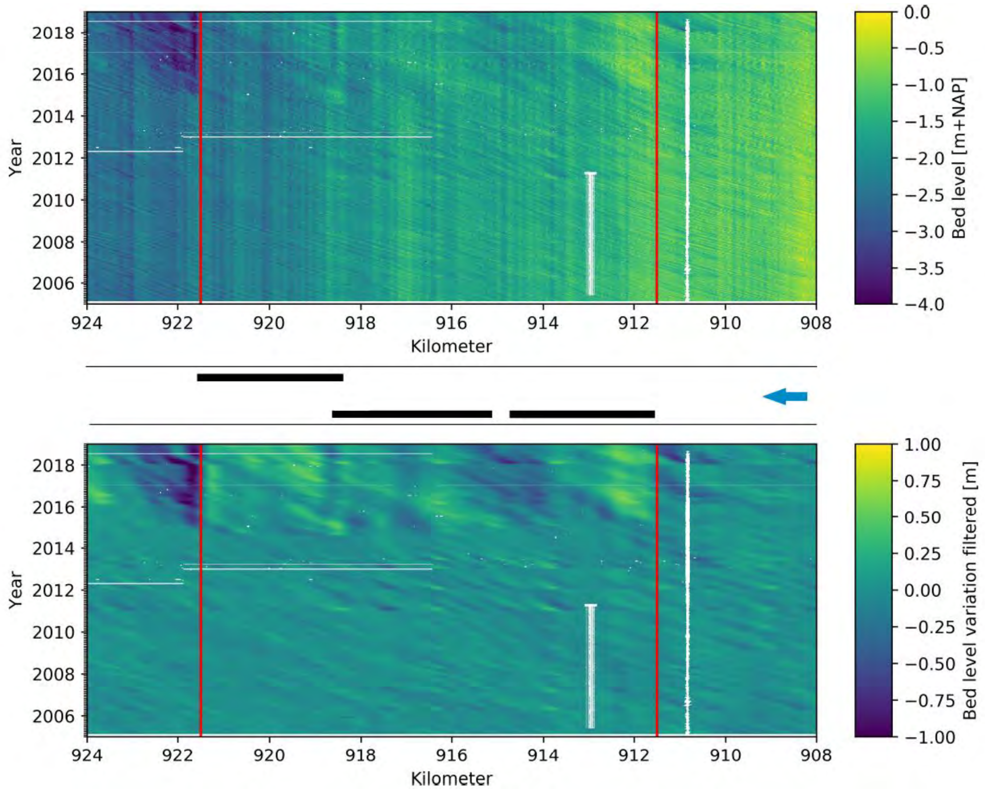

Figure 11 Bed level (top) and filtered bed level (bottom). Vertical red lines indicate the upstream and downstream ends of the longitudinal training walls section. Figure from Van Denderen *et al.* (2020).

Downstream of the aggradational waves, degradation is observed. Note, for instance, the degradation at RKM 912.5 in 2015. This effect cannot be explained by the one-dimensional simplified analysis (Section 3.2). A possible cause for these large degradational features is dredging of sediment by the contractor. The fact that the feature in RKM 912.5 is present right after construction and moves downstream without reappearing, supports this hypothesis. A second process that explains degradation downstream of the aggradation is flow over and across the longitudinal training walls. A substantial amount of discharge from the auxiliary channel towards the main channel would cause degradation in the main channel, in a similar manner as is observed at the confluences.

Mixed-size sediment processes may explain the degradational features. The aggradational features are probably composed of coarser sediment than originally found in the river bed, as fine sediment is preferentially transferred towards the auxiliary channel (e.g., Van Denderen *et al.* (2020)). This coarsening of the bed surface in the upstream part of the main channel would explain degradation downstream of it, due to the gradient in sediment transport capacity that it induces. The fact that the side channel appears to become finer (e.g., Van Weerdenburg (2018)) supports the previous statement. However, we acknowledge that the situation is too complex as: 1) only a small part of the total load of sediment is going to the auxiliary channel, and the question is whether such a minor extraction can create a noticeable difference in grain-size distribution of the main channel, and to what spatial scale. 2) The main aggradation is actually a reduction of degradation which is driven by a reduction of flow velocity (since discharge is diverted with possibly a small amount of sediment). The degrading section may be coarse already, while due to aggradation it may become finer. 3) Laboratory experiments at the Delft University of Technology (Van Os, 2020) show that it is not correct to assume that only fine sediment will enter the auxiliary channel: it depends also on the presence of a sill or closure structure at the entrance.

At RKM 917, a persistent degradational feature is observed, different from the one at RKM 912.5. This degradation is explained by the presence of the Passewaaij side channel, which was connected to the main channel in the same period of time as the construction of the longitudinal training walls.

The wavelet analysis by Van Denderen *et al.* (2020) shows the importance of dense spatiotemporal data. Only using such data one can relate the slight aggradation and subsequent degradation observed in 2018-2019 at RKM 921.5 (end of the study area) to the initial condition (2015) at RKM 918. Similarly, the increased degradation at RKM 915 in 2018 is enhanced by arrival of the degradational wave formed in 2015 at RKM 912.5. As previously found, features move at approximately 1 km/year.

The overall short-term impact of the longitudinal training walls is summarized by computing the mean of the bed elevation along the whole intervention area (Figure 12). The bed level has increased by approximately 10 cm in 4 years since construction was completed. Figure 12 also suggests that the equilibrium situation has not been reached. It also provides an order of magnitude of the effect of high-flow events. Moreover, it shows the power of the wavelet analysis in filtering long-term trends.

A different analysis of the data has been conducted by Van Weerdenburg (2018). He filtered the two-dimensional data-set in streamwise direction using a moving average with window size equal to 630 m, with the intention to filter dunes. In the transverse direction, a moving average with window size equal to 5 m has been used. His analysis in the streamwise direction is restricted to the river axis (i.e., to 5 m of data in the transverse direction). It is relevant to mention that perturbations with wavelength larger than that of dunes exist due to, for instance, groynes and river bars. Moreover, by restricting the analysis to the river axis, perturbations appear due to transverse features such as, for instance, river bends. Finally, the definition of the river axis changed after the construction of the longitudinal training walls. From a temporal perspective, the analysis is restricted to data from April and October between 2011 and 2018. For these reasons, we consider that the analysis by Van Denderen *et al.* (2020) provides an ampler picture of the bed elevation dynamics of the main channel.

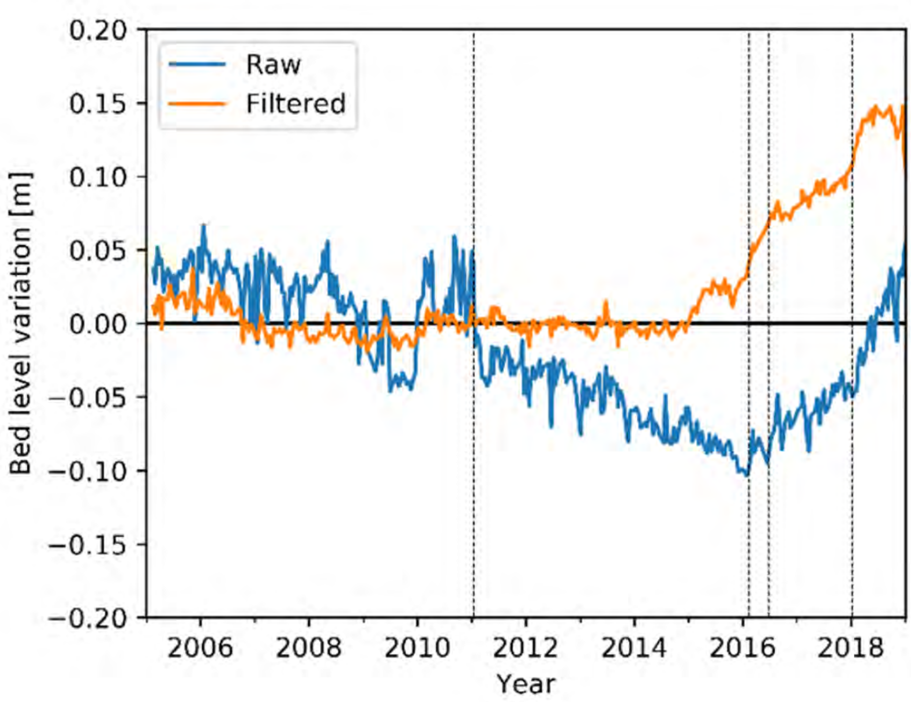

Figure 12 Raw and filtered mean bed level along the intervention area. Vertical dotted lines indicate high-flow events. Figure from Van Denderen et al. (2020).

However, Van Weerdenburg (2018) provides insight into bed elevation changes in the transverse direction (Figure 13). He notes that the aggradational wave at the upstream end of the intervention area (i.e., right after the entrance of the first auxiliary channel) is displaced to the left (i.e., close to the longitudinal training wall) (Figure 14). This observation shows one of the limitations of the simplified one-dimensional analysis. Aggradation in the main channel occurs, but it focuses on the water diversion due to local effects because of flow partitioning. The data do not show degradation on the right-hand side. Nevertheless, it could be possible that aggradation on the left displaces the streamlines towards the right causing degradation (or less aggradation) and forcing a bar pattern.

When aggregating the bed level measurements in areas covering the whole length of each longitudinal training wall, Van Weerdenburg (2018) finds overall degradation on the order of 10 cm during construction of the longitudinal training walls. Overall degradation at the time of the construction of the longitudinal training walls has also been reported by (Marchesin, 2018), who conducted an analysis similar to the one by Van Weerdenburg (2018). Interestingly, this is not visible in the analysis conducted by Van Denderen *et al.* (2020). A detailed analysis would be necessary to find the origin of the discrepancy between results. The results from Van Weerdenburg (2018) show significant scatter and, for instance, a 10 cm increase in bed level along the area of the first longitudinal training wall (Wamel) between spring of 2011 and spring of 2012 (i.e., before construction of the longitudinal training walls). The method employed in filtering the data and the use of a limited number of measurements in time may cause the variability.

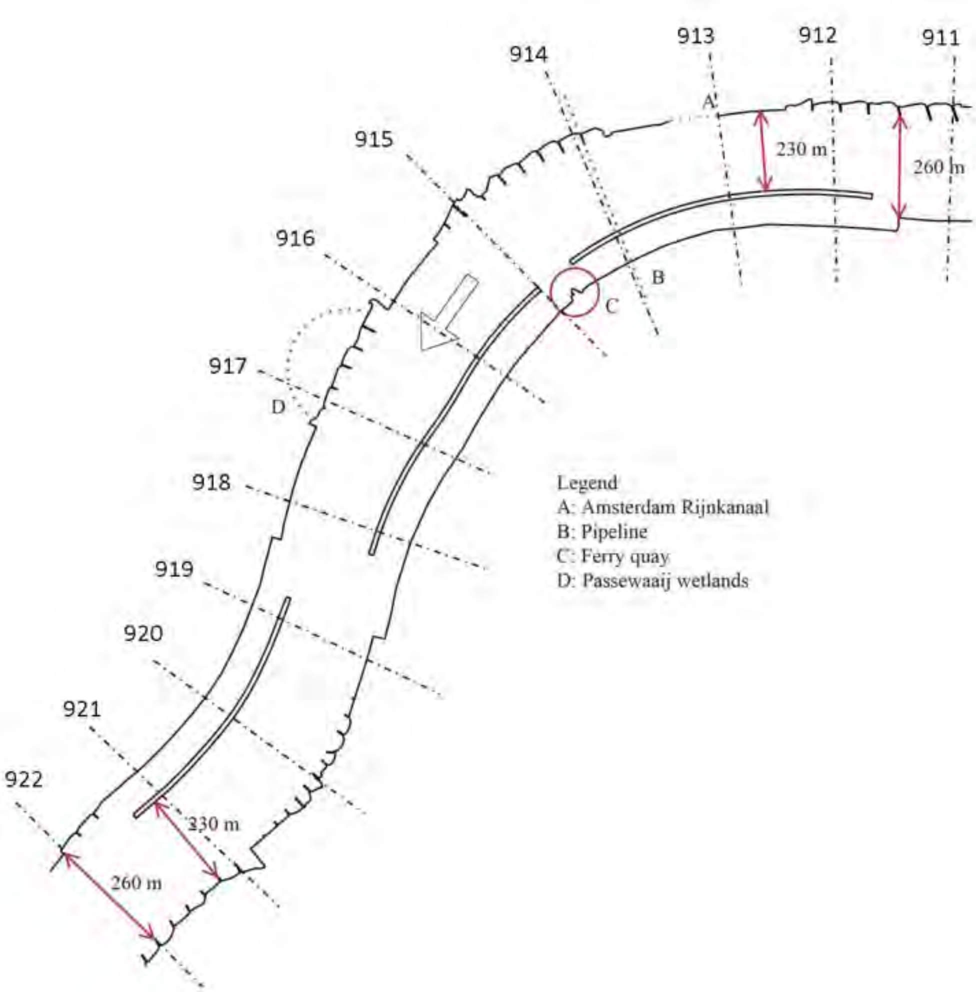

Figure 13 Cross-sections analysed by Van Weerdenburg (2018). Figure from Van Weerdenburg (2018).

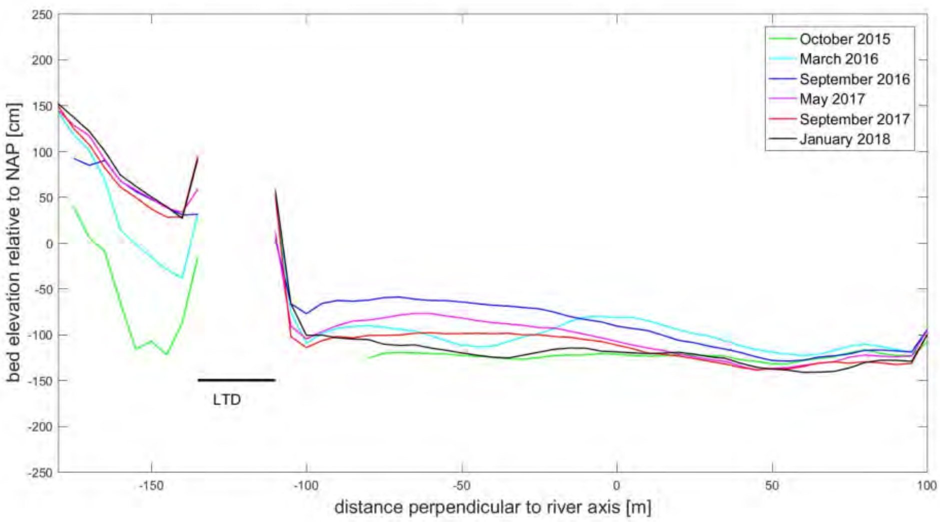

Figure 14 Transverse bed elevation changes at Rhine-km 912. Figure from Van Weerdenburg (2018).

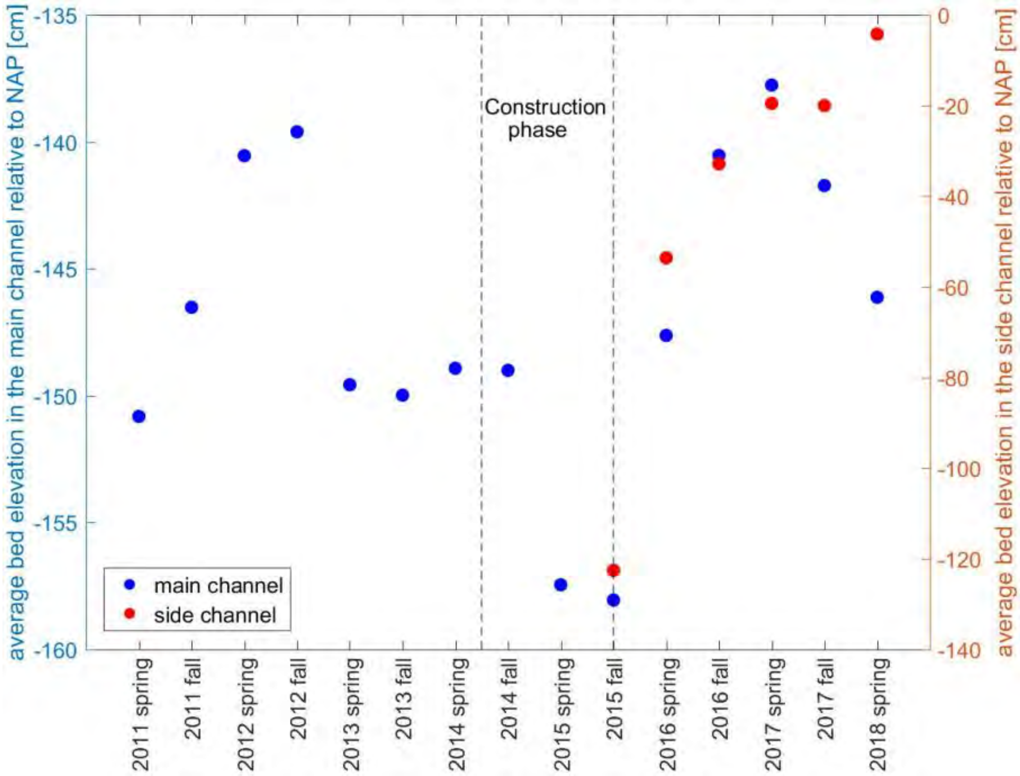

Figure 15 Development of mean bed elevation with time at Wamel. Figure from Van Weerdenburg (2018).

Apart from the main channel, Van Weerdenburg (2018) studies the bed elevation dynamics of the auxiliary channel. Bed elevation measurements in the auxiliary channel are restricted to the areas under water and with sufficient flow depth for the surveying boat to navigate. Thus, there is an important bias towards the deepest sections. The changes in bed elevation must be understood as changes in bed elevation of the deepest areas within an auxiliary channel. The measurements for all auxiliary channels show a clear siltation tendency. The auxiliary channel at Wamel (Figure 15), Dreumel (Figure 16), and Ophemert (Figure 17) show an increase in bed elevation of 0.8 m, 0.6 m, and 1.0 m in the first year, respectively. The auxiliary channel at Wamel shows a subsequent 0.6 m of aggradation until the spring of 2018 while the other two auxiliary channels stabilize.

The product of 1 m aggradation by the area of a 2 km long and 60 m wide auxiliary channel yields a rough estimate of 120 000 m^3 of sedimentation. When compared to an estimate of the annual load of the Waal including pores equal to 300 000 m^3 (Frings *et al.*, 2019), it clearly shows that aggradation is at least in part due to bank erosion. Section 4.3 deals with this matter in detail.

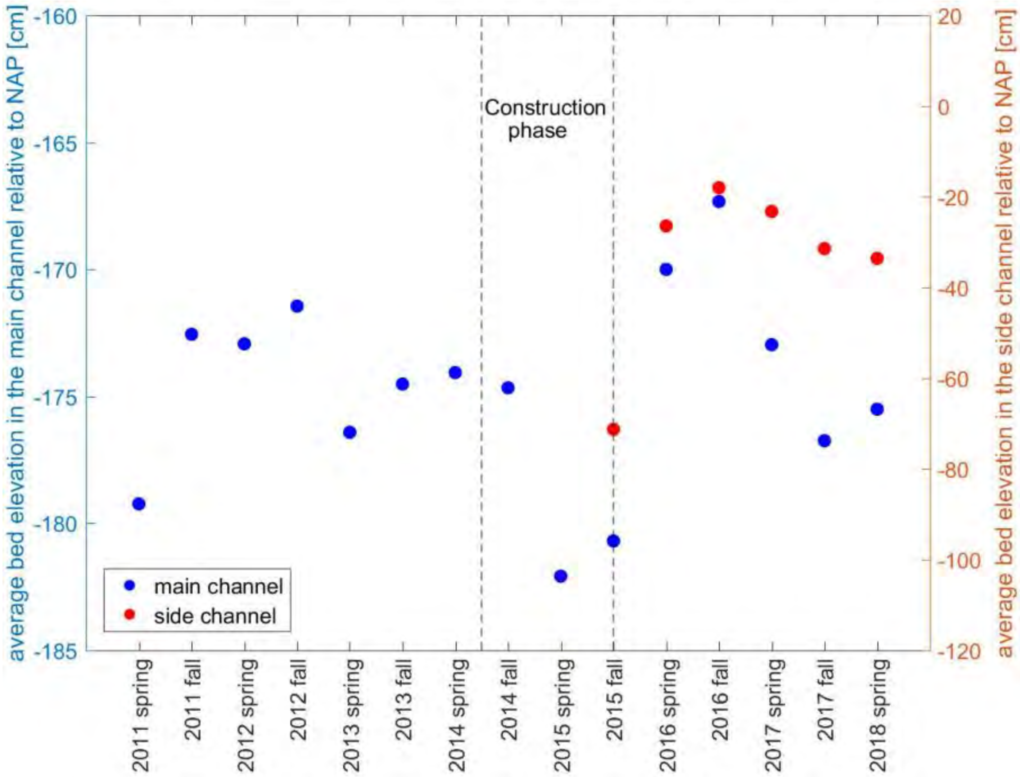

Figure 16 Development of mean bed elevation with time at Dreumel. Figure from Van Weerdenburg (2018).

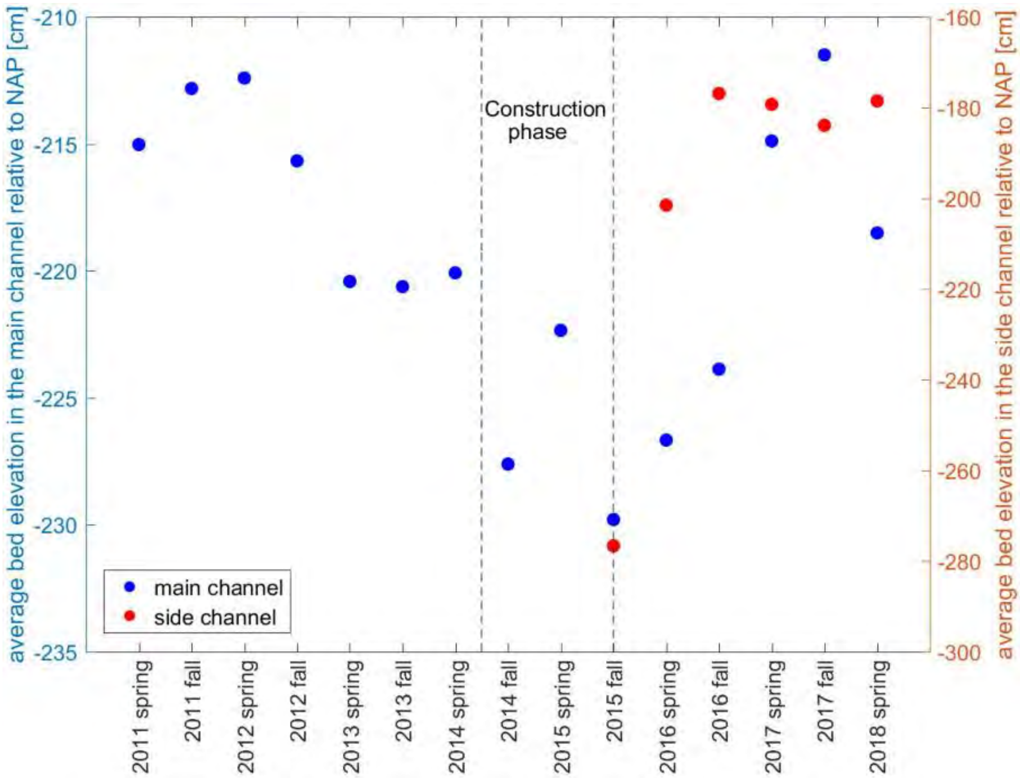

Figure 17 Development of mean bed elevation with time at Ophemert. Figure from Van Weerdenburg (2018).

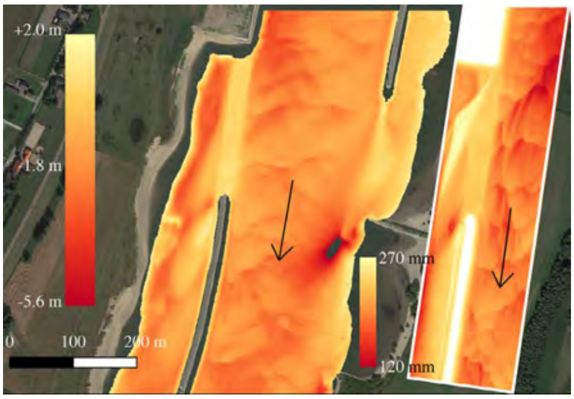

Figure 18 Qualitative comparison of bed levels from the laboratory and field measurements: both show the expected bars in the side channel (Section 3.3), although location and intensity differ. Left: bed level from multibeam echosoundings in the Waal River field pilot on 7 February 2017, with respect to Amsterdam Ordnance Datum (NAP). Right: bed level at the end of experiment A1, with respect to the flume bottom. The main flow direction is indicated by the arrow. Figure and caption (adapted) from De Ruijsscher *et al.* (2019).

De Ruijsscher *et al.* (2019) study the effect of the sill shape and position in preventing or enhancing sediment transport towards the auxiliary channel. They conducted a series of laboratory experiments that agreed reasonably well with field measurements. Their experiments and field observations reproduce the two eddy bars that were expected in the upstream reach of the auxiliary channel (Figure 18). The researchers termed the upstream bar “divergence bar” and the downstream bar “inner-bend bar”. These bedforms have an effect on bed topography of the auxiliary channel but their effect on the main channel dynamics is very limited, as these have no significant influence on the water level and flow pattern at the entrance. Their influence on the sediment partitioning has not been assessed and we expect it to be negligible.

De Ruijsscher *et al.* (2019) measured the cumulative sedimentation in the auxiliary channel as a function of the sill shape (Figure 19) by subtracting the final bed elevation in their laboratory experiments from the initial one (Figure 20). They find that the cumulative sedimentation is minimized when the division between the auxiliary channel and the main channel is at a constant elevation. From our perspective, this result indicates that the shape of the inlet has an effect on the bedforms forming at the entrance but it is no evidence that the inlet shape influences the sediment partitioning between the main channel and the auxiliary channel. Assuming a constant sediment transport rate, one expects different bedforms to develop depending on the inlet shape. The sediment transport rate has a strong influence on the time development rather than on the shape.

De Ruijsscher *et al.* (2019) provide evidence that, in essence, a detail study of the local dynamics at the upstream end of a longitudinal training wall is crucial for predicting the long-term morphodynamic development a such a system.

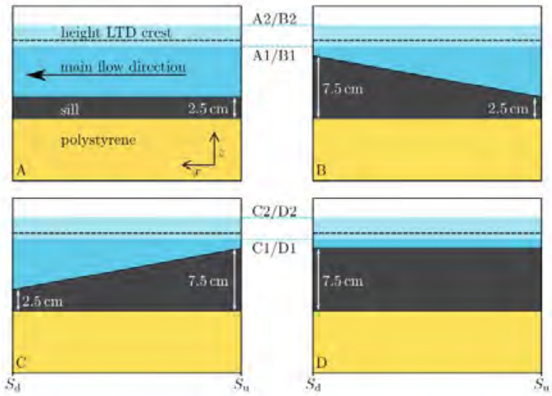

Figure 19 Schematic side view representation of the sill geometries and water levels in the experiments by De Ruijsscher *et al.* (2019). The sill is shown in grey, and the water column in blue (low/high water level). The longitudinal training wall crest height is indicated by the dashed line as a reference. Figure and caption (adapted) from De Ruijsscher *et al.* (2019).

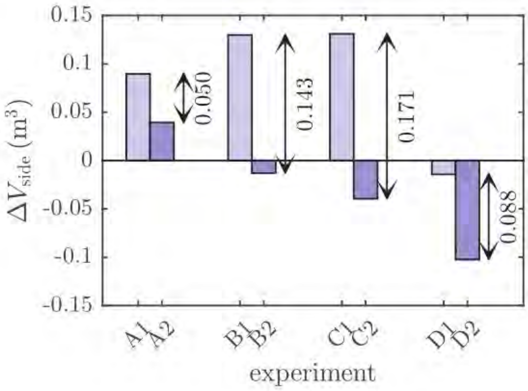

Figure 20 Cumulative sedimentation in the side channel for each of the experiments conducted by De Ruijsscher *et al.* (2019), with respect to the initial flat bed. For each sill geometry, the difference in sedimentation between the high and low water situations is indicated. Figure and caption (adapted) from De Ruijsscher *et al.* (2019).

De Jong *et al.* (2021) analysed multibeam measurements using the PMAP procedure (Kater, 2014), which combines different measurements and averages data per river section. A slight degradational trend until Ophemert was present prior to construction of the longitudinal training walls and even aggradation was observed around and downstream of Ophemert. During construction there is overall degradation in the area (Figure 21). After construction of the longitudinal training walls (and groyne lowering downstream) was completed, the initial trend at Wamel, Dreumel and Ophemert appears to show relative sedimentation. This is in line with other analyses such as the one by Van Denderen *et al.* (2020). Based on the current data, De Jong *et al.* (2021) conclude that it is not possible to derive conclusions about the long-term development, as the bed elevation is still in the short-term phase of adaptation to the intervention. Nevertheless, the short-term findings indicate a reduction of degradation in the long term.

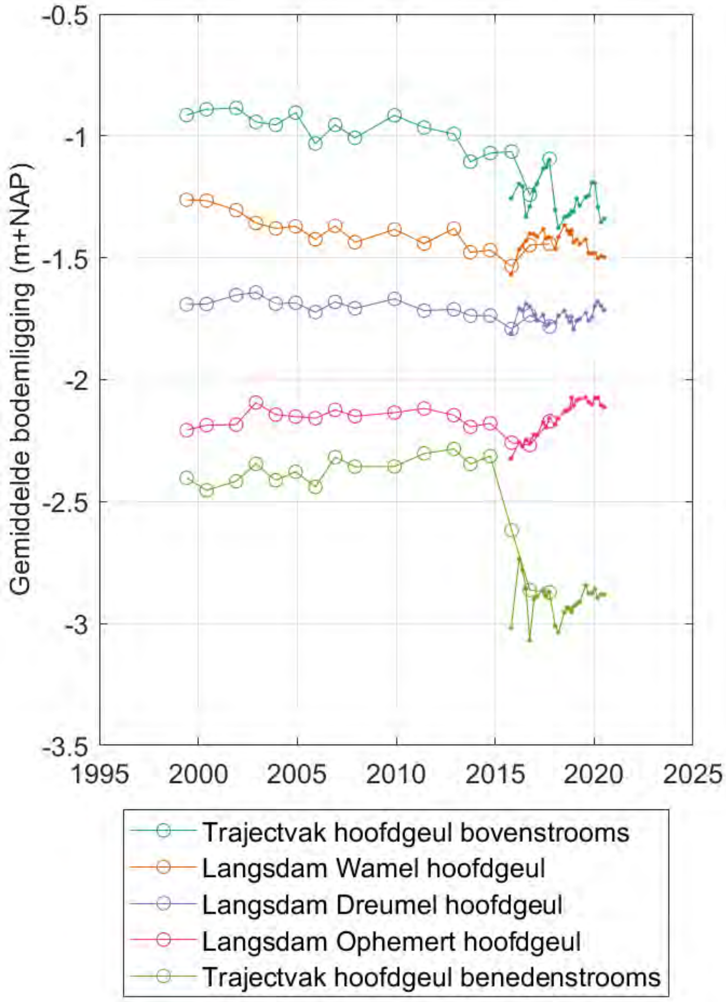

Figure 21 The average over different reaches of the Pmap *average* bed level. See De Jong *et al.* (2021) for a detailed explanation of the definition of the areas and methodology.

Czapiga *et al.* (2021) conducted an analysis of the bed level changes based on their own polygons. De Jong *et al.* (2021) compare the results by Czapiga *et al.* (2021) to those of the PMAP analysis concluding that the trends are the same.

In April 2018 the sills at the Wamel and Dreumel inlets were raised. The PMAP analysis shows that the sedimentation in the main channel observed prior to changing the inlets turns into erosion after the inlets were changed. This suggests that indeed the inlets can be used in modifying the dynamics of the longitudinal training walls. Nevertheless, one should be cautious in deriving conclusions. First, not enough time has passed for clearly identifying the effects of a modification of the inlets. Roughly only 2 years passed since construction until the inlets were changed and only 2 years have passed since changing the inlets until now. Given the annual variability in flow, the observed behaviour cannot be solely ascribed to changing of the inlets. Moreover, local variability is large. While aggradation is observed after changing the inlets in both Wamel and Dreumel, the order of magnitude of the aggradation at Dreumel is smaller than that in Wamel. Finally, it is possible that the observed change in trend after modification of the inlet is a coincidence. The 2D bed level data shows degradation upstream of Wamel in week 2 of 2018. It is unclear what the origin of this change in bed elevation is. This trench propagates downstream reaching the inlet when it was changed.

Apart from this trench appearing in the data, other waves pass through the river caused by, for instance, the varying flow. In Figure 11, perturbations in the bed level are observed upstream from the longitudinal training walls. These travel at, approximately, 1 km/year. As such, several years are needed to filter out the effect of these waves.

4.3 Bank erosion

After removal of the groynes and set-back of the straight river banks (*gestrekte oevers*), the resulting inner banks of the auxiliary channel remained unprotected. Since completion of the project, several parts of these banks have been eroding at a corridor scale. The magnitude of this erosion is first judged on the basis of a recent visual inspection as part of this project, and by observing aerial photography from Google Earth® .

The erosion of banks can have multiple effects, but these have not yet been confirmed by the data:

- The channel cross-section area will increase if the eroded sediment is transported downstream away from the erosion site (fine sediments from banks may disappear from the cross-section). Hence, the auxiliary channel may gradually attract more water than anticipated.
- The channel cross-section area will not increase much if the bank material remains on the bed in the vicinity of the eroding banks (mostly for relative coarse sediment). The bank channel will become shallower and wider and may develop bars and channels (width-to-depth ratio increase).
- Unforeseen land loss may become an issue for the local land owners.

The evaluation team made the following observations at the auxiliary channel of Wamel (entire length) on April 8, 2020:

- Along the section where groynes were removed, the original beaches with mild slopes and some trees remain quite intact (Figure 22 and Figure 23). There are no signs of strong erosion. Presumably the toe of these sections are protected by remains of the groynes (or their foundations) on the bed. Some gravel and rock were found along these beaches which suggests this (these are materials from the former groynes).
- Along the excavated sections (former *gestrekte oevers* that were set back) very steep side slopes were found with a clear erosion signature. The Google Earth® images show an average erosion of about 5 m up to 10 m at the water line (Figure 24 and Figure 25). These slopes generally consist of alternating layers of sand and clay. As sand is washed out between the clay layers, the clay layers collapse by cantilever effects, causing the slope to form small terraces. Blocks of clay (rounded by fluid motion) accumulate on the slopes as can be seen in Figure 24. These alternating horizontal layers are characteristic for the evolution of these flood plains, and can be found along all the river branches.
- Seepage of groundwater from the flood plains after a period of inundation decreases the strength of these banks and increases bank instability. The presence of pools of water trapped behind the slightly elevated banks (*hangwater*) causes a relatively high negative pressure on the slopes, which creates seepage and possibly “piping” through the sand layers.
- Some intermediate groynes (from stones of old groynes) were constructed in the channel, but at other locations than former groynes (Figure 23). They will provide some protection to the banks, as they “push” the highest flows away from the bank.
- The main eroding bank is between RKM 912.9 - RKM 914, with a length of about 1 km. The top-level (flood plain) is at elevation 7.5 m+NAP, and the toe of the slope roughly on 1 m+NAP. The erosion of 5 m has then roughly produced a sediment volume of 32 500 m^3. A similar erosion (length and rate) can be found in the Dreumel channel, where a similar set-back of the river bank was implemented between RKM 916 and RKM 917.

From the observed behaviour of the river banks the following can be recommended for maintenance:

- Bank erosion is strongest where former straight banks (without groynes) have been excavated and left unprotected. To control the erosion process, a mild slope, with shallow and lightly protected toe is preferable. Some drainage solutions for seepage can be considered.
- The effect of vegetation on the (mild) slopes may provide additional strength.

LiDAR measurements of the bank area have been taken on a yearly basis. These data have been combined by Flores *et al.* (2021) with multibeam echosounder data of the auxiliary channels to obtain a complete picture of the dynamics of the bank with the objective of calculating net aggradation and degradation.

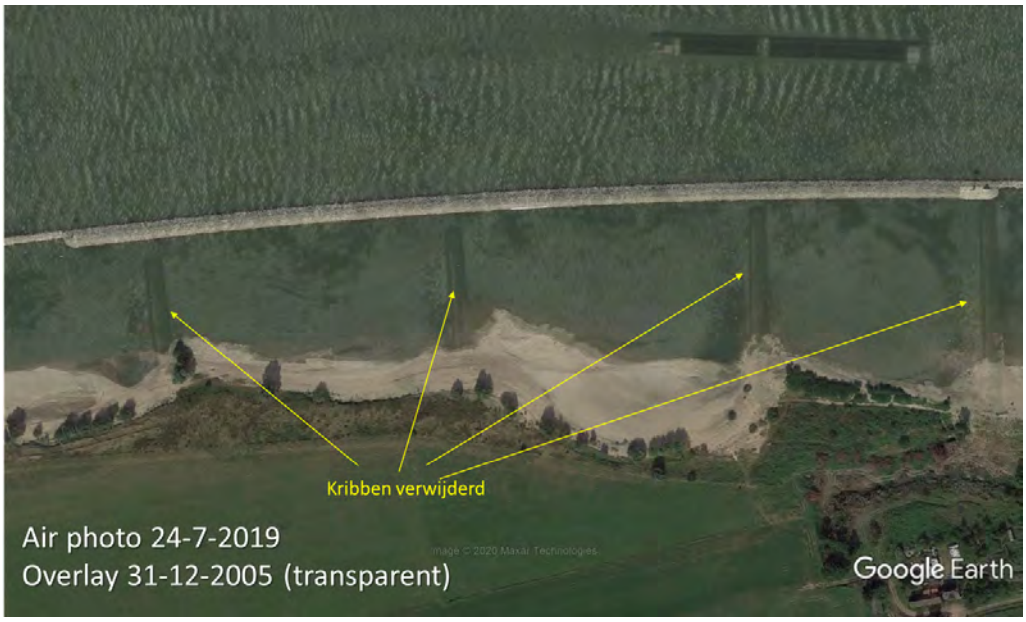

Figure 22 Google Earth® aerial photograph of auxiliary channel at Wamel at RKM 912.5. Aerial photograph of 2019 and 2005 are overlaid to see the former location of the removed groynes.

Figure 23 Google Earth® aerial photograph of auxiliary channel at Wamel at RKM 912.5. Aerial photograph of 2019 and 2005 are overlaid to see the former location of the bank line that was set backward, and the location of the new groynes relative to the old groynes. The lower left corner is the ferry crossing Tiel-Wamel.

Figure 24 Google Earth® aerial photograph of auxiliary channel at Wamel at RKM 913.9 with photograph of the eroding bank at this section (photo taken at location of pin in upstream direction).

Figure 25 Google Earth® aerial photograph of auxiliary channel at Wamel at RKM 913.7 with photograph of the eroding bank at this section (photo taken at location of pin in upstream direction)

They observe that close to the banks there is net degradation while close to the longitudinal training walls there is net aggradation. This seems to indicate bank erosion on one side and aggradation of the recreational boating channel of the auxiliary channel on the other side. The yearly retreat of the bank line between 2014 and 2019 at Wamel and Dreumel oscillates between 0.1 m/year and 3.2 m/year with an average of 1.2 m/year at Wamel and 2.0 m/year at Dreumel. The rate of erosion, based on yearly measurements, decreases with time, which indicates stabilization of the bank given a constant forcing.

It is relevant to take into consideration that the multibeam measurements that were taken as close as possible in time to the yearly LiDAR measurements are considered as representative for the whole year. This is a caveat given the dependence of the bed topography in the underwater area on changes in the discharge. This effect should be filtered out when several measurements are taken or if the LiDAR measurements were obtained under similar flow conditions.

4.4 Grain size

There exists a decadal set of measurements of the grain size distribution along the main channel conducted by *Rijkswaterstaat*. While this is in principle a powerful data-set, the frequency of measurements in both space and time is relatively low (Chavarrías and Ottevanger, 2019). This causes the scatter to be large and prevents drawing definite conclusions about changes in grain size distribution.

Van Weerdenburg (2018) analysed the data-set and found no clear trends (Figures 26-28. The data from 2017 that he analysed did not show a coarse right-hand side with respect to the axis, while data from previous measurement programmes do show such a difference. This is due to a coarsening of the axis between the last two campaigns. Nevertheless, it is not possible to conclude that this mild effect is due to the construction of the longitudinal training walls.

A sediment sample at the upstream and downstream ends of each auxiliary channel was taken during the fall of 2017. The bed surface of the side channel appears to be finer than the main channel. However, as with the rest of the grain size data, it proves to be insufficient to draw conclusions due to insufficient spatial and temporal resolution.

Flores *et al.* (2021) measured the composition of the substrate in the auxiliary channels and the main channel between Dreumel and Ophemert by means of side-scan sonar in combination with soil samples for validation. The objective of the study was studying abiotic life. Their analysis compares the data from 2019 to data from 2020.

The auxiliary channels show larger variability than the main channel. We explain this from the presence of fine sediment in the auxiliary channels, which is transported in the main channel. Also, gravel in the auxiliary channel at Ophemert represents a large proportion of the identified sediment. This is most probably part of an old deposit as gravel is not found in the main channel.

In one year, the proportion of gravel in the auxiliary channel at Ophemert decreases, which can be due to deposition of finer sediment from the banks. The soil classified as “mixed” increases in all auxiliary channels. Sediment originally forming the banks depositing in the recreational boating channel explains the outcome.

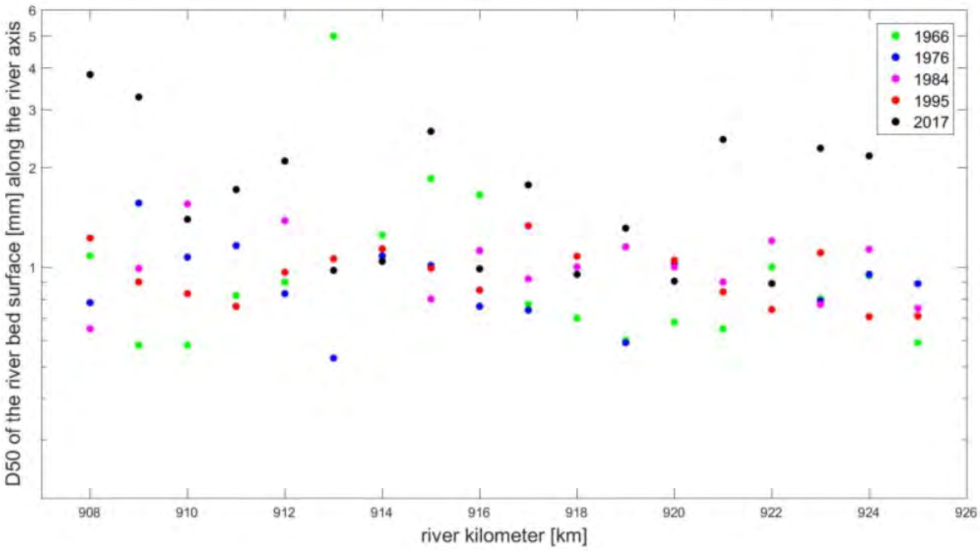

Figure 26 D_{50} at the bed surface along the river axis in the area where the longitudinal training walls have been constructed. Figure from Van Weerdenburg (2018).

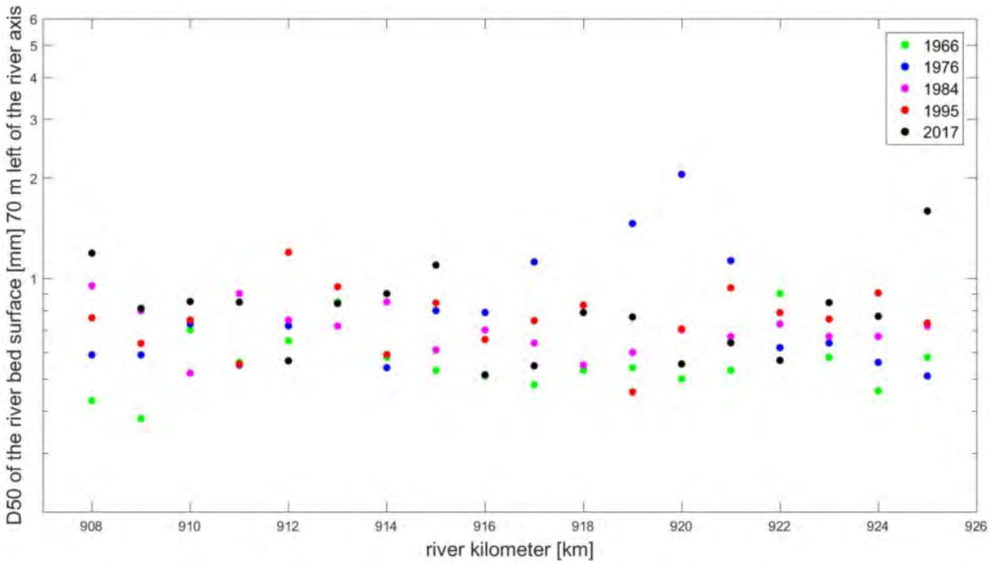

Figure 27 D_{50} at the bed surface along the left-hand side in the area where the longitudinal training walls have been constructed. Figure from Van Weerdenburg (2018).

Deltares

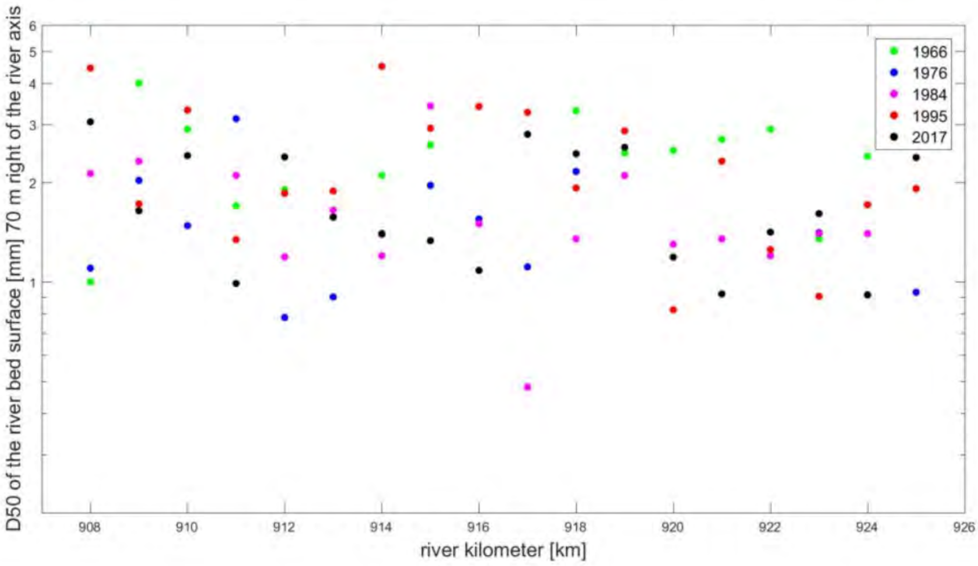

Figure 28 D_{50} at the bed surface along the right-hand side in the area where the longitudinal training walls have been constructed. Figure from Van Weerdenburg (2018).

4.5 Stage-discharge relations

In Section 4.2 we have seen the difficulties of analysing changes in mean bed elevation using echo-sounder measurements. In short, the temporal frequency of the measurements is in general lower than one would like to properly filter the effect of individual flow events, and the data is subject to perturbations due to the presence of bedforms that require filtering.

The water level is continuously monitored with high temporal resolution and it is not subject to large oscillations compared to the bed level (due to the presence of bedforms). Changes in time in the relation between the discharge and the water level (or stage) can be signs of morphological development, but also signs of changes in hydraulic roughness (by, for instance, small-scale morphology or vegetation) or signs of changes downstream that produce backwater effects.

In this section we study the relation between water level and discharge. The discharge in the Waal River is used as a reference in Section 4.5.1. This analysis is limited by the fact that the discharge is actually derived from the water level at Tiel, which is affected by the construction of the longitudinal training walls. Using the discharge at Lobith as a reference (Section 4.5.2) overcomes this limitation. However, this second analysis is limited by the effect of Room for the River interventions and a change in the discharge distribution at the Pannerdensche Kop. The analysis of raw measurements (Section 4.5.3) completes the pictures. While being the most sensible for studying the changes, this data-set is limited by the amount of data.

Figure 29 Location of the measurement stations. Source: Google Earth®.

4.5.1 Discharge reference at Tiel

In this section we study the relation between water level and discharge in three stations (Figure 29): Dodewaard (upstream of the study area), Tiel (within the study area), and Zaltbommel (downstream of the study area) to find evidence of trend breaks in overall aggradation and degradation.

We consider the period between 1-1-2010 and 1-1-2020. Of the three considered stations, only the station at Tiel provides a measure of the water discharge. The time series at the three stations is shown in Figure 30, Figure 31, and Figure 32. Data have been obtained from *Rijkswaterstaat* database (https://waterinfo.rws.nl/).

For a given time at which a measurement of the water level is available, the closest measurement in time of the water discharge is associated to it. We discern between values before 1-8-2014 (i.e., before starting construction) and after 31-10-2015 (i.e., after finishing construction). Subsequently, we consider bins of 150 m^3/s and obtain the maximum, minimum, mean, and standard deviation from all water level points within the bin. Figures 33-38 show the resulting stage-discharge relations for the entire dataset and focussing on low-flow conditions (i.e., conditions in which the water level is below the crests of the longitudinal training walls). In Figures 39-41, we plot the difference in mean water level between the situation before and after intervention.

The discharge at Tiel provided by *Rijkswaterstaat* is a function of the water level of Tiel and has not been adjusted since implementation of the longitudinal training walls. Thus, the stage-discharge relation at Tiel provides no information of changes at Tiel. The relation we derive presents little dispersion around the mean. The dispersion we observe is due to averaging values within a bin.

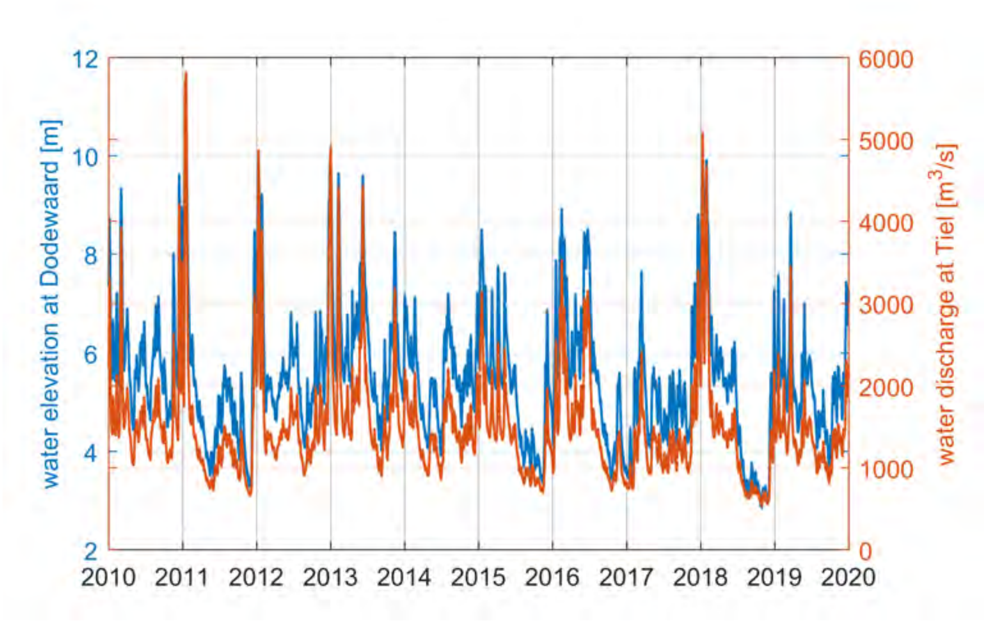

Figure 30 Water level at Dodewaard and water discharge at Tiel as a function of time.

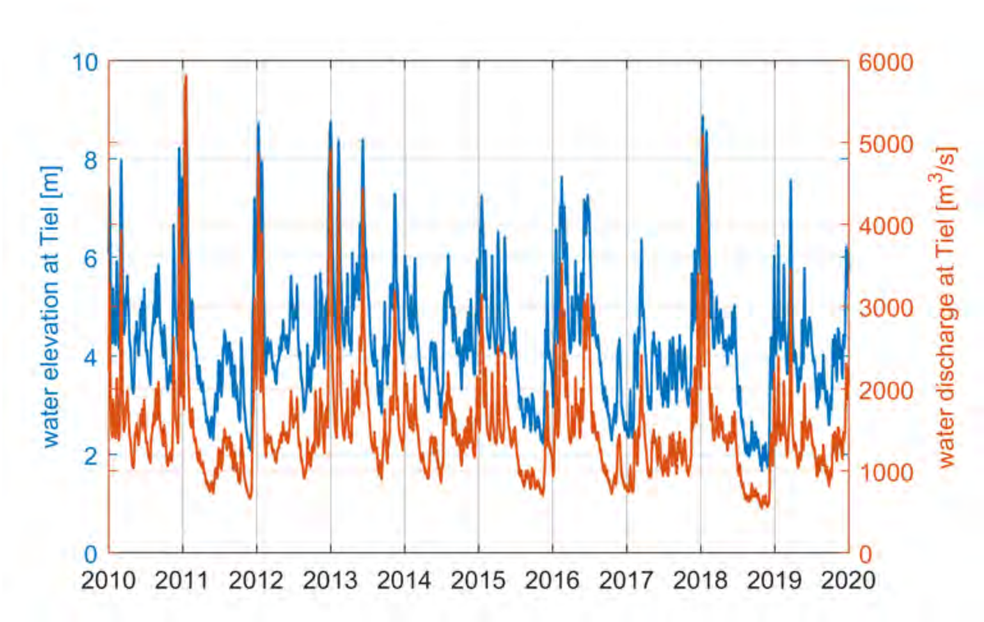

Figure 31 Water level at Tiel and water discharge at Tiel as a function of time.

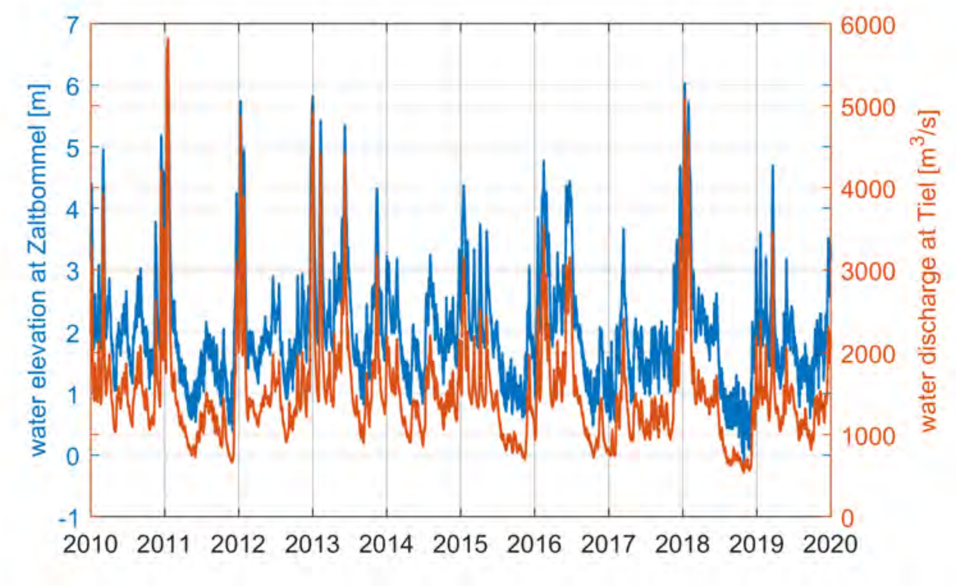

Figure 32 Water level at Zaltbommel and water discharge at Tiel as a function of time.

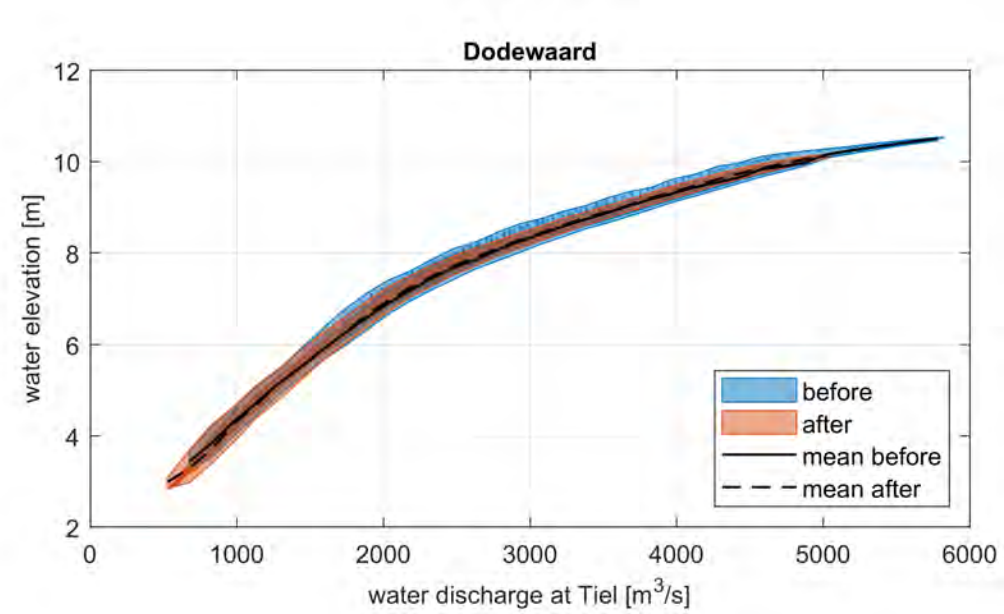

Figure 33 Water level at Dodewaard as a function of the water discharge at Tiel.

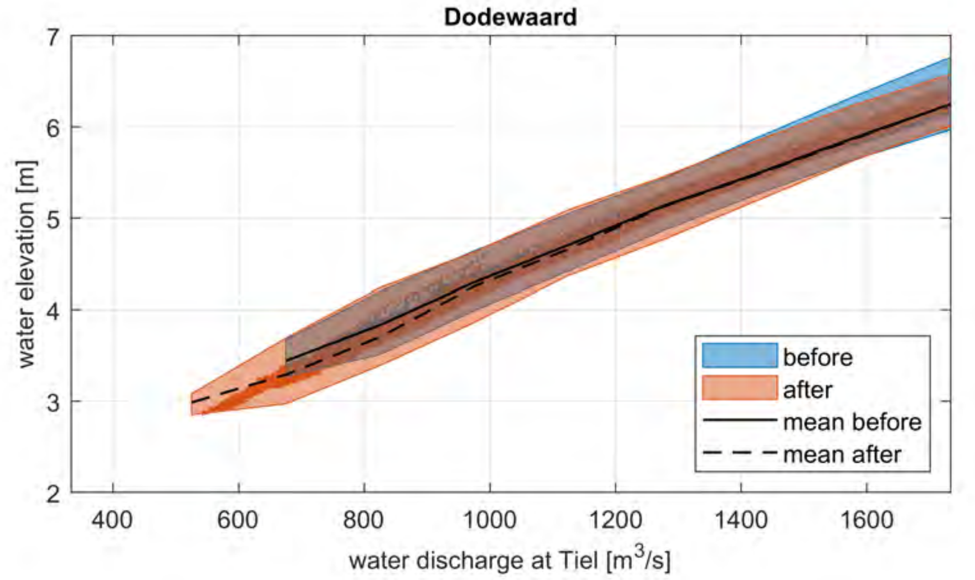

Figure 34 Water level at Dodewaard as a function of the water discharge at Tiel focusing on low-flow conditions.

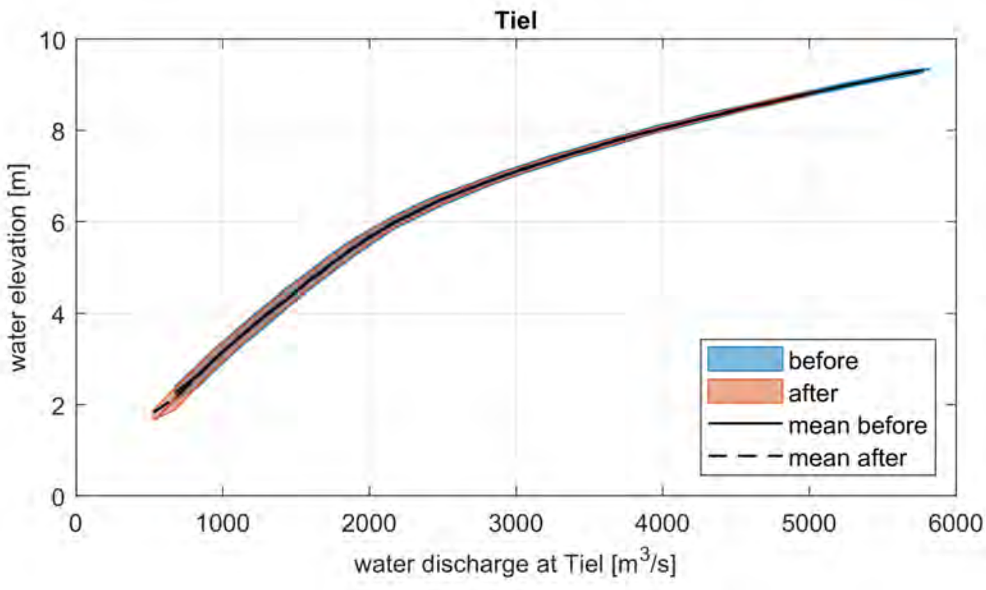

Figure 35 Water level at Tiel as a function of the water discharge at Tiel.

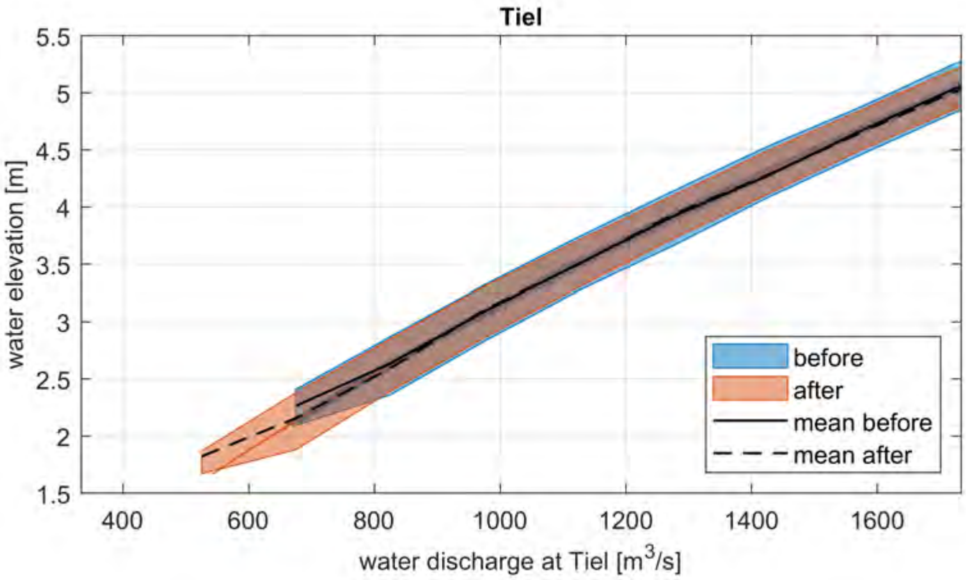

Figure 36 Water level at Tiel as a function of the water discharge at Tiel focusing on low-flow conditions.

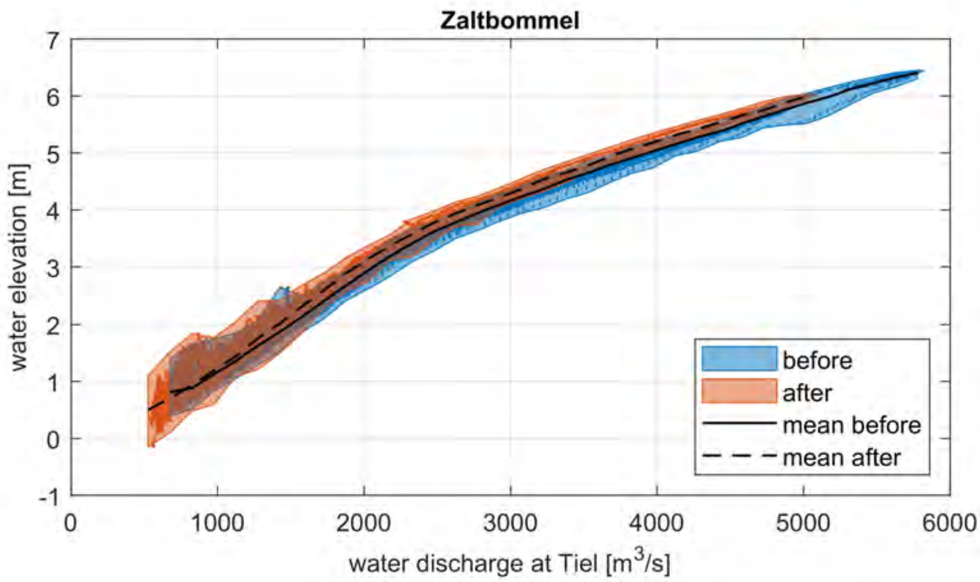

Figure 37 Water level at Zaltbommel as a function of the water discharge at Tiel.

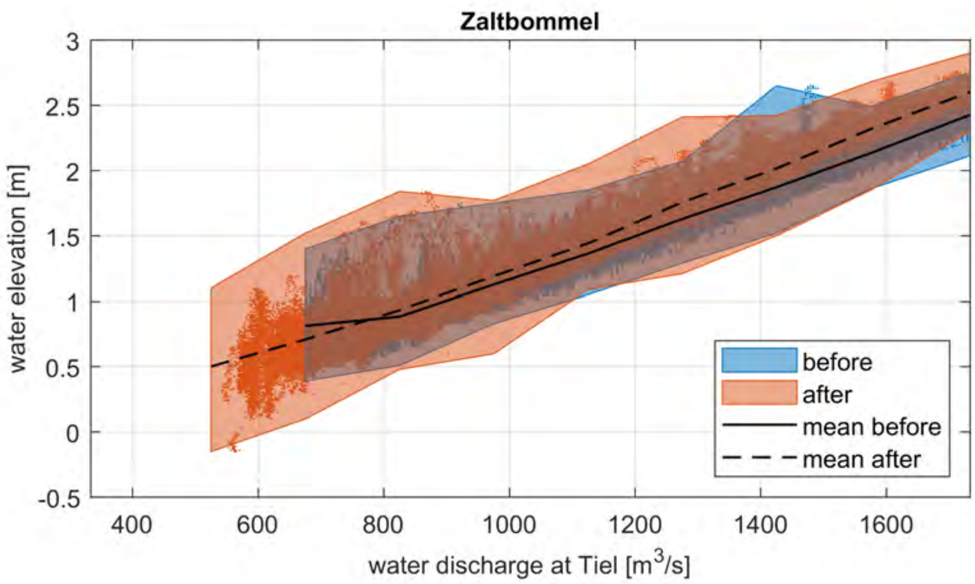

Figure 38 Water level at Zaltbommel as a function of the water discharge at Tiel focusing on low-flow conditions.

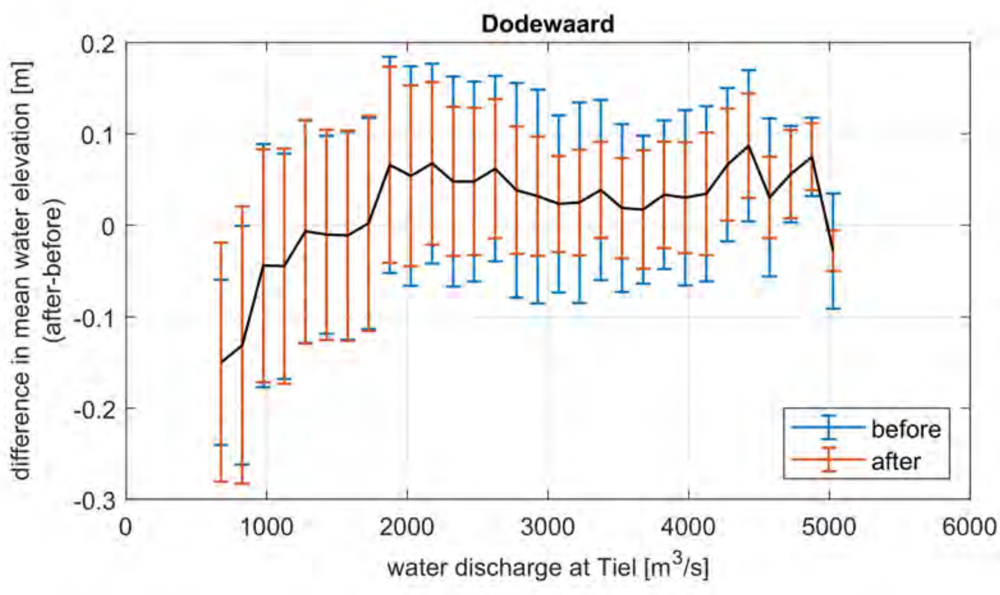

Figure 39 Difference in mean water level at Dodewaard between the conditions after the construction of the longitudinal training walls and before construction as a function of the water discharge at Tiel. The errorbars indicate the standard deviation of the measurements.

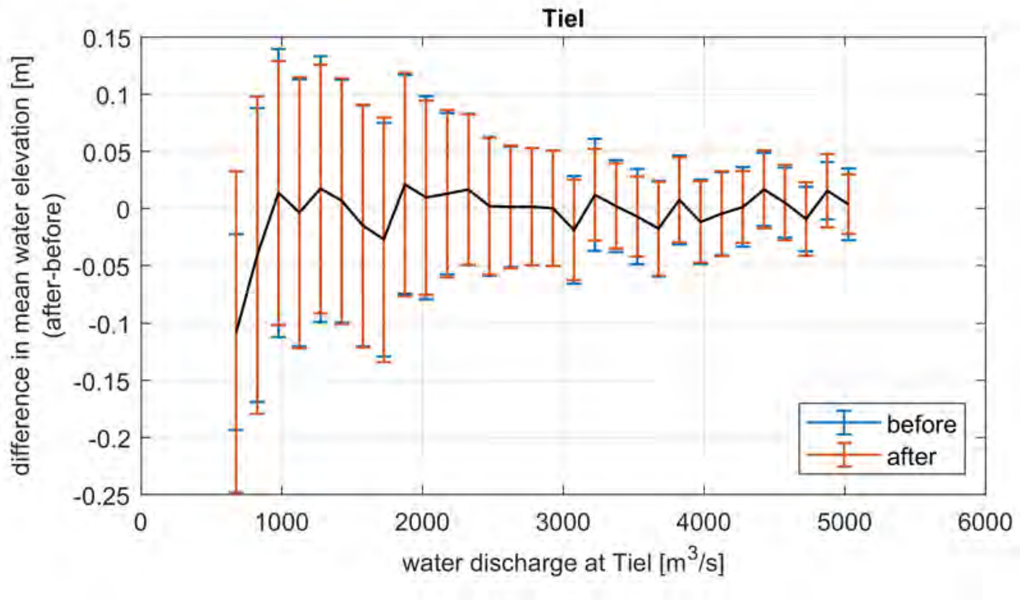

Figure 40 Difference in mean water level at Tiel between the conditions after the construction of the longitudinal training walls and before construction as a function of the water discharge at Tiel. The errorbars indicate the standard deviation of the measurements.

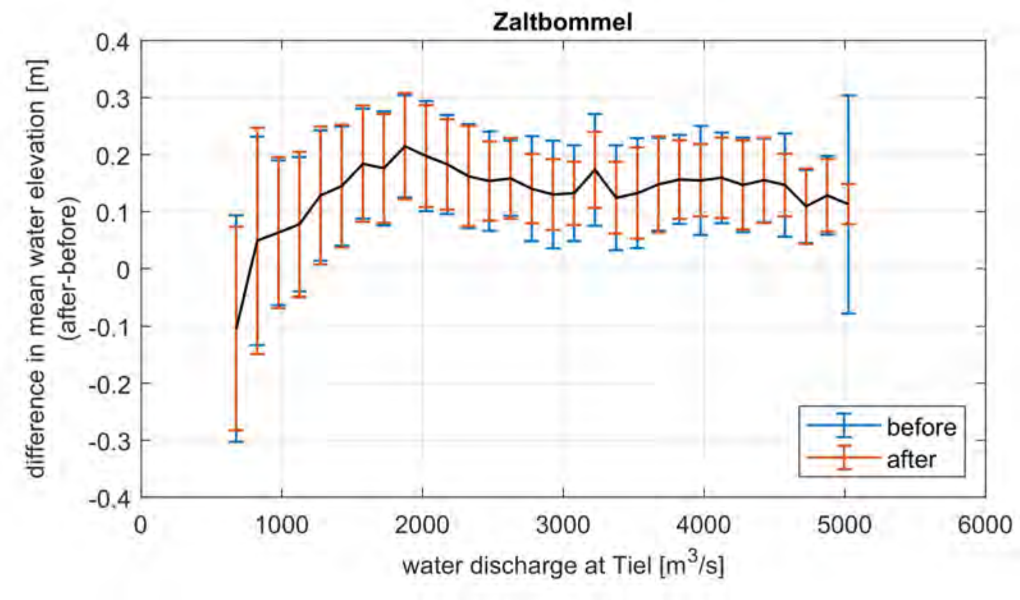

Figure 41 Difference in mean water level at Zaltbommel between the conditions after the construction of the longitudinal training walls and before construction as a function of the water discharge at Tiel. The errorbars indicate the standard deviation of the measurements.

The stage-discharge relation at Dodewaard before construction of the longitudinal training walls shows little difference with respect to the stage-discharge relation after construction. For a discharge below 1000 m^3/s, the water level may have lowered while it may have increased for higher discharges. Nevertheless, given the data scatter, these results are not conclusive. It is important to note that the number of data points differs between conditions before and after, and that the time series is not sufficiently long to filter particularities of single flood or drought events. The distance between stations is approximately 12 km, which is relatively short compared to the length scale of backwater effects induced by the longitudinal training walls (Appendix A). Thus, although morphodynamic changes may not be clearly discerned from changes in flow conditions, we would expect to observe a lowering of the water level for high discharged due to the construction of the longitudinal training walls if these are successful in their objective of reducing peak water levels (Section 3.2). However, due to the manner in which the discharge at Tiel is obtained, actually, we are comparing the water level at Tiel with the water level at Dodewaard. Even if, for a given discharge, the longitudinal training walls would substantially lower the water level at Dodewaard, this would not be visible if the stage-discharge relation of Tiel is not updated. It is recommended to update the stage-discharge relation at Tiel.

The stage-discharge relation of Zaltbommel shows an increase in water level for discharges above 800 m^3/s which is above one standard deviation from the mean (Figure 41). We do not expect changes in water level due to the construction of the longitudinal training walls. Moreover, this result is unexpected given the interventions that took place in the area in order to reduce high water levels (e.g., lowering of the groynes). The most reasonable explanation is that the increase in water level is an artefact due to the fact that the water level at Tiel is used as a reference, which is affected by the construction of the longitudinal training walls. Hence, the apparent increase in water level at Zaltbommel is most probably due to a decrease in water level at Tiel.

A closer inspection of the results highlights that one single high-flow event in January 2011 is responsible for a substantial lowering of the mean. This is the largest high-flow event of the entire time series and no similar one has occurred after the construction of the longitudinal training walls. Several similar events should be recorded in the time series for providing a conclusive answer. Last, one needs to consider the inaccuracies introduced by the fact that the water level at Zaltbommel is affected by tides.

4.5.2 Discharge reference at Lobith

To avoid the limitations of using the discharge at Tiel, we repeat the analysis, this time using the discharge at Lobith. The water discharge at Lobith is assumed to be more accurate, given that it is obtained using a relation that considers the overall bed degradation observed in the BovenRijn, hysteresis, and the operation of the weir at Driel, among other factors (Ogink and Stolker, 2004). On the other hand, when relating the water discharge at Lobith to water levels along the Waal, we are assuming that the water distribution at the Pannerdensche Kop has not changed due to interventions. Similarly, we assume that the operation of the weir at Driel has remained constant with time, as well as the time that it takes for the peak of a flood wave to travel from Lobith until the area of interest.

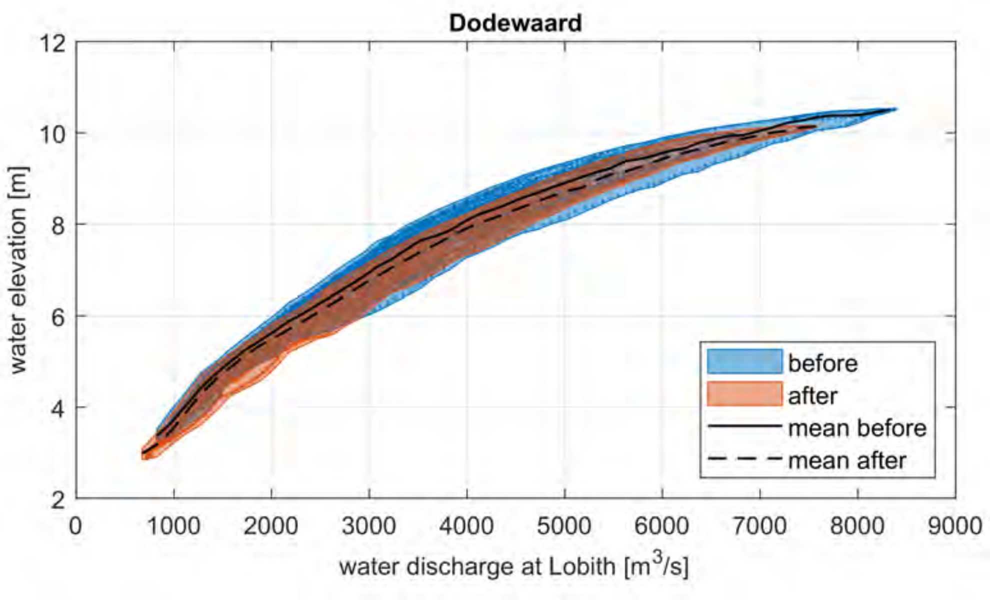

Figure 42 Water level at Dodewaard as a function of the water discharge at Lobith.

Figures 42-47 show the stage-discharge relations obtained using the water discharge at Lobith and Figures 48-50 present the changes in mean water elevation. The scatter in the data is larger than when using the discharge at Tiel for obtaining the stage-discharge relations. This stands to reasons given the fact that, as explained, the relation between the discharge at Lobith and the water level along the Waal depends on more factors than the relation with the discharge at Tiel. The mean water level at Dodewaard seems to substantially decrease after 2015. This contrasts with the previous results for Dodewaard using the discharge at Tiel, where it seemed that the water level increased. Alongside with the hypothesis that the construction of the longitudinal training walls has lowered the water level, it may be possible that Room for the River interventions have changed the water distribution at the Pannerdensch Kop. Such a signal would not be visible when using the discharge at Tiel as a reference. The change in water level occurs for both high and low discharges. This supports the fact that an important factor apart from the longitudinal training walls plays a role, as we expect that, in the short term, the longitudinal training walls lower the water level under high-flow conditions, while they increase it under low-flow conditions. The change in water elevation is between 0.1 m and 0.2 m, and the standard deviation is approximately 0.2 m. The data may support that the water level has lowered, but the change in water elevation is not enough to conclude anything specific.

A similar picture is observed in the stage-discharge relation of Tiel. The mean water elevation seems to be lower after construction of the longitudinal training walls. In this case, the effect is larger for high flows than for low flows, which supports the hypothesis of the longitudinal training walls playing a major role. Nevertheless, as for the relation at Dodewaard, no conclusive remarks can be made as regards to changes in bed elevation.

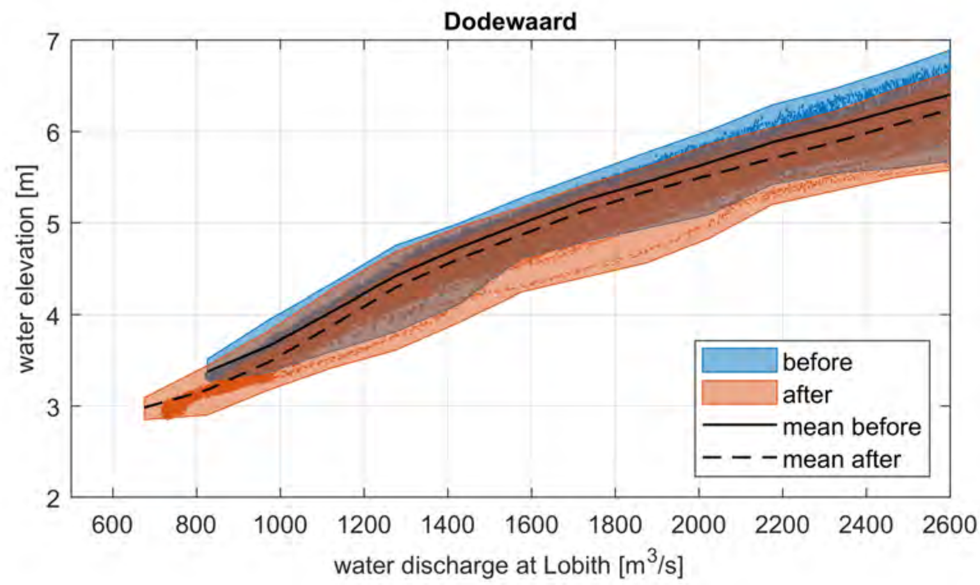

Figure 43 Water level at Dodewaard as a function of the water discharge at Lobith focusing on low-flow conditions.

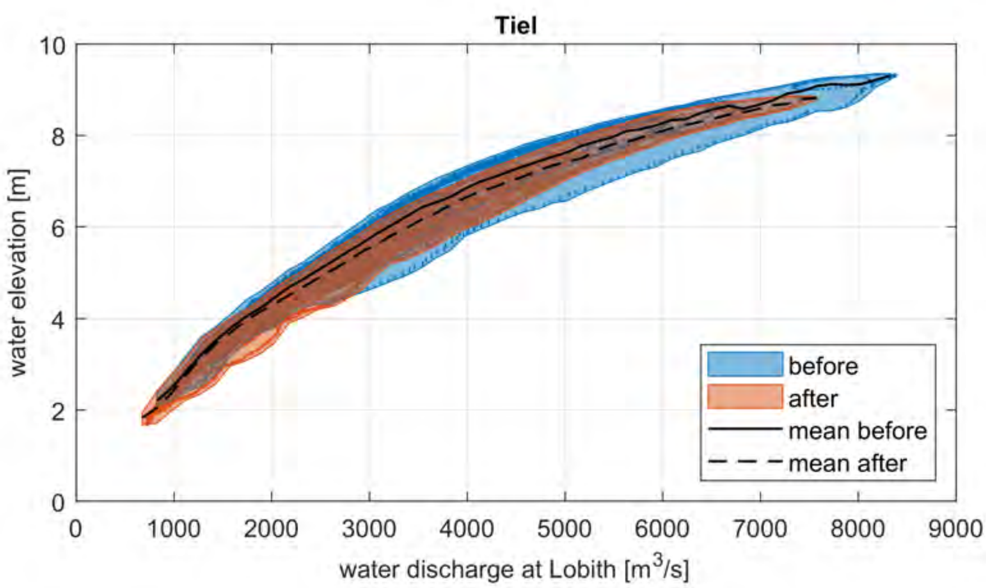

Figure 44 Water level at Tiel as a function of the water discharge at Lobith.

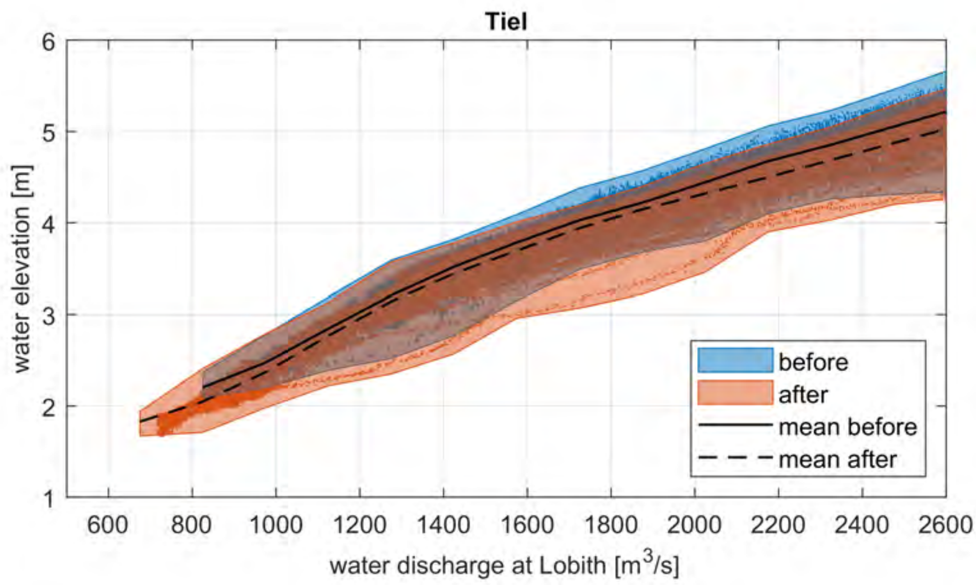

Figure 45 Water level at Tiel as a function of the water discharge at Lobith focusing on low-flow conditions.

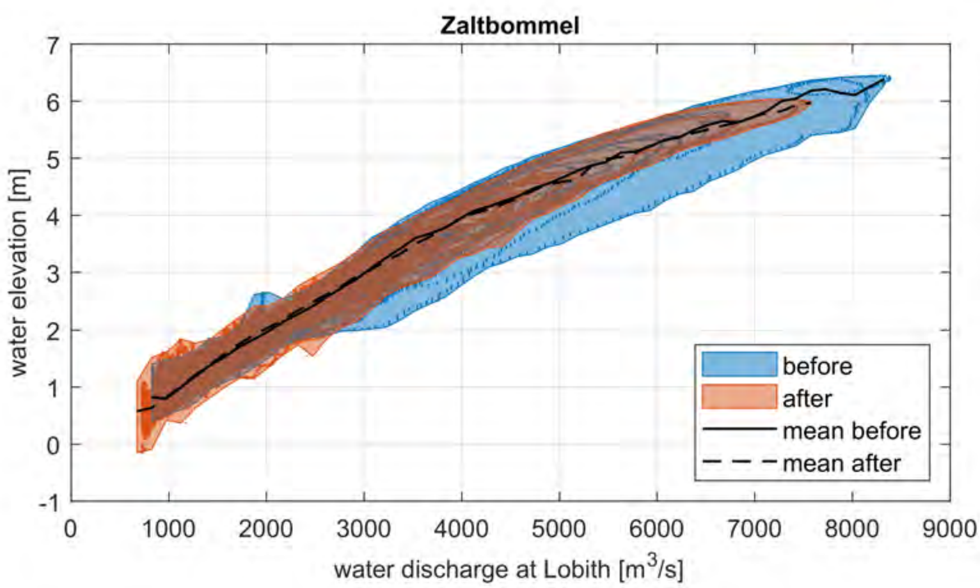

Figure 46 Water level at Zaltbommel as a function of the water discharge at Lobith.

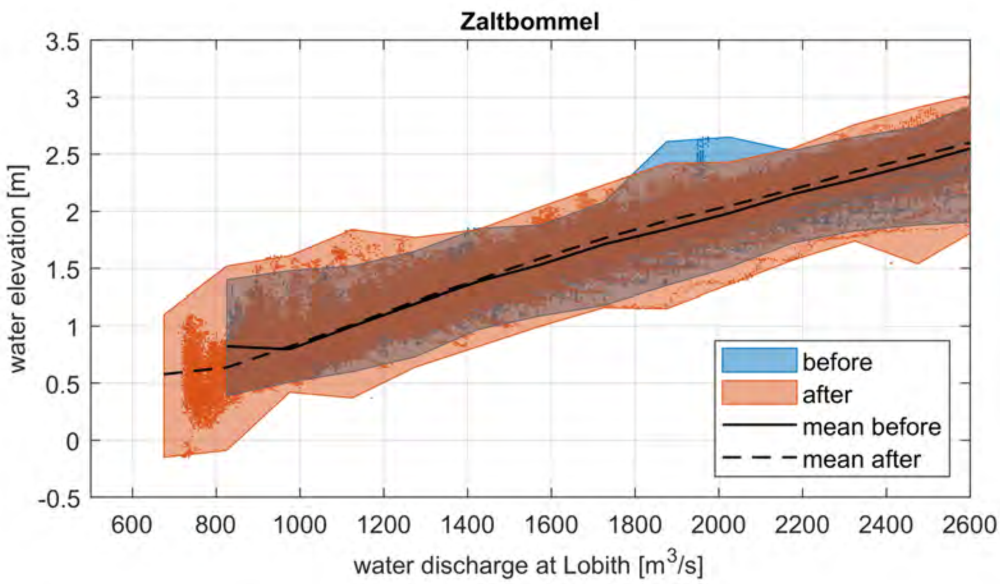

Figure 47 Water level at Zaltbommel as a function of the water discharge at Lobith focusing on low-flow conditions.

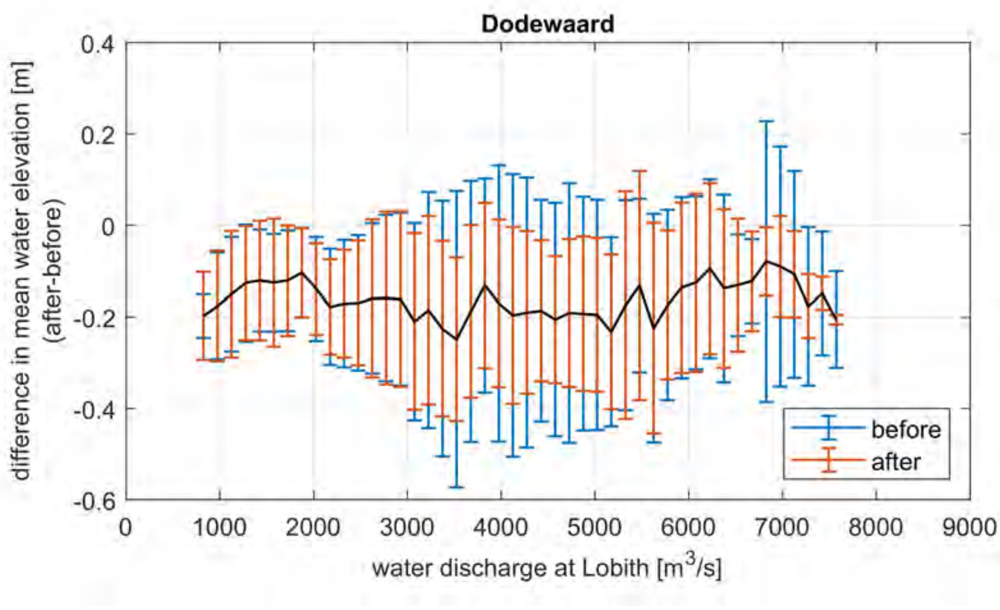

Figure 48 Difference in mean water level at Dodewaard between the conditions after the construction of the longitudinal training walls and before construction as a function of the water discharge at Lobith. The errorbars indicate the standard deviation of the measurements.

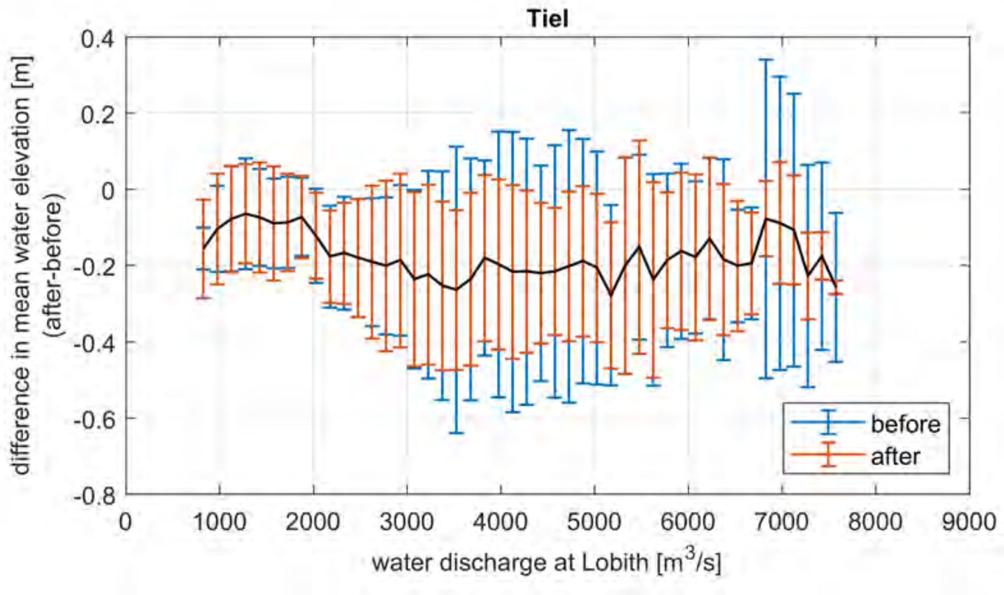

Figure 49 Difference in mean water level at Tiel between the conditions after the construction of the longitudinal training walls and before construction as a function of the water discharge at Lobith. The errorbars indicate the standard deviation of the measurements.

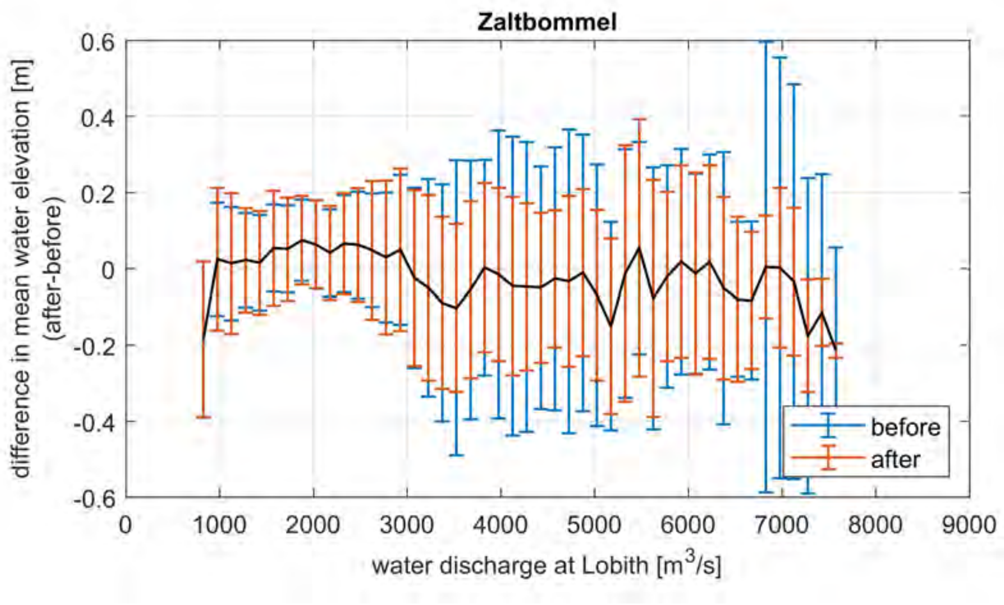

Figure 50 Difference in mean water level at Zaltbommel between the conditions after the construction of the longitudinal training walls and before construction as a function of the water discharge at Lobith. The errorbars indicate the standard deviation of the measurements.

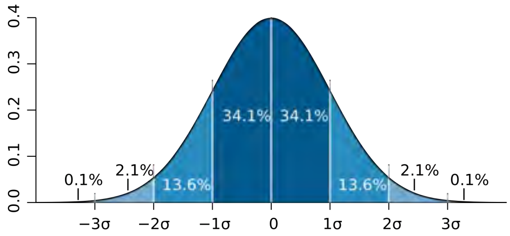

Figure 51 Normal distribution. The probability of obtaining a measurement between the mean and 1 standard deviation smaller (or larger) than the mean is 0.341. Figure from M. W. Toews CC BY 2.5.

The stage-discharge relation at Zaltbommel shows no significant change before and after construction of the longitudinal training walls. While this would be the expected behaviour if the only intervention would have been the construction of the longitudinal training walls, there have been other interventions with the intention of lowering the water level and we would expect to see such a signal in the data. Apart from the limitations discussed above as regards to using the discharge at Lobith, we note that the high-flow event of 2011 substantially lowers the mean before intervention. The uniqueness of the event in the time series prevents a definite conclusion about changes in water level. Using the median rather than the mean may overcome the large effect of single events. It is recommended to study this possibility in future analysis.

Sieben (2020) reports measured water levels before and after the construction of the longitudinal training walls. These data may indicate a lowering of the water level under high-flow conditions, but the data are too scarce to be statistically significant. In the figures we present the cloud scatter and the standard deviation, which is approximately 10 cm based on half a million points. That means that, assuming a normal distribution to simplify the analysis, the probability of obtaining one measurement between the mean and 10 cm below (or above) the mean is approximately 34% (Figure 51), which already shows that one cannot discard the null hypothesis that the longitudinal training walls have no effect on the water level.

Moreover the discharge measurements of the data reported by Sieben (2020) cannot be said to be uncorrelated. For the same flood wave, several measurements exist. Although several measurements seem to indicate a lowering of the water level, they refer to the same event. The same occurs in the long time series measurements. But in the latter case, the amount of data is that large that the chances that two data points selected randomly are correlated is very small.

4.5.3 ADCP discharge measurements

ADCP discharge measurements at Tiel, the upstream end of the Waal (river kilometre 868) and Lobith (river kilometre 863.9) conducted between 2009 and 2020 have been recently delivered and analysed by De Jong *et al.* (2021). These complement the analysis of the long time series and allow overcoming the limitation of the discharge at Tiel being derived from the water level at Tiel in the long time series publicly available. The downside is that there are less data available. For Tiel, upstream in the Waal, and at Lobith there are 274, 512, and 129 measurements, respectively.

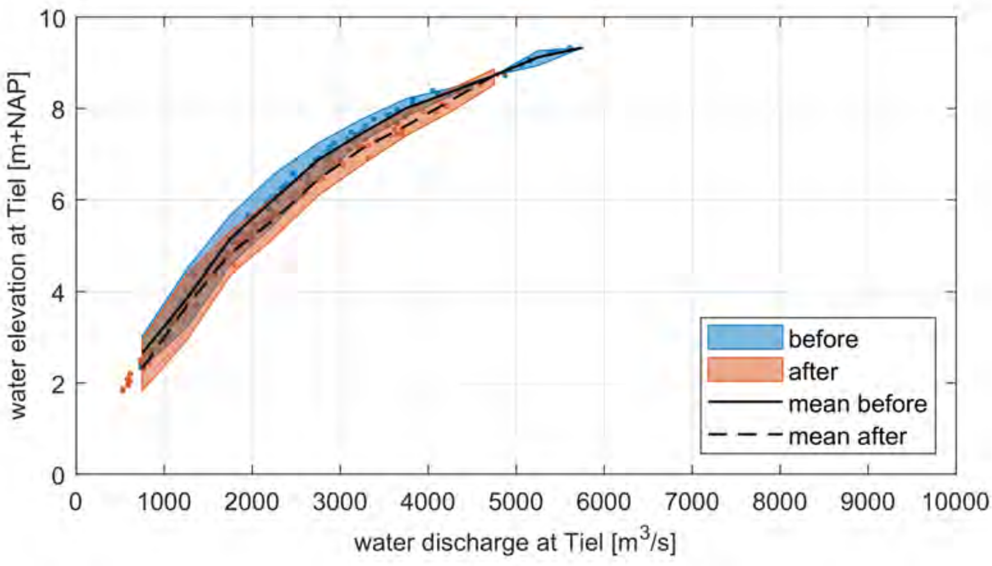

Figure 52 Measured water level at Tiel as a function of the measured water discharge at Tiel.

Figure 52 shows the stage-discharge relation at Tiel and Figure 53 the difference between the situation before and after construction of the longitudinal training walls. The water level at Tiel is consistently lower after intervention. The decrease varies around 30 cm for the different discharges. The decrease seems to be larger for the discharges above 2000 m^3/s than for the low discharges around 1000 m^3/s, as it is expected to happen due to the construction of the longitudinal training walls. Nevertheless, contrary to the expected behaviour, for the very low discharges below 1000 m^3/s there is more lowering after intervention than for the low discharges. Also, for the very large discharges around 4500 m^3/s, for which one would expect the longitudinal training walls to lower the water level, this lowering appears to tend to 0.

The stage-discharge relation at the upstream end of the Waal shows a consistent lowering of the water level of approximately 30 cm for all discharges (Figures 54 and 55). This cannot be ascribed to the construction of the longitudinal training walls as they are more than 50 km downstream. Causes for the lowering are the ongoing long-term degradational trend as well as possible changes in discharge distribution at the Pannerdensche Kop. Nevertheless, the expected trend at the bifurcation of Pannerden is to actually increase the water level in the Waal River. This stage-discharge relation highlights the limitations of the analysis. While we observe a lowering of the water level at Tiel after the construction of the longitudinal training walls, this is not the only cause of changes. The observation of a similar change in the same period of time at the upstream end of the Waal does not allow to firmly conclude that the observed changes are due to the construction of the longitudinal training walls.

Figures 56 and 57 present the stage-discharge relation at Lobith. Data scarcity prevents obtaining a continuous-enough relation. Nevertheless, the data suggest a lowering of the water level with time. This relation is not affected by a change in discharge partitioning, as it is upstream of the bifurcation. Two main remaining cause explaining the behaviour: the ongoing long-term degradation (Sloff, 2019) and the impact of Room for the River interventions.

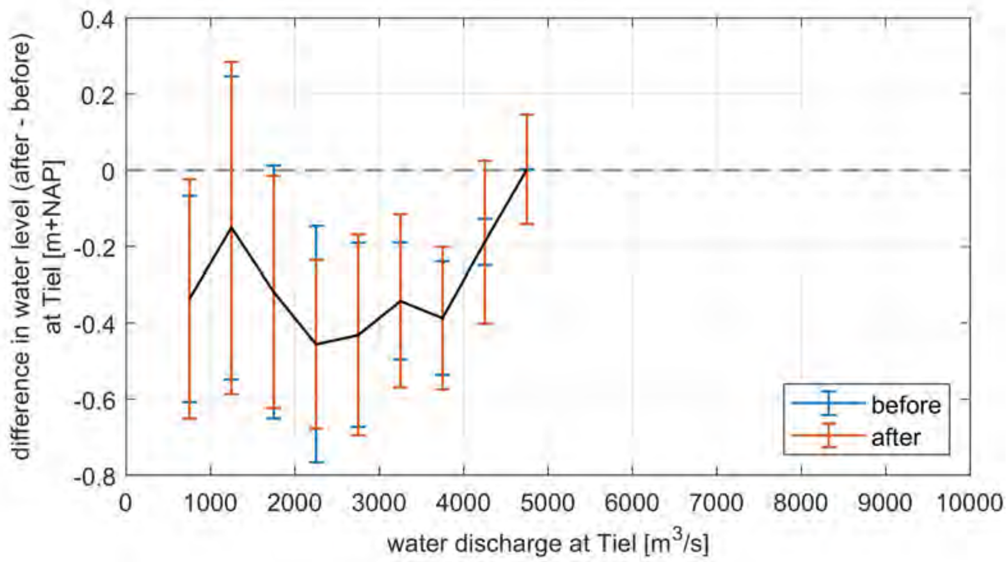

Figure 53 Difference in measured water level at Tiel before and after intervention as a function of the measured water discharge at Tiel.

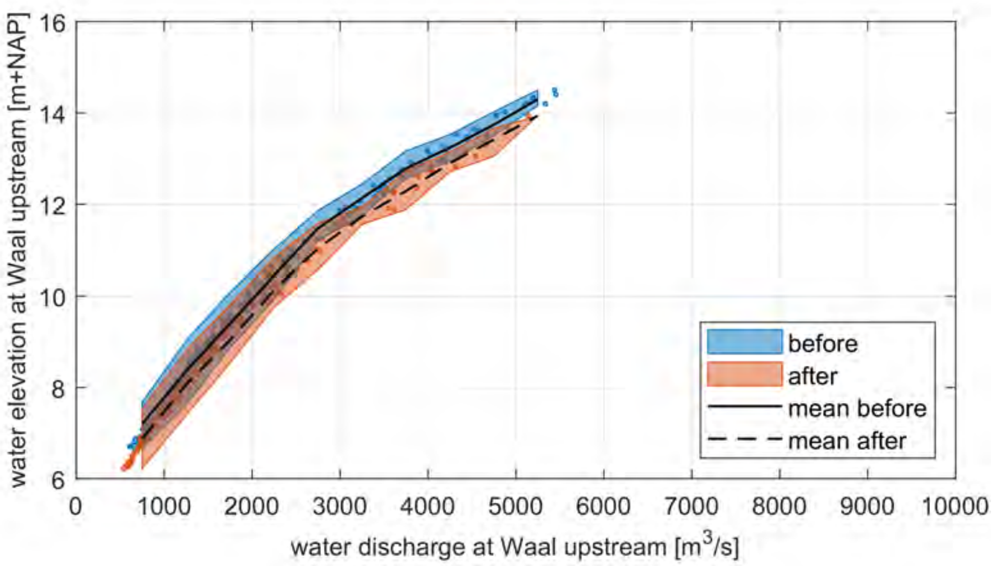

Figure 54 Measured water level at the upstream end of the Waal as a function of the measured water discharge at the upstream end of the Waal.

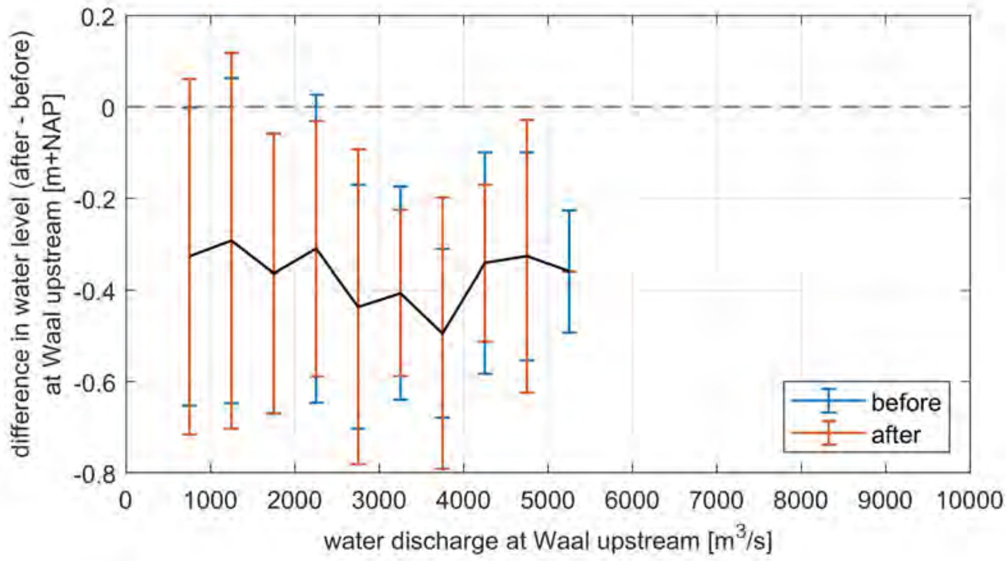

Figure 55 Difference in measured water level at the upstream end of the Waal before and after intervention as a function of the measured water discharge at the upstream end of the Waal.

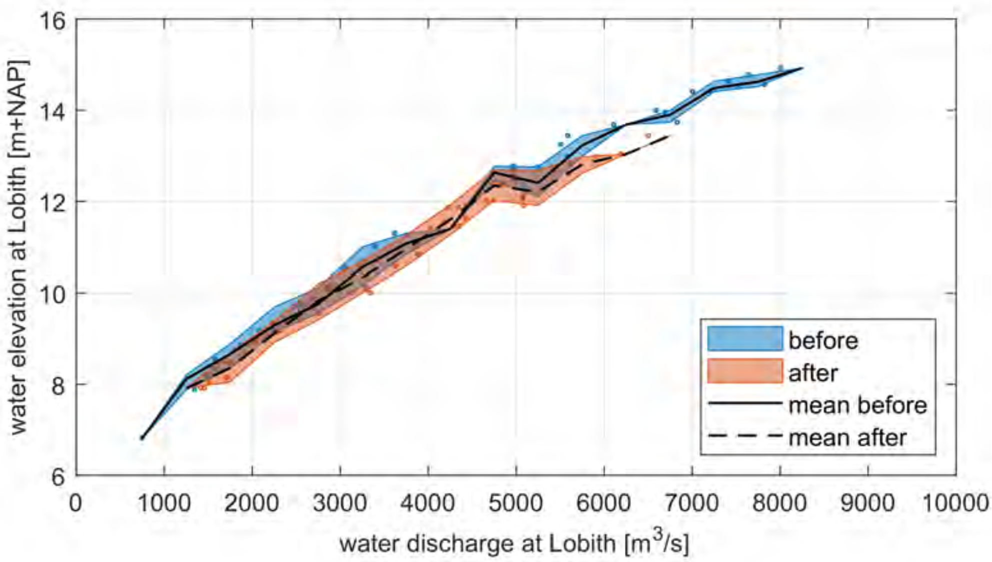

Figure 56 Measured water level at Lobith as a function of the measured water discharge at Lobith.

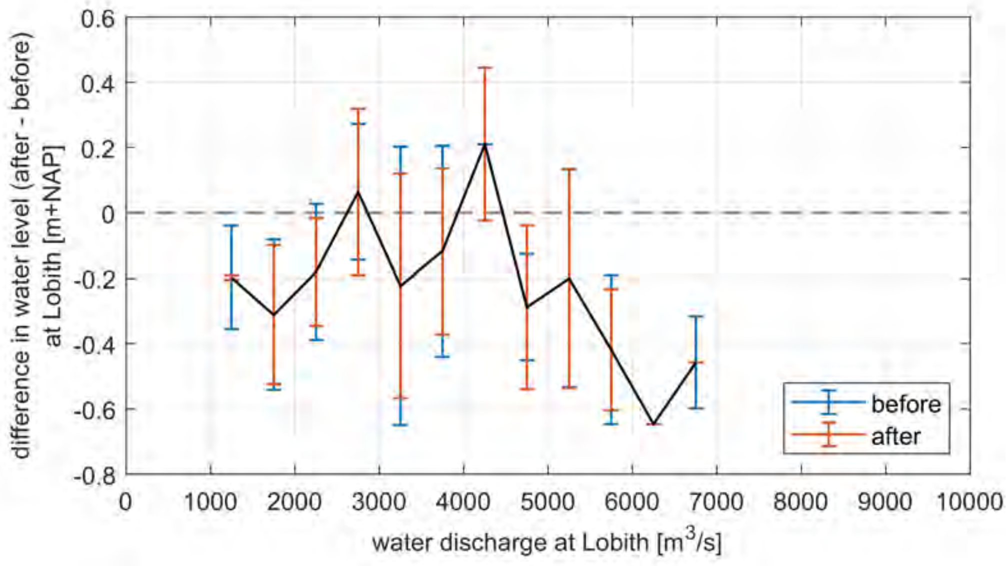

Figure 57 Difference in measured water level at Lobith before and after intervention as a function of the measured water discharge at Lobith.

The water level at Zaltbommel is plotted against the discharge at Tiel (Figure 58) and the water level at Tiel (Figure 59). The difference in water level is shown in Figure 60. For a discharge at Tiel above approximately 1500 m^3/s, a lowering of the water level at Zaltbommel is observed. This supports the idea that the apparent increase in water level when using the long time series (Figure 37) is due to a change in water level at Tiel. The comparison between water levels shows that, for the same water level at Zaltbommel, the water level at Tiel is higher before than after intervention, further supporting the above reasoning.

Finally, it is remarkable that none of the results clearly indicate a break in the trend of changes in water level for a particular discharge at which the longitudinal training walls are overtopped. Given the variability of the data, the trend break can be hidden by it.

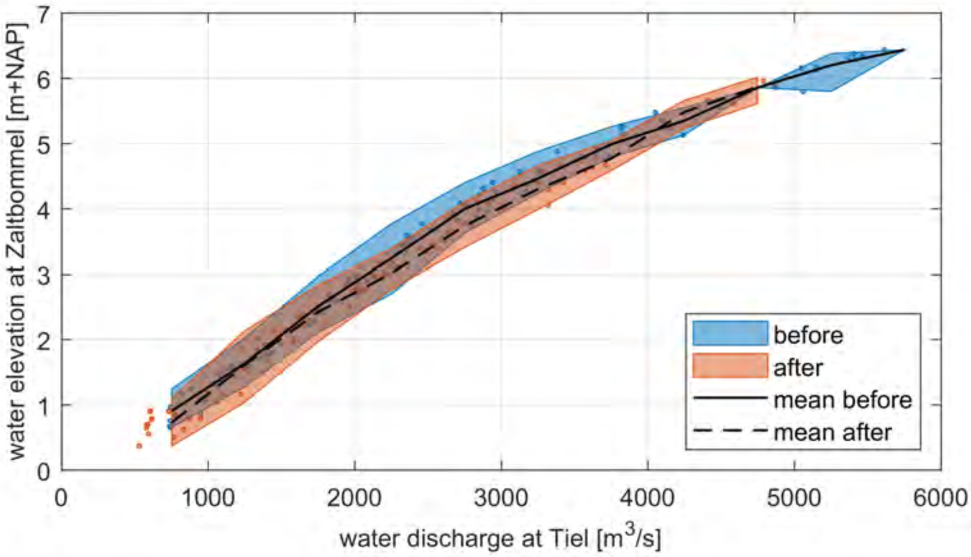

Figure 58 Measured water level at Zaltbommel as a function of the measured water discharge at Tiel.

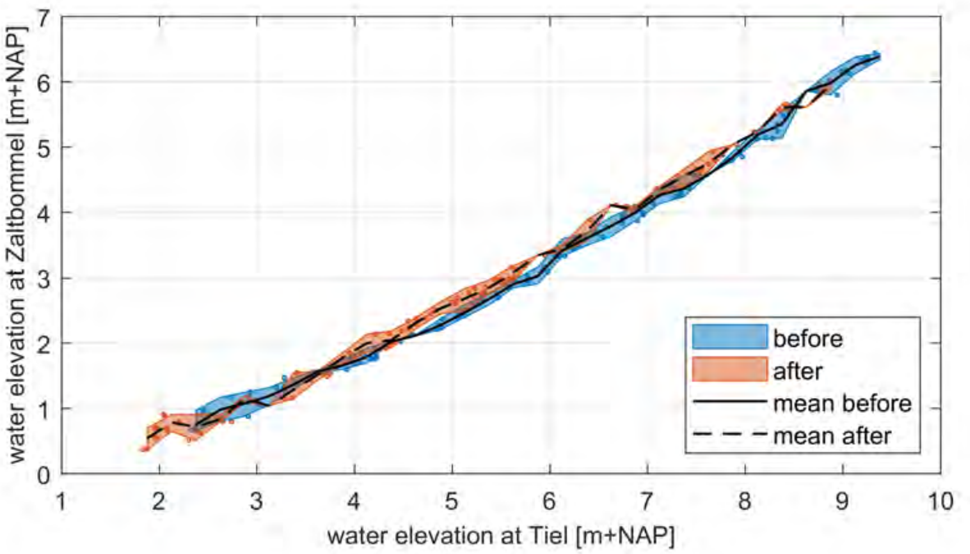

Figure 59 Measured water level at Zaltbommel as a function of the measured water level at Tiel.

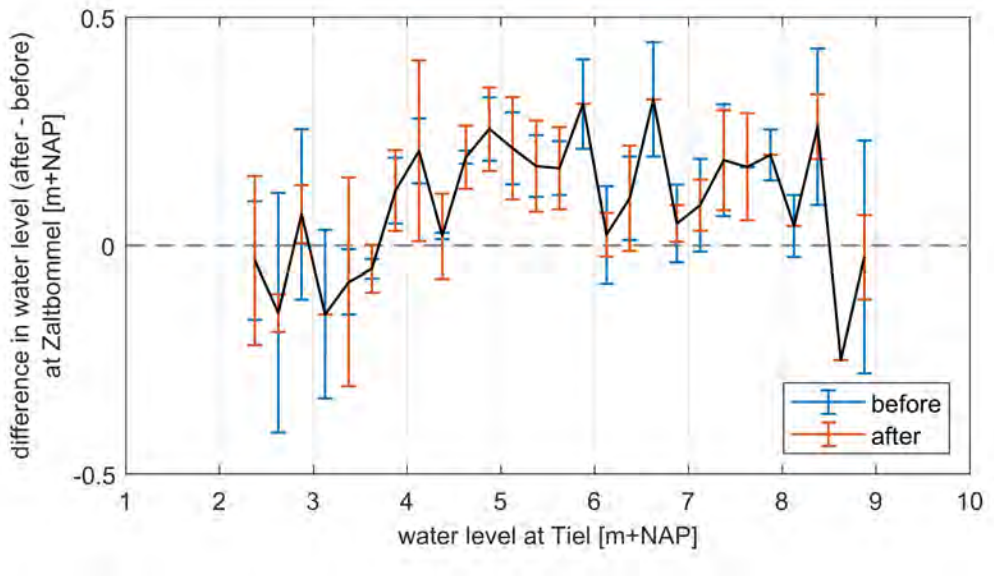

Figure 60 Difference in measured water level at Zaltbommel before and after intervention as a function of the measured water level at Tiel.

4.6 Sediment transport at entrance sill

De Ruijsscher *et al.* (2020c) (also presented in De Ruijsscher *et al.* (2020b)) measured the flow pattern at the entrance of the most downstream longitudinal training wall (Ophemert). Flow profile velocities were measured using acoustic Doppler current profiler (ADCP) attached to a vessel. Suspended load was computed from backscatter. Water samples were obtained once under exceptionally low flow conditions and along the main channel.

The flow pattern strongly varies with discharge. Under low flow conditions, in which the water level is below the crest level, there is an upstream horizontal secondary circulation cell and downstream there is a flow separation zone. When the water level exceeds the crest level, the strength of the secondary flow cell decreases, and the flow separation zone disappears.

The complex flow pattern hinders derivation of strong conclusions about sediment transport patterns. Moreover, limited data on suspended load and lack of bed load data prevents drawing solid conclusions on the type of sediment transport mode. Nevertheless, De Ruijsscher *et al.* (2020c) hypothesizes that coarse sand is transported as bed load in the main channel and not transported in the side channel. Although it is unclear whether bed load passes the sill, De Ruijsscher *et al.* (2020b) concludes that the sill appears to have a significant contribution to the morphodynamics of the auxiliary channel.

Bed level changes in the auxiliary channels cannot be directly related to the bed load entering the auxiliary channels as the dynamics of these have been dominated by bank erosion (Section 4.3). Moreover, the elevation of the sills have changed several times since construction and the time passed is small compared to the timescale of morphodynamic changes. Given these limitations, no conclusions are derived regarding the amount of sediment over the entrance sills. Gaining understanding of the detailed flow structures at the entrance is essential for improving our prediction capabilities. To this end, we recommend to monitor the three-dimensional flow velocity at the main-channel side of the sill using ADCP.

4.7 Dredging

Rijkswaterstaat has provided data regarding dredging in the Waal River. The data-set consist of 1 199 370 dredging-instances since March 2005 until January 2019 noting, among other things, the coordinates and amounts dredged. This data-set has been processed for studying whether there has been a change in dredging amounts since the construction of the longitudinal training walls.

The monthly dredged volume shows large variability. It shows an increasing trend until 2007. For less than a year there is no dredging. It peaks in 2008 and gradually decreases decreases until 2014, when it remains reasonably constant up to the present (Figure 61). There are large differences in dredging volume depending on the river kilometre (Figure 62). In particular, the area around Nijmegen concentrates the largest amount of dredged sediment followed by the downstream part of the Waal.

Focusing on the area of the longitudinal training walls, the same decreasing dredging trend with time is observed (Figure 63). In the 3 years after construction for which we have data (2016-2018) less sediment is dredged than in the 3 years previous to intervention (2011-2013). Nevertheless, this is the same trend as observed in general prior to intervention since 2008 and in general in the entire Waal River.

Auxiliary channels are presumably more dynamic than secondary channels (*nevengeulen*) given that they are closer to the summer bed and discharge a larger proportion of the total water. This may cause the maintenance of auxiliary channels to be larger than that of secondary channels. Nevertheless, the currently available data does not support nor reject the above hypothesis, which remains speculative.

We conclude that the analysis of the dredging data does not indicate that there has been a substantial change in dredging amount due to the construction of the longitudinal training walls. With the observed dredging volumes it is not possible to extract the impacts of the longitudinal training walls. Dredging volumes are not directly connected with discharge or occurrence of floods. Moreover, the effects of several interventions are combined. For instance, a dredging effort came from the opening of the Passewaaij side channel and at the same time the impact of groyne lowering affect the domain of interest.

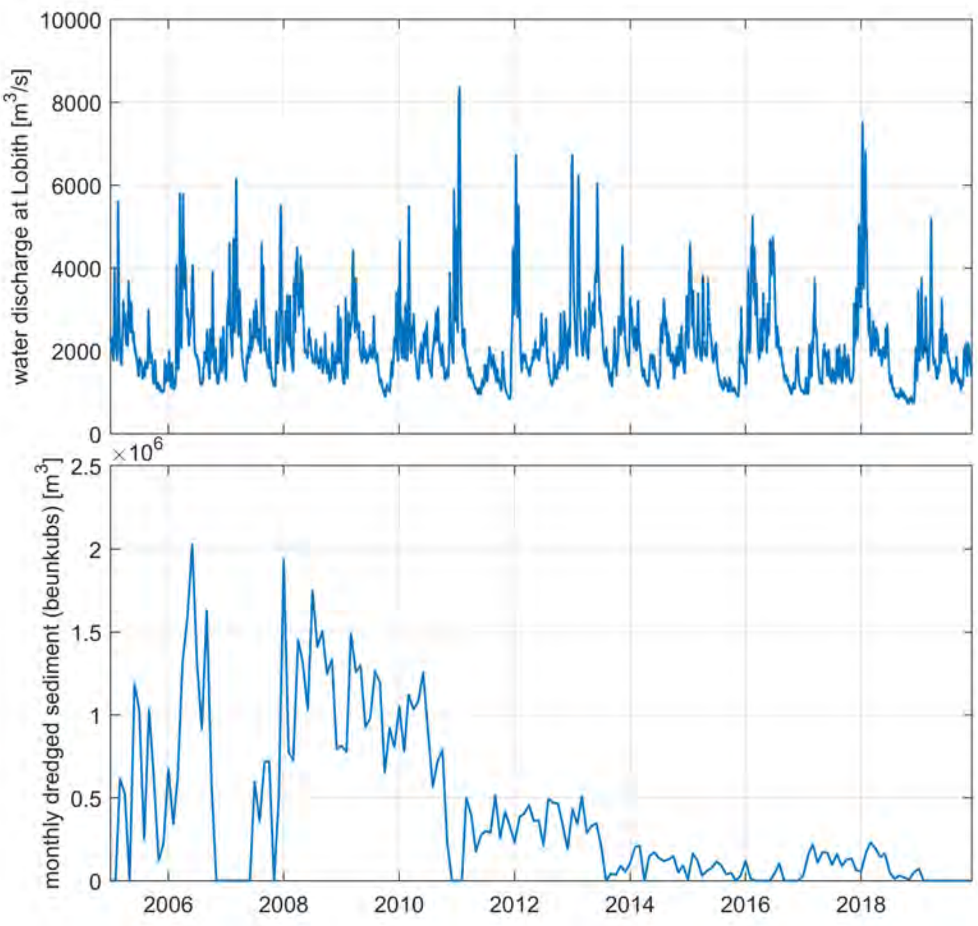

Figure 61 Monthly dredged sediment along the Waal River.

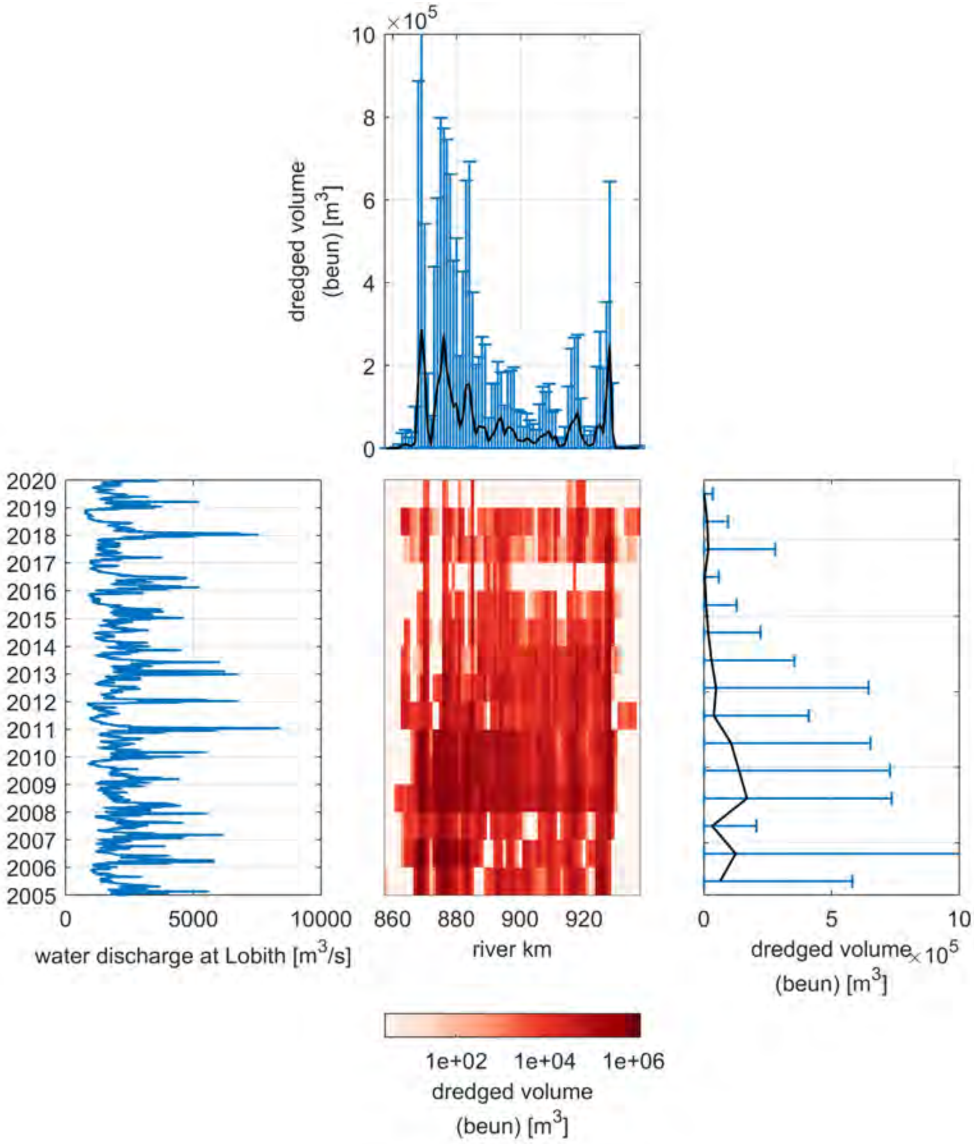

Figure 62 Yearly and per-kilometre dredged sediment along the Waal River. Bars indicate maximum and minimum value within a bin. Black line indicates the mean.

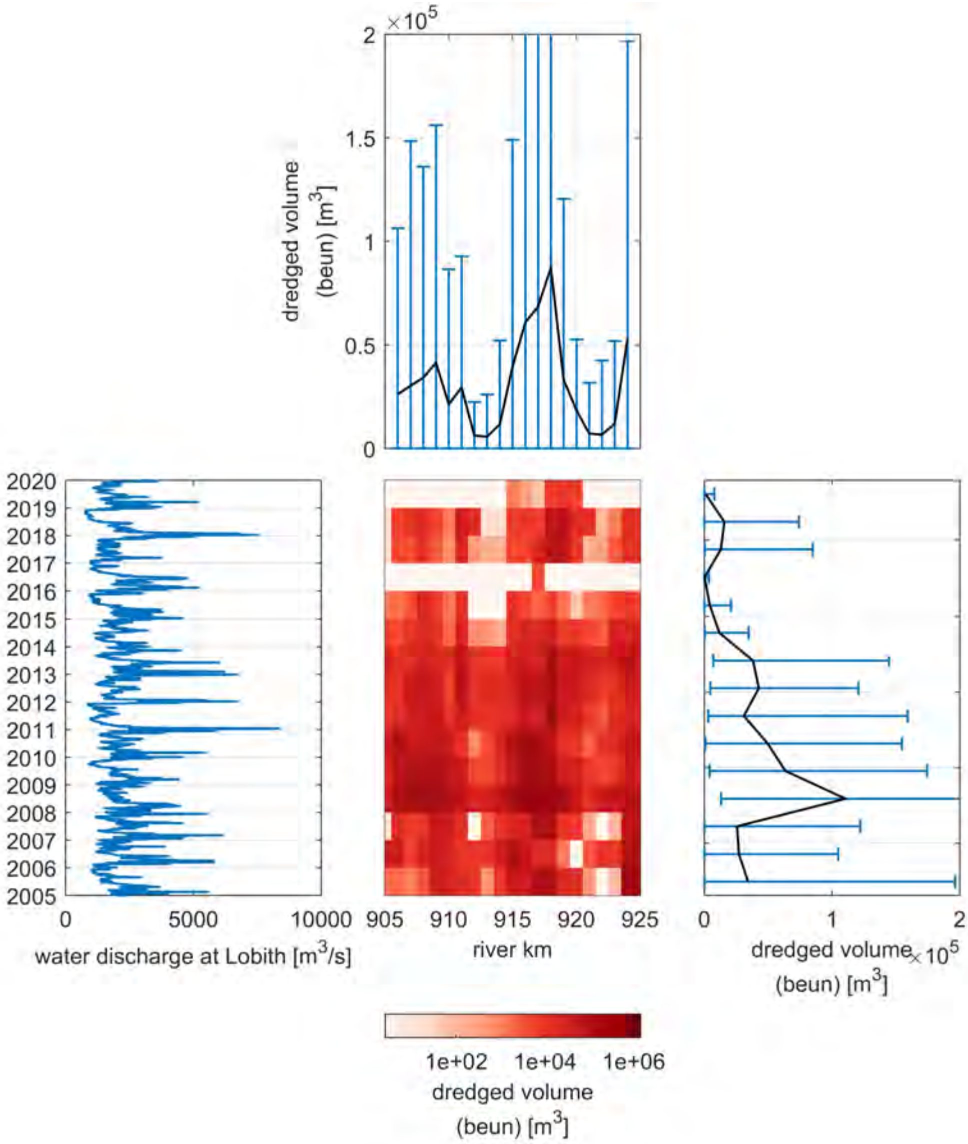

Figure 63 Yearly and per-kilometre dredged sediment along the longitudinal training walls. Bars indicate maximum and minimum value within a bin. Black line indicates the mean.

4.8 Vegetation development

For studying the vegetation development the satellite images available in Google Earth® are employed. Figures 64-67 show the development between 2016 and 2020 at the upstream end of the longitudinal training wall at Wamel. The image of 2017 is of low quality and it is not shown.

Figure 64 Satellite image of the upstream end of the longitudinal training wall at Wamel in 2016.

Figure 65 Satellite image of the upstream end of the longitudinal training wall at Wamel in 2018. Red circles indicate some of the vegetation growing.

Figure 66 Satellite image of the upstream end of the longitudinal training wall at Wamel in 2019. Red circles indicate some of the vegetation growing.

Figure 67 Satellite image of the upstream end of the longitudinal training wall at Wamel in 2020.

There is no vegetation on the longitudinal training walls in 2016 right after construction. In the summer of 2018, pioneering vegetation is visible. This has grown in 2019 and is not visible in 2020. The image in 2020 was taken at the end of March after a large flood event that lasted from the beginning of February until the end of March with two peaks of 6150 m^3/s and 5750 m^3/s at Lobith (Figure 68). This event most probably has been responsible for removing the vegetation that grew from 2018. A smaller flood event occurred in March 2019 that lasted for approximately two weeks with a peak discharge of 5200 m^3/s. This event appears to have been not strong enough to remove the existing vegetation. In January 2018 there was a larger flood event than the one in 2020 with a peak discharge of 7550 m^3/s. Most probably this event also removed all vegetation, but the low-quality image from 2017 does not allow to verify this point. It is important to also consider that the image in 2020 is at the beginning of spring whereas the other ones are in summer, when vegetation is usually more developed.

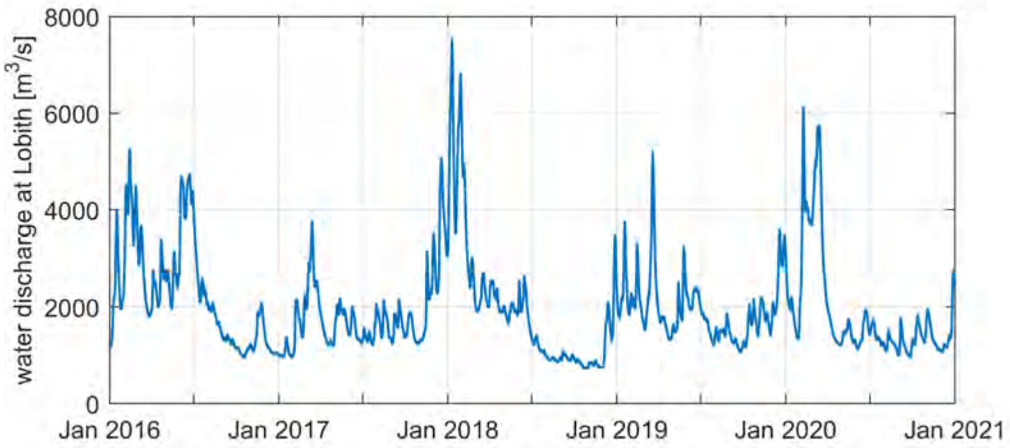

Figure 68 Hydrograph at Lobith.

The pattern of growth and removal of vegetation is observed at all locations on the longitudinal training walls. Appendix B shows the middle part of the longitudinal training wall at Wamel as an example. Moreover, the same pattern is also observed on the groynes (Figures 69-72). In this case, in 2016 there was already a large amount of vegetation that was partially removed by the flood in 2018. The removal may have been complete, as happened with the 2020 flood event, but it may have had time to develop until summer 2018 when the picture was taken.

The groynes present a higher vegetation density than the longitudinal training walls. A possible reason is that, from land, seeds can be more easily transported to the groynes than to the longitudinal training walls, where it may only be deposited if arriving floating in the water or transported by wind or animals. Another reasonable explanation is the availability of soil suitable for plants to grow. Groynes already have soil available while the open structure of the longitudinal training walls and the limited time that has passed since construction presumably limit the available soil.

Less vegetation is a benefit for *Rijkswaterstaat* in terms of a reduction of the maintenance costs. Moreover, the vegetation on the longitudinal training walls is parallel to the flow direction and hence exerts less resistance than the vegetation of the groynes, which is perpendicular to the flow direction. On the other hand, accessing and removing vegetation from the longitudinal training wall is more costly than from the groynes, as the longitudinal training walls are not accessible by foot.

Figure 69 Satellite image of the groyne at the upstream end of the longitudinal training wall at Wamel in 2016.

Figure 70 Satellite image of the groyne at the upstream end of the longitudinal training wall at Wamel in 2018.

Figure 71 Satellite image of the groyne at the upstream end of the longitudinal training wall at Wamel in 2019.

Figure 72 Satellite image of the groyne at the upstream end of the longitudinal training wall at Wamel in 2020.

4.9 Sediment transport capacity

(De Jong *et al.*, 2021) analysed ADCP measurements for studying the effect of the construction of the longitudinal training walls regarding changes in velocity and their implications on sediment transport. Measurements at 4 different discharges were available both before and after intervention.

The analysis by De Jong *et al.* (2021) shows that for a discharge at Lobith equal to approximately 922 m^3/s, an increase in flow velocity on the order of 10% is observed. An increase in flow velocity was expected as flow is concentrated in the main channel thanks to the longitudinal training walls. For a discharge at Lobith equal to 3436 m^3/s, 4170 m^3/s, and 5087 m^3/s, a decrease in flow velocity was in general observed. The change in flow velocity between the situation before and after intervention decreases as the discharge increases. For a discharge at Lobith equal to 3436 m^3/s, 4170 m^3/s, and 5087 m^3/s the decrease is approximately 15%, 5% and 2%, respectively.

The overall consequence of the velocity changes for sediment transport is a reduction of the capacity by approximately 40% (De Jong *et al.*, 2021). This is in line with the measured sedimentation and numerical results.

The deposition of sand on floodplains is ecologically valuable for stream valley flora. The longitudinal training walls were not expected to cause any significant changes in sand deposition, although some ecologists had expressed concerns that the training walls would block sand fluxes to the floodplains (Kurstjens, 2019). Field observations showed that sand has also been deposited on floodplains along the training walls, even in considerable quantities downstream of the pilot (Reeze *et al.*, 2016; Van Winden *et al.*, 2018).

4.10 Discharge partitioning

De Jong *et al.* (2021) analysed data compiled by Sieben (2020) about discharge in the auxiliary and main channels. Only measurements at the same river kilometre and day have been considered in order to compute the fraction of discharge along the auxiliary channel and the effect of the change in inlet opening. Figures 73 and 74 present the fraction of the discharge along the auxiliary channel as a function of the river kilometre and the total discharge, respectively. De Jong *et al.* (2021) give more detailed figures.

The amount of discharge along the auxiliary channel varies between less than 5% and more than 25% of the total discharge. For a larger total discharge, a larger fraction is transported along the auxiliary channel. This is the expected behaviour: for low discharges flow is concentrated in the main channel and as the discharge increases a larger proportion is transported along the auxiliary channel. De Jong *et al.* (2021) concluded that the effect of varying the inlets was not visible in the data.

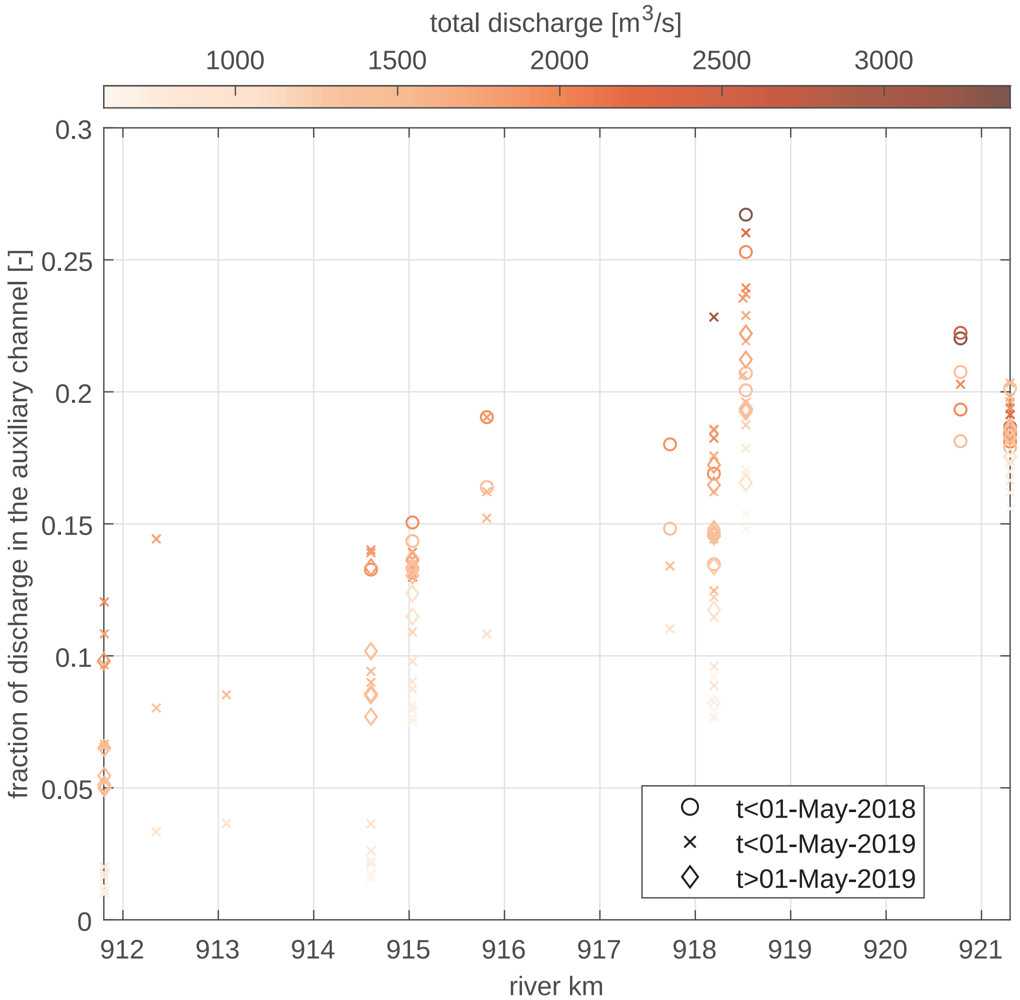

Figure 73 Fraction of discharge along the auxiliary channel for a varying river kilometre.

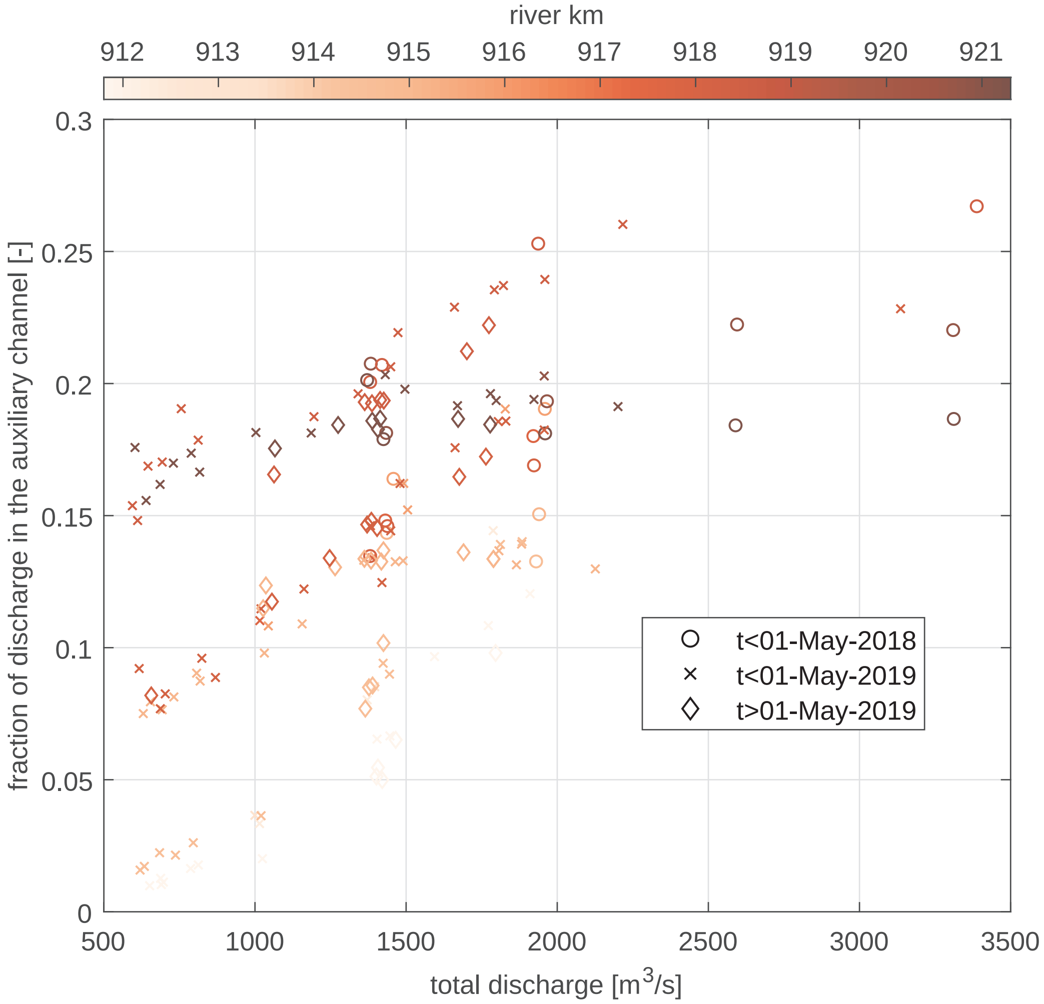

Figure 74 Fraction of discharge along the auxiliary channel for a varying total discharge.

4.11 Discussion on the data analysis

Different methods have been used in analysing the changes in bed level. In particular, De Jong *et al.* (2021) use the PMAP analysis and Van Denderen *et al.* (2020) use the wavelet analysis. The most relevant outcome is that both methods show the same morphodynamic trend. The PMAP method is more straightforward than the wavelet analysis as it requires less choices. On the other hand, the wavelet analysis allows for proper filtering of spatio-temporal scales. In the PMAP analysis an implicit filtering is done when selecting the polygons in which the analysis is conducted. Ideally, both analysis would always be conducted to identify shortcomings in either analysis.

Several processes play a role in the morphodynamic behaviour due to the construction of longitudinal training walls which have not been considered in detail due to lack of data. For instance, the passages of ships not only resuspend sediment, but also generate waves which enhance bank erosion. Longitudinal training walls protect banks from these waves.

Apart from overall aggradation or a reduction of degradation, the construction of the longitudinal training walls has removed the “groyne flames” that form at a depth scale at each groyne field due to local three-dimensional flow features, which is positive for decreasing the maintenance costs. All mechanisms that we consider that are important for studying the morphodynamic impact of longitudinal training walls are summarised in Figure 75.

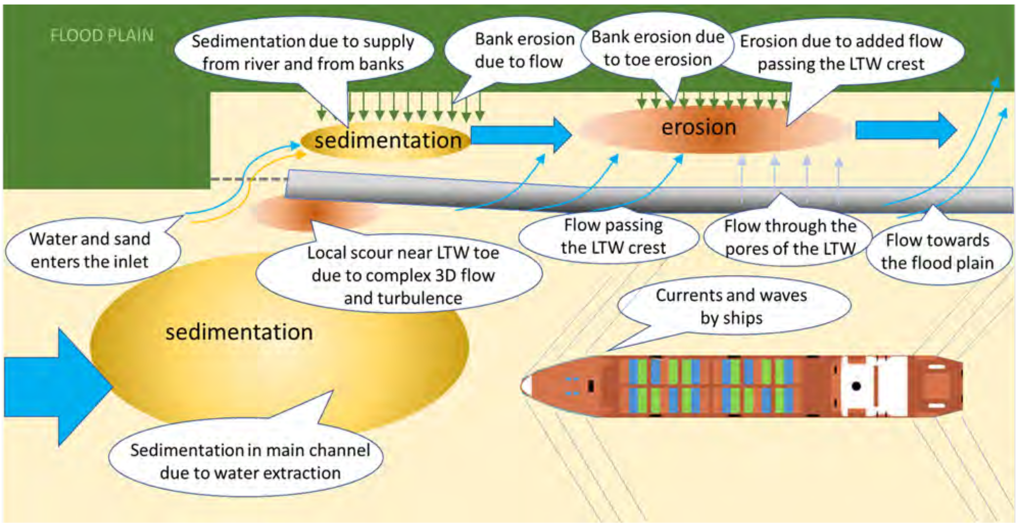

Figure 75 Mechanisms that play a role in the morphodynamic behaviour due to the construction of a longitudinal training wall.

Bank erosion on the order of metres is clearly observed. It is unclear what the future situation will be. Bank erosion may continue, but it will eventually reduce and stop. Prediction of bank erosion rates is excessively uncertain to be useful for the short- and mid-term management. Moreover, the future maintenance policy cannot be neglected. Contrary to the costs associated to dredging due to bank erosion, the costs of dredging due to deposition of sediment at the auxiliary-channel entrance do not decrease with time. The estimation of the long-term costs depend on the delicate balance between sediment and water partitioning causing deposition or erosion at the entrance. It is recommended to subscribe to the policy followed by *Rijkswaterstaat* in other cases for dynamically managing the banks (*Beheer van Dynamische Oevers*).

At higher discharges, the preserved original shape of the cross-section at the Wamel ferry landing can be seen as a local narrowing with respect to the enlarged cross-sections upstream and downstream. The eroding effect on the main channel at the ferry landing is equivalent to the eroding effect of supplying and re-extracting water as employed in our simplified analysis. In theory, this erosion in the smaller cross-section at the ferry landing is enhanced by the lower water levels after implementation of the training walls. Morphological effects of local features other than the Wamel ferry landing and the Passewaaij side channel have not been analysed. Carrying this out would give a more complete perspective.

In between longitudinal training walls, a hump in bed level is expected to occur. If excessive, this would increase the maintenance costs. This may cause an increase in the maintenance costs for the ferry (*veer*). Nevertheless, the ferry has a smaller flow depth than the transport vessels, which are the critical factor. The local bed level changes in the landing on the left-hand side will depend a great deal on the dynamics of the outflow of the auxiliary channel at Wamel, from which little is known.

5 Morphodynamic numerical modelling

The final effects of the construction of longitudinal training walls cannot be derived straightforwardly from measured data, as the time that has passed since the intervention is relatively short, and one cannot easily isolate the effects of the longitudinal training walls from the effects of other interventions and the variability in discharge or other variables.

Numerical simulations overcome the limitations mentioned above, as one can model a case with and without longitudinal training walls far into the future keeping all other conditions the same between the two cases. Paarlberg and Omer (2021) conduct such numerical simulations. We refer to their report for the simulation details. The model has been calibrated based on measurements at fixed stations (*Monitoring Waterstaatkundige Toestand des Lands (MWTL) waterstandpeilschalen*) at the start of the project. Most important for morphodynamic purposes is that the simulations include dredging-and-dumping functionality. Model outcomes in terms of absolute water levels, flow velocities, bed levels, discharge distributions, and dredged sediment are known to be imprecise. Hence, comparison of absolute values is excluded and only relative comparisons are made. Sediment transport partitioning between the main and auxiliary channels is known not to be well reproduced and is a topic of ongoing research. Moreover, bank erosion is not modelled. As a consequence, morphodynamic development in the auxiliary channel is not captured correctly. Nevertheless, changes in velocity in the main channel (and as a consequence changes in sediment transport capacity in the main channel) are expected to be well reproduced.

Three simulations are conducted that model morphodynamic development for 20 years:

- V0+: No longitudinal training walls.
- V1: Longitudinal training walls as they were built.
- V2: Longitudinal training walls with closed sills.

Appendix C presents figures showing the two-dimensional change in bed level for each run as well as the differences between runs. Here we focus on the longitudinal profiles.

Figure 76 shows the difference in bed elevation after the last flood event between a case with longitudinal training walls with open sills (V1) and a case without longitudinal training walls (V0+). The presence of the longitudinal training wall causes the bed level at Wamel to become higher along the main channel. This is particularly noticeable at the upstream end. The negative difference in bed elevation along the auxiliary channel does not have to be interpreted as degradation throughout the simulation. The difference comes from the fact that the initial condition of the simulation with longitudinal training walls has the excavated auxiliary channel.

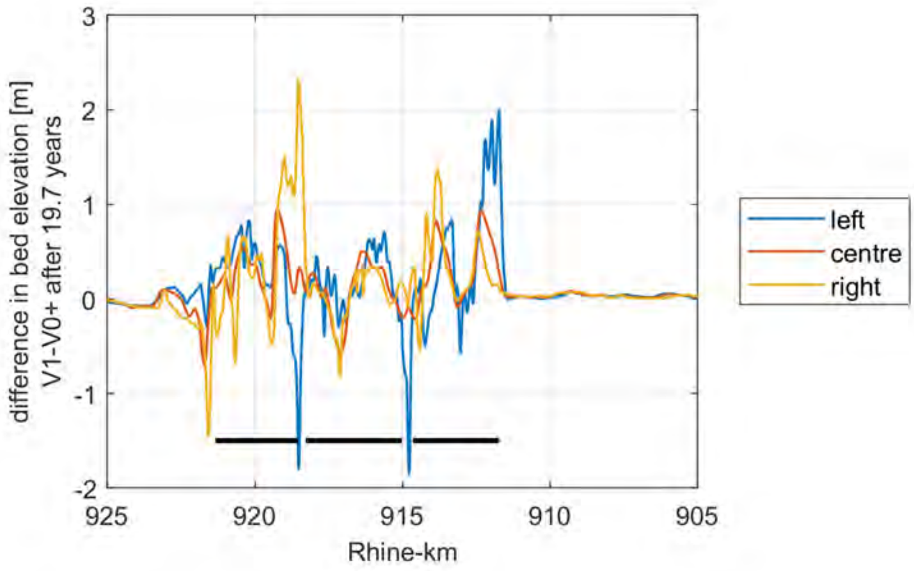

Figure 76 Longitudinal profile of the computed difference in bed elevation after the last high-flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls. Simulations with dredging and dumping.

At the Wamel ferry landing between the training walls of Wamel and Dreumel, the inflow from the auxiliary channel causes degradation. Overall aggradation due to the longitudinal training walls is also visible at Dreumel and Ophemert, although at Dreumel there is also a region with slightly lower bed elevation. At the inflow of Ophemert, substantial aggradation with respect to a case without longitudinal training walls is observed. This occurs in combination with degradation at the outflow of Dreumel and is due to the local flow pattern at the sills. Finally, no substantial change is observed upstream of Dreumel.

Based on the results from the numerical model by Paarlberg and Omer (2021), we conclude that longitudinal training walls cause an overall increase in bed elevation, despite local degradation at the inflow locations. Contrary to the results of previous numerical simulations (Section 3.5), the numerical simulations by Paarlberg and Omer (2021) predict an overall increase in bed elevation along all longitudinal training walls.

On the contrary, a situation with closed sills does not cause overall aggradation (Figure 77). Both at Wamel and Dreumel the bed level pattern significantly changes due to the longitudinal training wall without clear overall aggradation or degradation. At Ophemert overall degradation is expected to occur. Similarly to the previous case, no significant effect is seen upstream of the longitudinal training walls.

We conclude that, as expected, the sill opening is crucial in setting the dynamics of the river system. A significant amount of flow must occur along the auxiliary channel under both high and low flow conditions for the longitudinal training walls to be effective in reducing overall bed degradation.

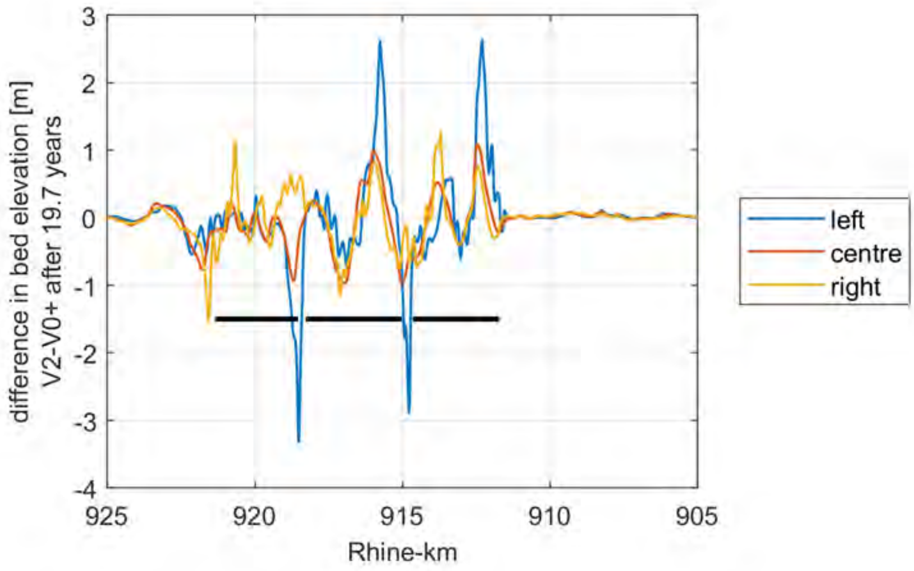

Figure 77 Longitudinal profile of the computed difference in bed elevation after the last high-flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls. Simulations with dredging and dumping.

The simulations we have shown include dredging and dumping. This is realistic, as it resembles the river policy expected to be present in the coming years. Nevertheless, from a morphodynamic point of view, considering dredging and dumping hides the tendency of the river to a new state after introducing longitudinal training walls. For instance, the maximum amount of aggradation occurring is limited by the dredging rules that prevent excessively shallow points. Similarly, deepening areas are less obvious as dredged sediment is deposited. This information is implicit in dredging-and-dumping volumes, but the cumulative effect and the nonlinear response to it is lost. For this reason, one is interested in studying whether the presence of longitudinal training walls will change the dynamics of the system without considering the effect of dredging and dumping.

Figures 78 and 79 present the longitudinal profiles comparing the simulations without dredging and dumping. Comparing with the previous figures, it is clear that the effect of dredging does not change the conclusions previously derived. Figures 80-82 show the difference in bed level after the last high-flow event for the same situation (i.e., without longitudinal training walls, with as-built longitudinal training walls, and with closed sills) with and without considering dredging and dumping.

The largest difference is found at the downstream end of the longitudinal training wall at Wamel where the bed level on the right-hand side is approximately 50 cm higher when not considering dredging. This is understandable, as dredging occurs in this area if active. Nevertheless, the overall impression is the same, showing that the dredging effort is not an essential component in the modelling exercise with regard to the morphodynamic development.

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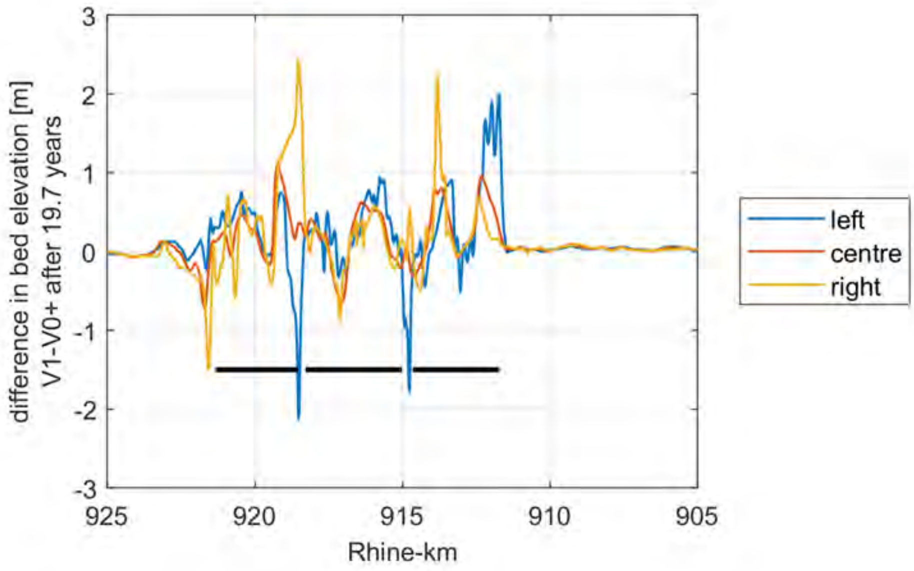

Figure 78 Longitudinal profile of the computed difference in bed elevation after the last high-flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls. Simulations without dredging and dumping.

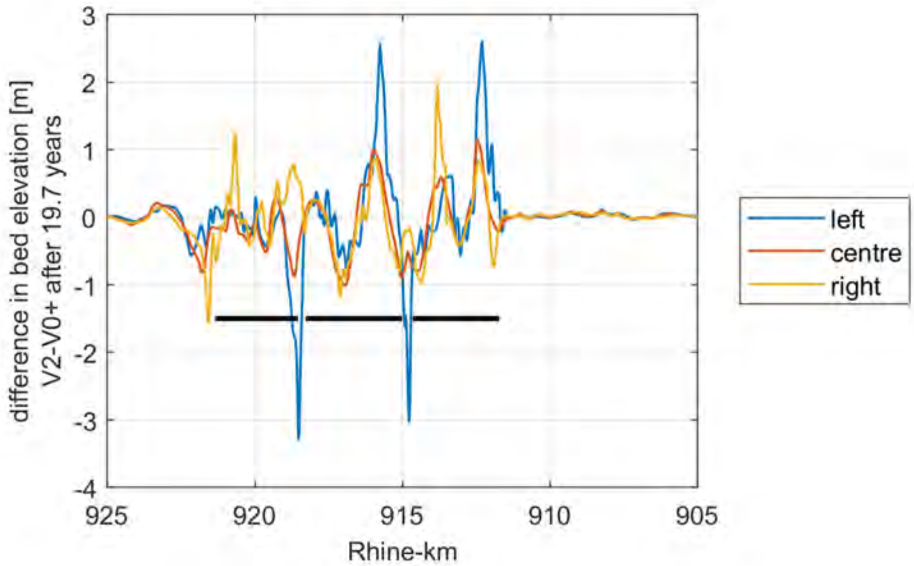

Figure 79 Longitudinal profile of the computed difference in bed elevation after the last high-flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls. Simulations without dredging and dumping.

The numerical simulation with as-built inlets shows increased dredging at the inlet of Wamel and Ophemert compared to a simulation without longitudinal training walls (Figures 83-84). This is in line with the effect of a water extraction in the main channel. The increase in dredging is not drastic and it is below the predicted one at Sint Andries. In assessing the results it is relevant to remember that an important question, the amount of sediment directed towards the auxiliary channel, is not properly resolved in the model.

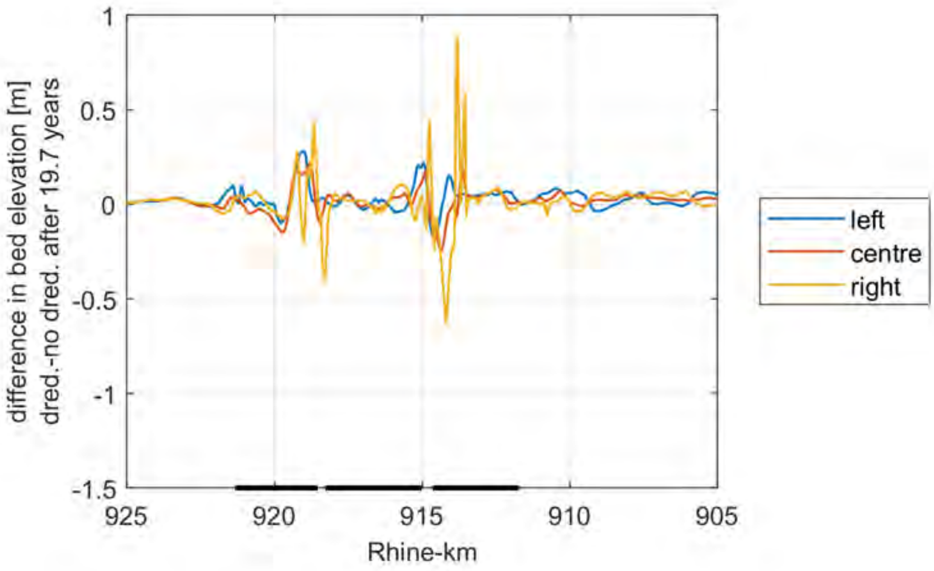

Figure 80 Longitudinal profile of the computed difference in bed elevation after the last high-flow event between a case considering dreding and dumping and a case not considering dredging and dumping for the situation without longitudinal training walls.

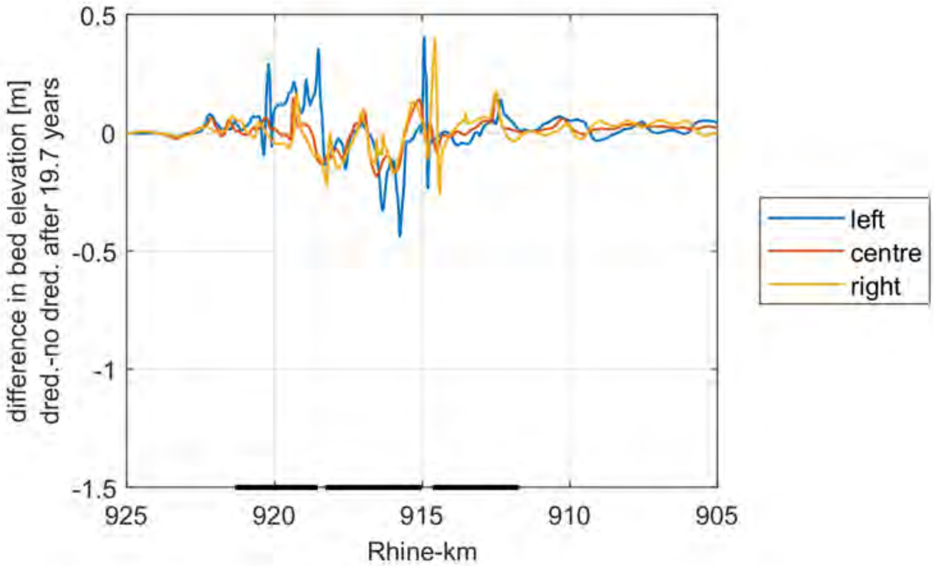

Figure 81 Longitudinal profile of the computed difference in bed elevation after the last high-flow event between a case considering dreding and dumping and a case not considering dredging and dumping for the situation with as-built longitudinal training walls.

The results of the numerical simulations support the idea that the overall impact of the longitudinal training walls with as-built inlets (i.e., open) is dominated by the effect of extracting water from the main channel (Section 3.2.3). In case of closed inlets, the numerical simulations predict a lower bed level compared to the reference case, as expected due to narrowing of the main channel (Section 3.2.2). The simulations do not accurately model morphodynamic changes in the auxiliary channel nor bank erosion and cannot be used to support the theory nor the measurements in this regard.

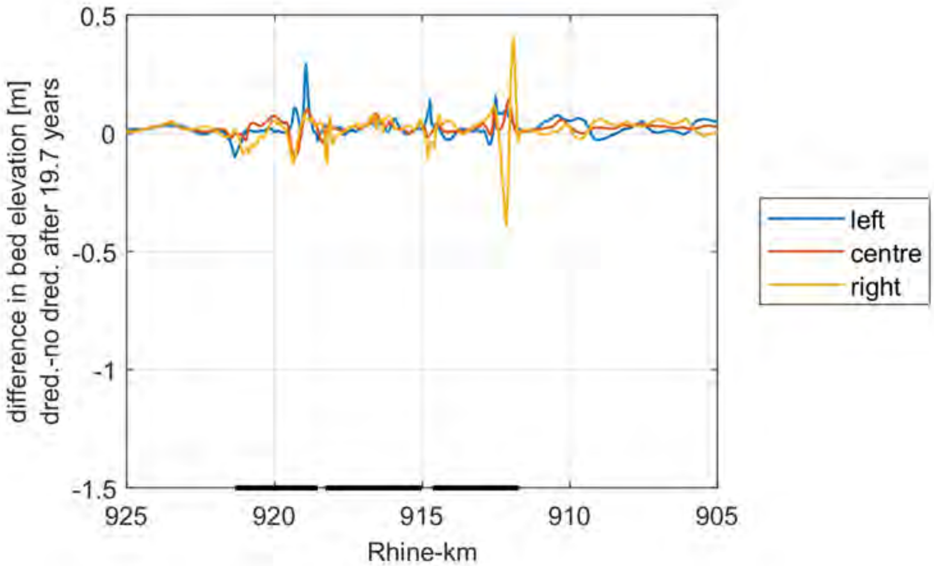

Figure 82 Longitudinal profile of the computed difference in bed elevation after the last high-flow event between a case considering dreding and dumping and a case not considering dredging and dumping for the situation with closed sills.

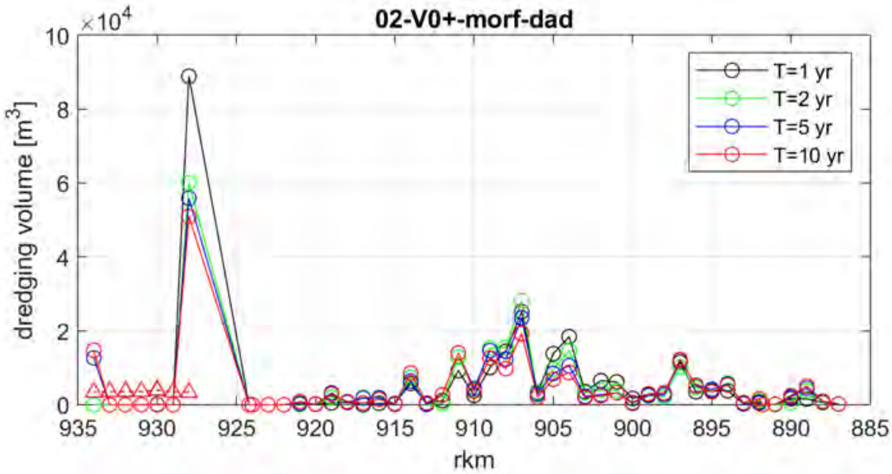

Figure 83 Dredged volume for a simulation without longitudinal training walls. Triangles indicate sand mining. Figure from Paarlberg and Omer (2021).

The numerical simulations do not include all the physical processes relevant for a detailed representation of the development that has occurred since construction. A key point is the sediment distribution towards the auxiliary channel and an even more important point for a direct comparison with the measured development is the schematized hydrograph applied in the runs, which is representative of the mean dynamics. Still, it is interesting to discuss the differences and similarities of the trends.

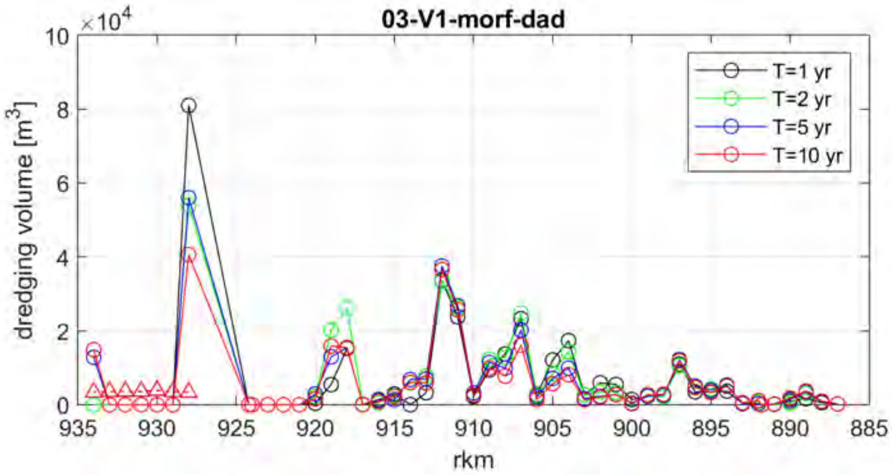

Figure 84 Dredged volume for a simulation with as-built longitudinal training walls. Triangles indicate sand mining. Figure from Paarlberg and Omer (2021).

Figure 85 shows the mean bed elevation inside polygons covering different areas in the longitudinal training walls for the measured data and the numerical simulations. Figures 86 and 87 zoom on different periods. The polygons are the same used in the PMAP analysis by De Jong *et al.* (2021). They all cover the main channel. "upstream" covers the area approximately 1.5 km upstream from the beginning of the longitudinal training walls sections. "Wamel", "Dreumel", and "Ophemert" are adjacent polygons covering each longitudinal training wall and "all LTW" is the combination of these three. "downstream" extends along approximately 1.5 km downstream from Ophemert longitudinal training wall. The measured data comes from the PMAP analysis and is a combination of yearly JMP data and 8-weekly measurements (see De Jong *et al.* (2021) for a detailed description).

As the hydrograph used in the simulations is schematized, there is no actual start day of the simulations. For the comparison the 1st of October of 2015 has been used.

The predicted bed elevation for all longitudinal training walls shows that, in the long term, a simulation with open sills yields overall mild aggradation and a case with closed sills overall mild degradation. A case with no longitudinal training walls falls in between the previous two cases on the degradation side. This is in line with the expectations. The impact of the sills and the longitudinal training walls is the same in all sections but with varying magnitude. Worded differently, the bed level is largest for a case with as-built sills, lowest with closed sills, and in between the previous two values without longitudinal training walls.

Upstream of the longitudinal training walls, there is only a very mild effect overruled by the variability due to discharge. For the section at Wamel the effect of the longitudinal training wall is larger than for the section at Dreumel and is largest for Ophemert. In Dreumel all cases show degradation and as-built sills minimizes it. In the downstream section, degradation is predicted for all cases and it is smallest without longitudinal training walls. This shows the impact of the erosion due to the streamwise increase in sediment transport at the confluence.

In these figures, the variability of the bed due to a varying (schematized) hydrograph is visible. The variation is reduced in the section with longitudinal training walls compared to upstream and downstream, which shows the effect of longitudinal training walls in converging flow during low flow and reducing peak water levels.

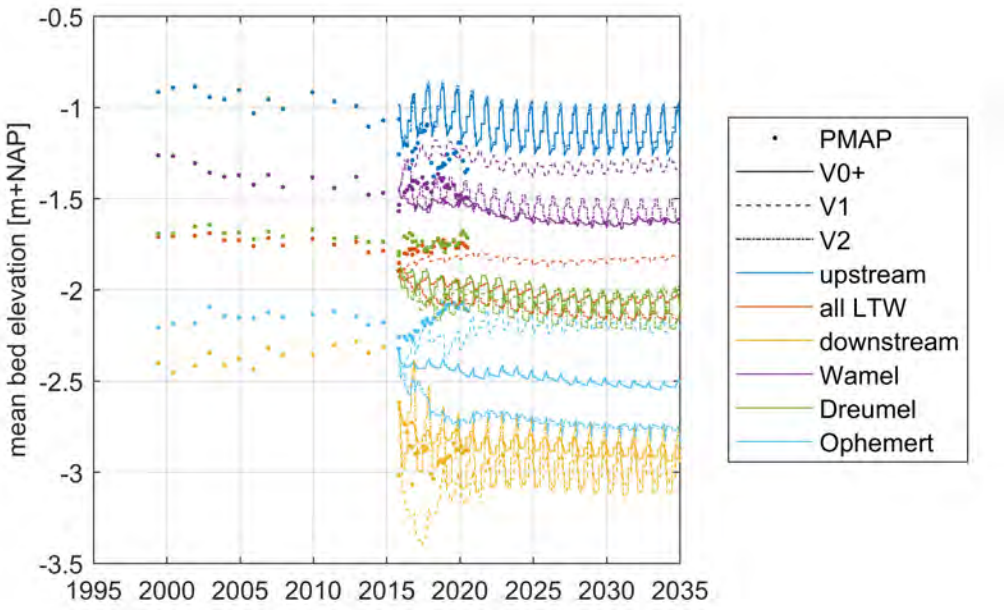

Figure 85 Mean bed elevation inside each polygon (colours) for the measured data (dots), a simulation without longitudinal training walls (V0+, solid lines), with as-built longitudinal training walls (V1, dashed lines) and with closed sills (V2, dash-dotted line).

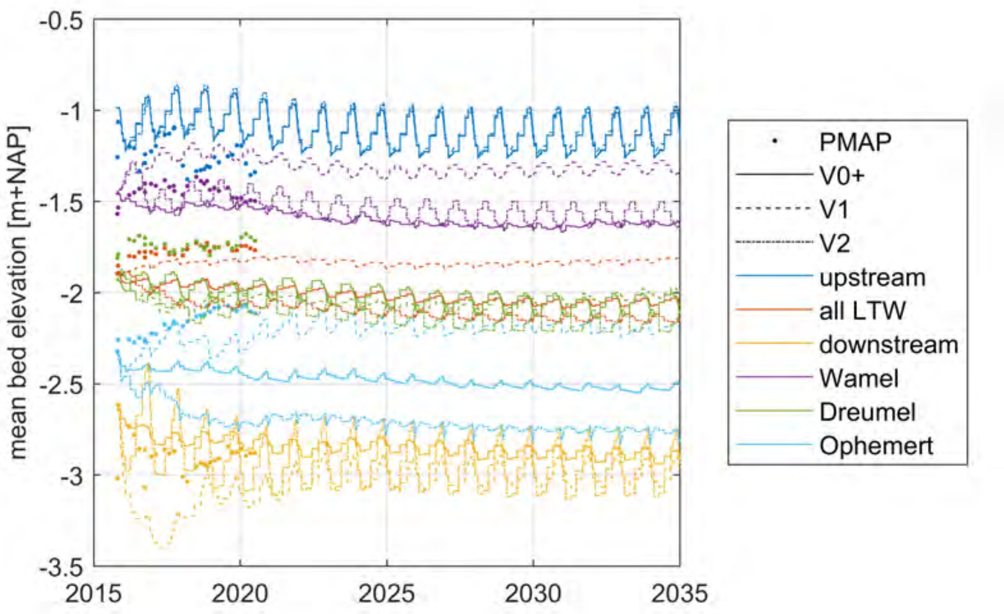

Figure 86 Mean bed elevation inside each polygon (colours) for the measured data (dots), a simulation without longitudinal training walls (V0+, solid line), with as-built longitudinal training walls (V1, dashed lines) and with closed sills (V2, dash-dotted line). Zoom on modelled period.

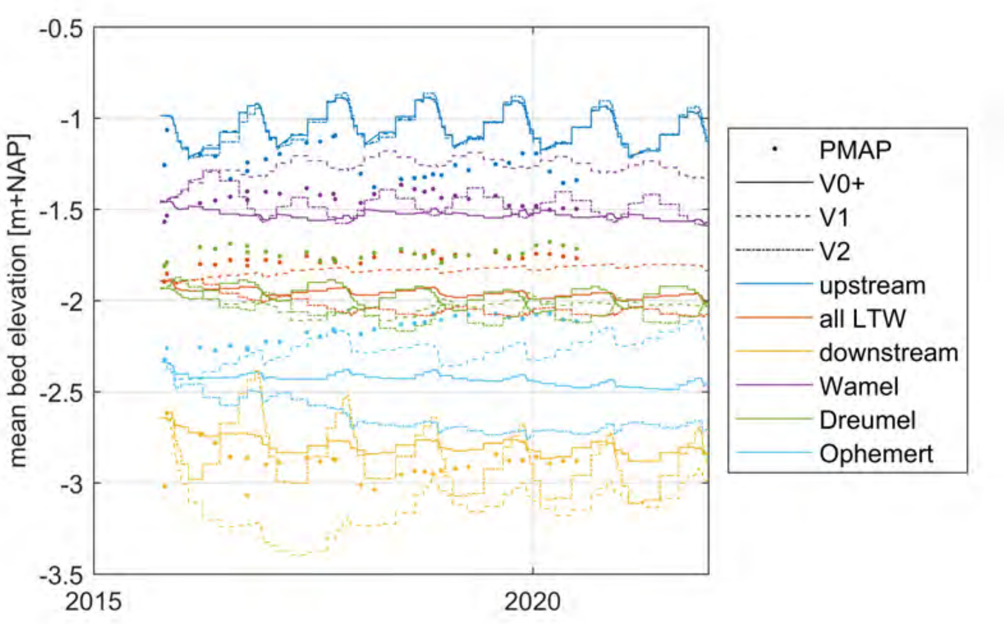

Figure 87 Mean bed elevation inside each polygon (colours) for the measured data (dots), a simulation without longitudinal training walls (V0+, solid line), with as-built longitudinal training walls (V1, dashed lines) and with closed sills (V2, dash-dotted line). Zoom on initial period.

When comparing to data, the first observation is that the order of magnitude of bed elevation and its changes are well reproduced in the simulations. The computed bed level for all longitudinal training walls with as-built sills is only slightly smaller than measured. In Dreumel, the predicted and simulated case with as-built sills predict a temporary increase and subsequent decrease in bed level, which is reproduced although with a larger magnitude in the numerical simulations. The agreement for Dreumel is lowest. The measurements show aggradation while simulations predict degradation. In Ophemert, the simulation with as-built sills shows an increase in bed level and stabilization, in a similar trend as the measured bed level.

An important outcome of the comparison is that a monitoring of less than 5 years does not indicate the long-term trend. For instance, the section in Wamel is predicted to first increase the mean bed level for later showing mild degradation. A second outcome is the importance of the variability due to discharge. Several years of measurements every 8 weeks need to be used in obtaining a trend that filters the variations of the discharge. Monitoring results can only be used for long-term planning and not for short-term intervention. Hence, we recommend to continue measuring for a prolonged period of time at a high temporal frequency (i.e., every 8 weeks) such that the variability due to discharge is captured.

The main added value of the numerical simulations is to clearly identify the effect of the longitudinal training walls isolating it from other processes happening in the field such as the adaptation to the groynes lowering, or possible changes in discharge distribution at the Pannerdensche Kop. The numerical simulations unequivocally show that the implementation of the longitudinal training walls is responsible for a decrease in degradation.

6 Experiences of maintenance by *Rijkswaterstaat*

This chapter has been written in Dutch to preserve the specific terminology used in the practice of maintenance at *Rijkswaterstaat*.

Een van de hoofdvragen in de eindevaluatie van de pilot is welke invloed langsdammen hebben op het onderhoud van *Rijkswaterstaat*. Antwoorden volgen deels uit de langjarige morfologische berekeningen met Delft3D om de effecten op benodigd baggeronderhoud te schatten en om te beoordelen in welke mate het lukt om de grootschalige bodemerosie af te remmen of tot staan te brengen. Daarnaast volgen antwoorden uit de ervaringen van *Rijkswaterstaat*. Dit hoofdstuk rapporteert deze ervaringen op basis van feitelijke informatie, verzameld door *Rijkswaterstaat*, en gesprekken met deskundigen van *Rijkswaterstaat* Oost-Nederland. Onderhoud omvat daarbij alle technische activiteiten om de constructie en het vaarwegprofiel in stand te houden.

Rijkswaterstaat en Deltares ontwikkelen momenteel een methodiek voor het combineren van verschillende gebruikseisen in het beheer van het zomerbed. Ze baseren deze methodiek op een basisrivierbodemligging (BRL). Functie-eisen worden vertaald in een bandbreedte van geschikte bodemliggingen waaraan de actuele bodemligging of een scenariobodem getoetst wordt. Die functie-eisen betreffen niet alleen de kerntaken van *Rijkswaterstaat* (waterveiligheid, voldoende water, schoon en gezond water, vlot en veilig verkeer over water) maar ook functies buiten de primaire verantwoordelijkheid van *Rijkswaterstaat*, zoals de stabiliteit van waterkeringen en de dekking boven tunnels, kabels en leidingen. De BRL zal in de toekomst een instrument worden voor het beheer van het traject van de langsdammen en het bijhorende onderhoud.

Het onderhoud aan de langsdammen wordt uitgevoerd volgens een prestatiecontract. Activiteiten hiervoor betreffen het repareren van schade aan de langsdammen, het verwijderen van begroeiing, en het uitvoeren van baggerwerkzaamheden om het vaarwegprofiel in stand te houden. Als onderdeel van het prestatiecontract monitort de aannemer de staat van het onderhoud via jaarlijkse inspecties, gestandaardiseerde conditiemetingen volgens NEN2767 [1] aan het begin en het einde van de looptijd van het contract, en incidentele inspecties na schademeldingen en tips of klachten uit de omgeving. Van Hoogenhuizen (2021) geeft een completer en gedetailleerder overzicht van gemaakte en voorziene onderhoudskosten (tabel 1)[2]. Hij concludeert dat aard en omvang van het toekomstig beheer en onderhoud in het traject ook afhankelijk is van de toekomstige functies van oevergeulen en langsdammen.

De profielen van de langsdammen en het dragend grondmassief zijn na aanleg niet vervormd door verzakkingen of afschuivingen. Ook zijn er geen noemenswaardige uitschuringskuilen ontstaan die de constructie aantasten. Volgens jaarlijkse vaststellingen van hun conditie zijn de dammen nog zo goed als nieuw. Voor constructieve aspecten hebben de langsdammen daarom nog geen onderhoud nodig gehad. Verder waarde de slechte toegankelijkheid de langsdammen vrij van vandalisme. Wel hebben aanvaringen schades veroorzaakt. De kosten van herstel blijken voor een langsdam een veelvoud van die voor een krib (informatie Onderhoudsteam, via Koen van Korlaar). Ook de havenpalen die de in- en uitvaart van de nevengeulen voor recreanten markeren zijn aangevaren. Tabel 2 geeft een overzicht van de opgetreden schades. Het herstel van havenpalen kost circa 90 000 € per incident.

[1] https://www.nen.nl/en/bouw/beheer-en-onderhoud/conditiemeting

[2] Toelichting: Een vergelijking tussen de begrote en daadwerkelijke kosten per onderhoudstaak leert dat: a. Er voor het herstellen van stortsteen de afgelopen jaren geen daadwerkelijke kosten gemaakt zijn. Dit komt omdat het nieuw areaal betreft. Er mag echter van uit gegaan worden dat deze kosten op langere termijn wel zullen komen. Daarom zijn ze wel in de 4de kolom, kosten voor lange termijn, opgenomen. b. Hetzelfde geldt voor bijstorten stortsteen, 3 beschermingsconstructies. c. Zwerfvuil is geen probleem geweest de afgelopen jaren, dus wordt deze ook niet voor de langere termijn opgenomen. d. Gebleken is dat er zich weinig vegetatie ontwikkelt op de langsdammen. Kosten vallen lager uit, ook voor de langere termijn. e. In de afgelopen periode heeft er maar 1 keer een toestandsinspectie plaatsgevonden. De kosten daarvoor waren zo'n 4 000 €. In het onlangs gegunde prestatiecontract wordt de opdrachtnemer verplicht elk jaar een inspectie uit te voeren. Kosten voor de lange termijn zijn dan 20 000 € per 5 jaar. f. Instandhoudingsinspectie is nog niet gedaan maar moet wel conform een frequentie van 1 keer per 5 jaar. g. De kosten voor het baggeren van de oevergeul waren de afgelopen 5 jaar flink hoger dan begroot. Mogelijk is daar met het bijstellen van instroomopeningen iets aan te doen, maar vooralsnog worden deze hogere kosten ook gehanteerd voor de langere termijn (4de kolom). h. De daadwerkelijke kosten voor het multibeamen waren het dubbele van wat geprognotiseerd was. Verwachting is dat op langere termijn meer inzicht is in de morfodynamiek van de oevergeul en daardoor minder gemeten hoeft te worden. Derhalve 60 000 € in de 4de kolom. i,j,k,l,m,n. Dit zijn de kosten voor het onderhoud van bebording, verlichting, vaarwegmeubilair en kantelwalbordopstellingen. De afgelopen jaren zijn daar geen kosten aan geweest omdat alles nog nieuw was en er niets kapot ging. Verwacht mag worden dat deze kosten wel komen. Kosten uit het B&O plan worden opgenomen voor de langere termijn. o. De kosten van schade door aanvaringen zijn veel lager uitgevallen dan in het B&O plan verwacht was. De daadwerkelijke gemaakte kosten worden dan ook door vertaald naar de langere termijn. Onderscheid in herstelkosten voor de lange termijn moet nog gemaakt worden tussen de variant mét en zónder recreatievaart. Zonder recreatievaart zijn in de toekomst geen havenpalen meer aanwezig die omgevaren kunnen worden. Vandaar 85 000 € zonder scheepvaart en zo'n 190 000 € met scheepvaart aan schadevaringen.

Kosten Onderhoudstaken [€]	Geprognotiseerde kosten B&O plan 2016 (2016-2021)	Werkelijk gemaakte kosten (2016-2021)	Verwachte Kosten lange termijn (per 5 jaar)	Verwachte kosten lange termijn zonder recreatie vaart (per 5 jaar)
a. Aanbrengen stortsteen Dam	500 000	0	500 000	500 000
b. Bijstorten stortsteen, 3 beschermingsconstructies	22 800	0	22 800	22 800
c. Verwijderen zwerfvuil	40 000	0	0	0
d. Vegetatie verwijderen	70 000	10 000	10 000	10 000
e. Toestandsinspectie	40 000	4000	20 000	20 000
f. Instandhoudingsinspectie	6000	0	6000	6000
g. Baggeren oevergeul	225 000	593 988	600 000	100 000
h. Multibeamen oevergeul	60 000	1 170 000	60 000	20 000
i. Conserveren palen voor bebording	39 375	0	39 375	0
j. Vervangen borden	6250	0	6250	0
k. Vervangen vaarwegmarkering	75 000	0	75 000	0
l. Vervangen zonnepanelen	7500	0	7500	0
m. Kantelwalopstelling onderhouden	50 000	0	50 000	0
n. Vervangen onderdelen kantelwalopstellingen	50 000	0	50 000	0
o. Scheefstand/aanvaring	500 000	193 760	190 000	85 000
totalen per 5 jaar	1 691 925	810 884	1 636 925	763 800
totalen per 1 jaar	338 385	162 177	327 385	152 760

Table 1 Onderhoudskosten.

Er zijn geen intrinsieke redenen waarom het herstellen van de bestorting van een langsdam na aanvaring zoveel duurder zou moeten zijn dan het herstellen van kribben of oeververdedigingen. Het verschil komt door de gekozen granulaire opbouw zonder geotextiel. Als een langsdam bij hoogwater wordt aangevaren, ontstaat een gat dat fijner materiaal blootstelt aan de stroming. De stroming spoelt dat materiaal uit en verstoort de sortering van de filterlagen. Om dat te herstellen dient een groot stuk van de dam te worden afgegraven om hem vervolgens weer te kunnen opbouwen. Bij kribben of oeververdedigingen hoeft dat doorgaans niet omdat de stortsteen er op een geotextiel ligt.

Datum	Schadenummer	Kilometer	Kosten (€)	Schadebeeld
10-02-2016	7600002044	913.175	3042	bestorting
26-02-2016	7600002056	918.900	122 446	havenpaal en bestorting
07-10-2017	7600002282	913.150	9430	bestorting
14-12-2019	7600002621	918.900	raming 192 000	havenpaal en bestorting

Table 2 Schadevaringen van langsdammen in de Waal (bron: Gerard Wittenberg).

Deskundigen van *Rijkswaterstaat* Oost-Nederland wijten de keuze voor een schadegevoelige granulaire opbouw zonder geotextiel aan de gekozen contractvorm op basis van design & construct (D&C). Hierin is de aannemer niet alleen verantwoordelijk voor de uitvoering maar ook voor het ontwerp. Een voordeel is dat de aannemer zo de ruimte krijgt om ontwerp en realisatie naar eigen inzichten te optimaliseren en innovaties toe te passen. Een nadeel is dat de onderhoudsfase vaak maar beperkt in de optimalisatie wordt meegenomen. De contractvorm wringt met de methodiek van life-cycle costing (LCC) die de totale kosten van assets beschouwt, voor de volledige levenscyclus van aanleg tot afbreken. Een D&C-organisatievorm doet niet gemakkelijk recht aan de in LCC beoogde optimalisatie van onderhoud. De deskundigen menen dat een andere contractvorm geleid zou hebben tot een minder schadegevoelig ontwerp.

De deskundigen van *Rijkswaterstaat* Oost-Nederland wijzen ook op een ander nadeel van D&C-contracten. Om de beoogde ruimte voor optimalisatie en innovatie te geven, moet de opdrachtgever de uitvraag functioneel specificeren. Dat wil zeggen dat de opdrachtgever de gewenste prestatie van een systeem vastlegt in eisen op basis van de functies van het systeem. Het is echter niet eenvoudig om alle functie-eisen expliciet te benoemen voor constructies die al zijn uitontwikkeld via eeuwen van proefondervindelijke optimalisaties en innovaties. Eigenschappen van gangbare constructies kunnen zo in de specificatie vergeten worden. Bovendien geven ook aannemers vaak de voorkeur aan concrete uitvragen boven meer abstracte functionele specificaties.

Tot onderhoud behoort ook het groenonderhoud om de langsdammen vrij te houden van begroeiing. Wortels van begroeiing kunnen namelijk stenen van hun plek duwen. Begroeiing verhoogt bovendien de hoogwaterstanden, beperkt het zicht van schippers op de rivier en belemmert het vanuit landschappelijk oogpunt gewenste weidse uitzicht. Het verwijderen van begroeiing blijkt echter moeilijk uit te voeren. Door de grove sortering van de breuksteen is het lastig en zelfs gevaarlijk om hiervoor personeel over de langsdammen te laten lopen. Onderhoud vanaf het water is kostbaar omdat hiervoor een groot schip met een lange giek moet worden ingezet. Binnen het onderhoudscontract is het groenonderhoud daarom gestaakt. Tot nu toe zijn de dammen desondanks redelijk vrij gebleven van vegetatie omdat ze tijdens hogere afvoeren worden schoongespoeld. *Rijkswaterstaat* zoekt naar een oplossing voor toekomstig groenonderhoud en raadt aan om hierover bij de bouw van nieuwe langsdammen goed na te denken.

De morfologische berekeningen met Delft3D geven inzicht in het benodigde baggeronderhoud in de hoofdgeul. Daarnaast zijn ook de oevergeulen in 2018 een keer gebaggerd. Circa 30 000 m^3 baggerspecie werd verwijderd, voornamelijk afkomstig van oevererosie. De oevergeulen zijn geen onderdeel van het prestatiecontract maar vallen onder het project WaalSamen. Per 1 april 2021 zullen de oevergeulen overgaan naar het prestatiecontract. Daarin wordt dan het op diepte te houden profiel voor de recreatievaart gespecificeerd.

7 Conclusions

7.1 Research questions

In this section each research question is answered.

1 What dredging effort is expected based on the modelled development of the main and auxiliary channels? 2 What are the differences in frequency and amount of dredging compared to other sections of the Waal River? 3 What are the consequences of varying the inlets regarding dredging?

Rijkswaterstaat expects the that the dredging effort is reduced after implementation of the longitudinal training walls. Previous numerical simulations suggested a minor change in dredging (Section 3.5). Based on measurements it is not possible to derive a conclusion about the effect of the construction of the longitudinal training walls on the dredging effort. The results of the numerical simulations should only be interpreted in relative terms and only apply to the main channel development. It is observed that the results of a simulation including dredging do not significantly differ from the results without dredging. Hence, the dredging effort is not expected to be a crucial factor. Still, the numerical simulation with as-built longitudinal training walls shows an increase in dredging effort. Closing the inlets causes no overall aggradation due to the construction of the longitudinal training walls contrary the situation with open inlets. This may slightly reduce the dredging effort.

4 What is the vegetation development in the longitudinal training walls? 5 What is the required management and maintenance as caused by the previously mentioned changes in vegetation development? 6 How does this relate to the maintenance and management of groynes?

A pattern of growth of vegetation and removal during high-flow events is observed on both the longitudinal training walls and groynes. Nevertheless, the density is much higher on groynes than on the longitudinal training walls. This is most probably related to the fact that the longitudinal training walls are isolated from the banks, hindering the arrival of seeds. The lower vegetation density decreases the costs of maintenance, although maintenance of the vegetation of the longitudinal training walls is in itself more expensive as it is more difficult to reach than groynes. A second benefit of the longitudinal training walls is that its vegetation is aligned with the flow direction, contrary to the vegetation on groynes, which is perpendicular to the flow direction. The same vegetation biomass causes less flow resistance on longitudinal training walls than on groynes.

7 What is the influence of the inlet openings regarding bed level changes?

No influence could be found of the shape of inlets at equal average sill crest elevations on the amount of sediment entering the auxiliary channels. Sustained differences in sill crest elevation, however, were found to significantly affect main-channel morphology through changes in the flow field.

An analysis of multibeam measurements using the PMAP procedure shows that a sedimentation trend changed into an degradation trend after closing the inlets. This may be coincidental, as an erosional wave probably caused by dredging reached the opening roughly at the same time as the inlet was changed. Nevertheless, this finding that the inlets can be used to steer bed level changes is supported by numerical simulations showing that a case with all inlets fully closed shows no aggradation trend, contrary to a situation with open inlets. While this behaviour is also expected from a theoretical point of view, it is relevant to consider that the measurement observations are based on a short time period. The time span is not long enough such that annual variations can be neglected.

The fact that inlet manipulation seems to be successful in controlling main-channel dynamics is no proof that it is successful in controlling the sediment distribution between the main channel and the auxiliary channel. The flow can be regulated unambiguously changing the inlet, as this has an immediate and easily-measurable reaction. However, there is no evidence of changes in sediment distribution due to a change in inlet shape. The morphodynamic development of the auxiliary channel is currently dominated by bank erosion occurring at a corridor scale and not by the sediment entering and exiting through the inlets and outlets. Hence, monitoring of the auxiliary channel for adjustment of the inlets is not realistic. Even with fixed banks, the development of the bed level in the auxiliary channel as a proxy for the sediment partitioning is subject to several limitations. The short-term development is highly dependent on the flow conditions and only after a sufficiently long time (order of years) clear conclusions can be derived about the amount of sediment entering the auxiliary channel based on measurements. There is still no clear understanding of the mechanisms controlling sediment partitioning at the inlets. This is a topic of ongoing research (Jammers, 2017; Van Os, 2020).

8 What are the upstream and downstream effects of the longitudinal training walls for a particular opening of the inlets?

From a theoretical point of view and considering that the auxiliary channels are not closed, in the short term, the construction of the longitudinal training walls is expected to cause a mild increase in the current degradational trend upstream and a degradational wave downstream. In the long (i.e., decadal) term, a mild decrease in degradation upstream (order of centimetres compared to no intervention) and no reach-scale effects downstream are expected.

The measured data do not provide information on the long-term development. Regarding the short-term development, it is not possible to isolate the effect of the construction of the longitudinal training walls from other measures, primarily the lowering of the groynes in the downstream reach. Moreover, superimposed to the reach-scale effects are the local effects due to the inlets. Downstream of Ophemert a large degradational pit due to inflow from the auxiliary channel is expected and observed.

The modelling results suggest no significant reach-scale change in bed elevation neither upstream nor downstream from the longitudinal training walls with respect to a case without longitudinal training walls. The numerical model does capture the formation of the local degradation, which is restricted to approximately 2 km.

9 Which morphodynamic trends in bed elevation have been measured and are expected to occur?

Measurements suggest that the bed level lowering has decreased. This is supported by the results of numerical simulations. From a theoretical perspective a decrease of the bed lowering is expected when the effect of water extraction from the main channel due to the construction of the longitudinal training walls dominates over the effect of narrowing.

Measurements of the velocity by means of ADCP suggest a slight increase of flow velocity when the water level is below the crest level and a decrease when the water level is above. This falls within the expected behaviour. The consequences of the velocity changes are a decrease in the sediment transport velocity, which is in accordance with the observed decreased rate of bed level lowering.

At the inlets and outlets, both numerical results and simulations indicate that the morphodynamic behaviour is dominated by local effects due to input and output of water discharge. At the locations where water is extracted (input), local aggradation (degradation) is observed.

A dynamic auxiliary channel may lead to larger time fluctuations in the discharge partitioning for the same total discharge possibly increasing the maintenance costs for preserving the desired water distribution, which appears to be the key dominant factor. This is something that cannot currently be studied based on the model results nor the data and deserves further investigation.

10 Which morphodynamic trends have been observed along the river banks?

The dynamics of the auxiliary channel are dominated by bank erosion. A stabilizing trend is visible in the data. Sediment from the banks is the main input of sediment to the recreational boating channel.

The type of numerical model employed to assess the long-term impact of the implementation of the longitudinal training walls cannot be used to assess the dynamics of the auxiliary channel due to the intrinsic three-dimensional character of the flow at the inlets and the complexity of sediment transport at these locations. Furthermore, accurate modelling of bank erosion is outside the capabilities of the current software.

11 Which signs of morphological development can be derived from stage-discharge relationships?

The data suggest that, for the same discharge, water levels have lowered after implementation of the longitudinal training walls. This reflects the enlarged space of the auxiliary channels and hence does not form a contradiction with the aggradation of the river bed in the main channel. The effect on water levels, however, cannot be ascribed to the system of training walls and auxiliary channels alone. The period of the pilot coincided with the lowering of groynes upstream and downstream, as well as with the opening of the side channel at Passewaaij. Moreover, the data scatter is so large that no strong conclusions on systematic changes in stage-discharge relationships can be drawn.

12 How is the discharge partitioned between the auxiliary channel and the main channel?

Measurements indicate that the amount of discharge along the auxiliary channels varies between 5% and 25% of the total discharge. For a larger total discharge, a larger proportion is transported along the auxiliary channel. This is in accordance to the expected behaviour. Changing the inlets has no visible effect in the discharge partitioning.

For a better understanding of the effect of the inlets in the discharge it is necessary to design a measurement programme specific to that purpose in which a larger amount of measurements in the auxiliary channel and the main channel are conducted at the same river kilometre and day.

7.2 General conclusions

The construction of the longitudinal training walls appears to have decreased on average the eroding trend or even have caused aggradation on the order of centimetres in the main channel. This implies that, from all the processes associated to the river intervention (reduction of the main-channel width, diversion of sediment to the auxiliary channel, change in friction especially under high-flow conditions, and water transfer from the main channel to the auxiliary channel), the most relevant process for the morphodynamic behaviour on a timescale of a few years is the fact that water discharge from the main channel is diverted to an auxiliary channel. This statement is supported by a simplified analytical study, the analysis of measured data, and the results of numerical simulations. If this process continues to be dominant, the construction of the longitudinal training walls can be expected to decrease overall bed erosion, as one of the objectives of the intervention.

Nevertheless, the statement that the longitudinal training walls decrease bed erosion needs to be taken with caution. The first limitation is that the time that has passed since construction is short compared to the timescale of morphodynamic changes. Hence, the observed trends until now are more representative of the short-term changes after the intervention than the long-term behaviour, which are opposite upstream of the inlets and of equal sign downstream of them. Moreover, the impact of the construction of the longitudinal training walls on the river bed was major, and years are required for this impact to fade. Additionally, the short time series and the dependence of the bed level on the discharge variability hinder derivation of strong conclusions about the long-term effect of the longitudinal training walls based on observations over a short time period. In this regard, it is interesting to note the extremely low discharge that occurred during summer 2018 and the reasonably high discharge of the previous winter, the effects of which perdure over time.

The second limitation in deriving the conclusion from data analysis that longitudinal training walls help in stopping the long-term bed degradation is that the resulting net aggradation is obtained for the whole river bed, whereas large local differences occur. While on average the river bed may have experienced aggradation, this can be due to certain locations having significant aggradation while some others experience negligible aggradation or even degradation. For instance, immediately downstream of the entrance to the auxiliary channel at Wamel, substantial aggradation on the order of decimetres has occurred while the central section of the auxiliary channel at Dreumel has experienced slight degradation. Furthermore, the analysis of the overall effect of the longitudinal training walls cannot be limited to the area between the entrance at Wamel and the exit at Ophemert, hence neglecting the large degradation occurring downstream of Ophemert, as flow from the auxiliary channel re-enters the main channel. This local degradation is relevant as it may cause navigational problems in the future.

Third, numerical simulations provide evidence that the longitudinal training walls indeed cause aggradation on the long term. However, the dynamics of the auxiliary channel are poorly reproduced. In particular, the amount of sediment entering the auxiliary channels is not well captured while this is an essential feature for predicting long-term development, as seen in the theoretical assessment.

The second conclusion from this study is that the dynamics of the side channel are currently dominated by bank erosion, which is possibly the main factor for aggradation in the auxiliary channel. The eventual closure of the auxiliary channel, as well as a severe reduction of the conveyance capacity, must be prevented, as it would cause an increase of the discharge of the main channel. This increase, in combination with the width reduction, would enhance degradation of the main channel. On the other hand, during high-flow events more sediment may be entrained from the auxiliary channel than it enters at the upstream end. Thus, not only the ability of the auxiliary channel to convey water, but also its sediment transport capacity is crucial for the success of the longitudinal training walls in decreasing degradation and facilitating other river functions. A clear maintenance policy must be set for maintaining a proper sediment and discharge distribution between main channel and auxiliary channel. Proper management of the full system is of vital importance and experience needs to be gained for learning how to control sediment and water partitioning.

Longitudinal training walls appear to be significantly more expensive to maintain than groynes due to the lack of geotextile. In case of impact of a ship, the filter layer is directly exposed to the flow, as it is unprotected. Maintenance costs should be a factor receiving more importance when assigning contracts.

8 References

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A Limitations of the theoretical assessment

Several crucial assumptions have been used in the theoretical assessment. These need to be carefully considered when interpreting the results. We have assumed that the length of the intervention was sufficiently large, such that at the upstream end of the intervened reach, normal flow can be assumed. If the reach is not sufficiently long, the effect of the backwater curve due to the intervention is felt at the upstream end, limiting the short-term effect of the intervention. Assuming that the change in normal flow depth due to the intervention is sufficiently small, we use the linear approximation of the backwater curve to compute its length scale (Samuels, 1989). The length scale varies per intervention between 11 km and 14 km. This means that, in general terms, 40 km (i.e., four times the length scale) upstream from the downstream end of the intervention, one can assume that the backwater effect is negligible. Thus, the intervention can be considered to be short. As a consequence, the short-term effect of the intervention has been overestimated and we would expect a smaller change than computed in the previous sections. Nevertheless, the long-term effect remains the same regardless of the length of the intervention.

In the theoretical assessment, the initial situation is assumed to be in equilibrium. This is far from representing the actual state of the Waal River, which is currently characterized by substantial degradation. Thus, an intervention that theoretically results in aggradation must, most probably, be understood as a decrease of degradation. One of the problems in analysing the theoretical results stems from the fact that the equilibrium (if any) of the Waal River is unknown. Insight into this equilibrium state would increase our understanding of the effect of interventions.

We have assumed a constant discharge equal to the one which causes the water level to be at the crests of the longitudinal training walls for studying the effect of the interventions. This can be understood as a morphodynamically representative or dominant discharge (Jansen *et al.*, 1979; Blom *et al.*, 2017). Although reasonable, we have not considered the probability distribution of the water discharge for computing the representative discharge. This would yield more accurate results. Nevertheless, given the uncertainty in the results, it does not add substantial information to the overview of the morphodynamic effects. More importantly, the equilibrium state under variable flow presents several complexities (Arkesteijn *et al.*, 2019) such as, for instance, the fact that downstream from the changes in channel properties, a hydrograph boundary layer forms, where the bed oscillates around a mean state (i.e., a dynamic equilibrium state).

The relative contribution of each component varies with the discharge. For instance, the effect of a friction reduction applies under flood conditions only while channel narrowing may be more relevant under low-flow conditions. None of these complexities are captured in the simplified analysis we have conducted.

As regards to the water extraction, it has been assumed that water is extracted at one location and enters the main channel at a location downstream of it. Apart from the fact that for submerged longitudinal training walls this approximation is questionable, the longitudinal training walls are permeable and have openings, which causes flow through the walls even under low-flow conditions.

We have assumed a constant value of parameter m in the Engelund and Hansen (1967) equation. A detailed analysis would consider the fact that it depends on friction. Nevertheless, the consequence of such a detail is negligible compared to the fact that the sediment transport rate as computed using such a closure relation without calibration can only be considered a first-order approximation. Moreover, we have assumed uniform sediment. Thus, none of the mixed-size sediment effects that can increase or decrease changes in bed level have been considered. We would expect, for instance, sorting between the sediment transferred to the auxiliary channel and the one that remains in the main channel. Due to the sill (*drempel*) at the entrance of the auxiliary channel, a larger fraction of fine sediment transported in the upper flow layers may be transported to the side channel compared to the coarsest fractions transported close to the bed. This would cause coarsening of the main channel. Depending on the relative coarsening compared to the overall loss of sediment to the auxiliary channel, the main channel would aggrade or degrade with respect to a unisize case.

The sediment extraction accounting for the sediment transported within the auxiliary channel has been assumed to be constant with time. This is far from realistic, as the side channel experiences morphodynamic changes too. Depending on the sediment and water partitioning, the bifurcation may be stable or unstable (Wang *et al.*, 1995; Le *et al.*, 2018a; van Denderen *et al.*, 2018; Schielen and Blom, 2018). If unstable, one of the branches will eventually close off, which means that eventually all the flow and sediment will be transported by the other branch.

The narrowing of the main channel is introduced gradually: the first hundreds of metres (up to 1 km) the main channel river is gradually narrowed. So at the inlet of the Wamel channel the river is still wide and the extraction of water is expected to create a shallow section in the main channel.

There is a large variability in flood plain geometry along the length of the study section. Large pools and areas with low summer levees will attract more flood water than higher and rougher areas. During floods flows will pass the longitudinal training walls to enter and exit the flood plain. Hence, there are multiple and diffuse extraction and insertion locations contrary to the simplified approach in which there is only one pair.

Also, the cross-sectional area (i.e, width and depth) of the auxiliary channel is not constant along the length of the dams. Therefore, also during floods this may cause sideways in- and outflows passing over the longitudinal training walls. It is very well possible, because this extraction is at high elevation, that the flows passing the longitudinal training walls crest are relatively clear of sediment or contain only a part of the suspended sediment load. The relatively clear water can then contribute to erosion of the auxiliary channel. In case of such erosion, this channel becomes bigger, and attracts more water, further erodes, et cetera. This process of uncontrolled amplification of the auxiliary channel was observed in Delft3D simulations for longitudinal training walls in 2019 at the lower end of the Dreumel channel (RKM 917 - RKM 918.2) (Omer, 2019). Similarly to the previous paragraph this would require multiple diffuse insertions and extractions.

Finally, we have reduced the complex three-dimensional morphodynamic behaviour occurring at several length scales to a simplified large-scale one-dimensional analysis. This means that effects such as the change in bar pattern, dune height and shape, or secondary flow have been neglected.

B Vegetation development

In this section we show the satellite images showing vegetation development in the middle part of the longitudinal training wall at Wamel.

Figure B.88 Satellite image of middle part of the longitudinal training wall at Wamel in 2016.

Figure B.89 Satellite image of middle part of the longitudinal training wall at Wamel in 2018.

Figure B.90 Satellite image of middle part of the longitudinal training wall at Wamel in 2019.

Figure B.91 Satellite image of middle part of the longitudinal training wall at Wamel in 2020.

C Results of the numerical simulations

C.1 Case without longitudinal training walls

C.1.1 With dredging

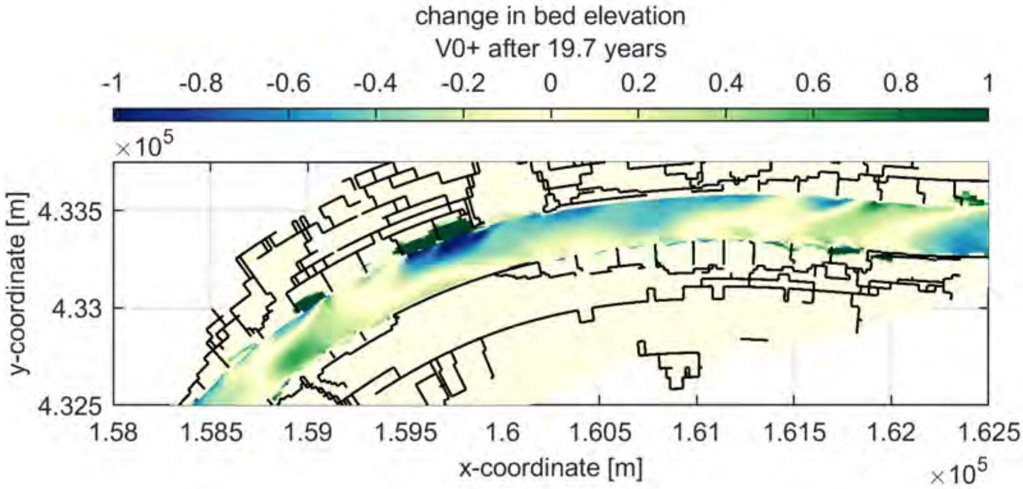

Figure C.92 Change in bed elevation at Wamel after the last high flow event for the case without longitudinal training walls with dredging.

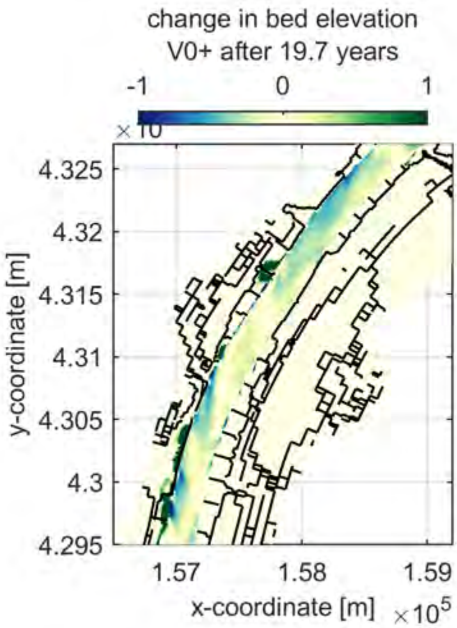

Figure C.93 Change in bed elevation at Dreumel after the last high flow event for the case without longitudinal training walls with dredging.

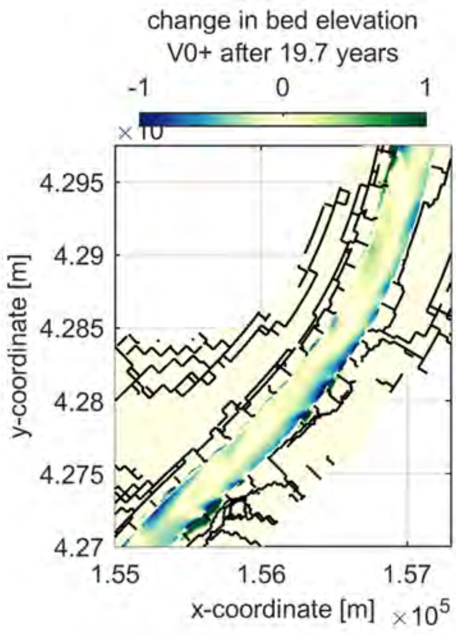

Figure C.94 Change in bed elevation at Ophemert after the last high flow event for the case without longitudinal training walls with dredging.

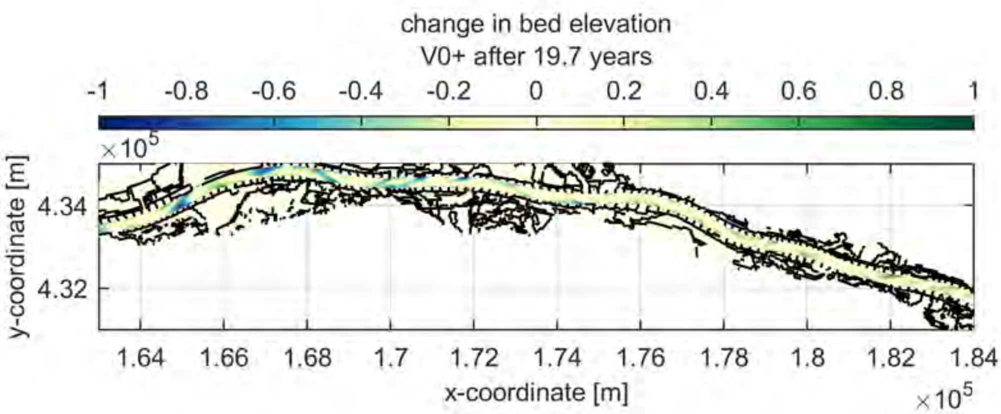

Figure C.95 Change in bed elevation upstream from Wamel after the last high flow event for the case without longitudinal training walls with dredging.

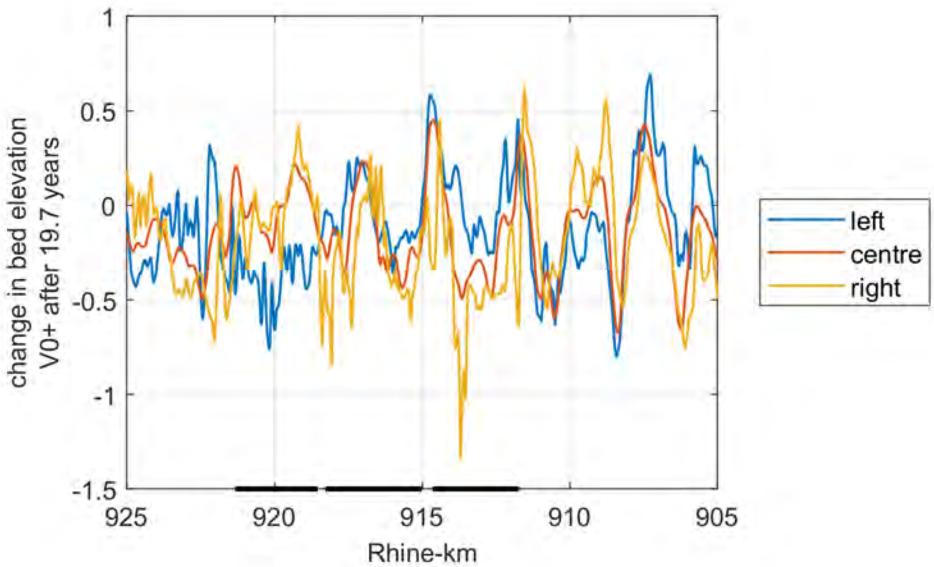

Figure C.96 Longitudinal profile of the change in bed elevation after the last high flow event for the case without longitudinal training walls with dredging.

C.1.2 Without dredging

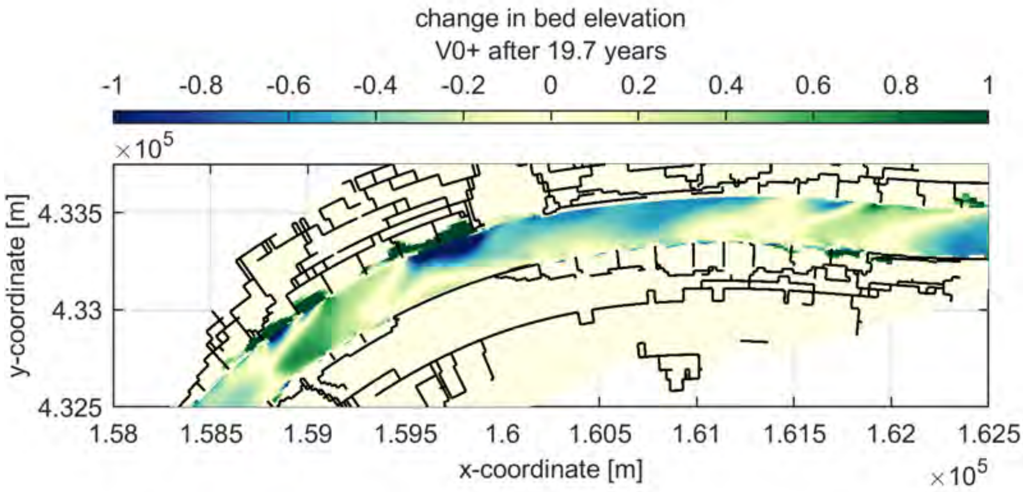

Figure C.97 Change in bed elevation at Wamel after the last high flow event for the case without longitudinal training walls without dredging.

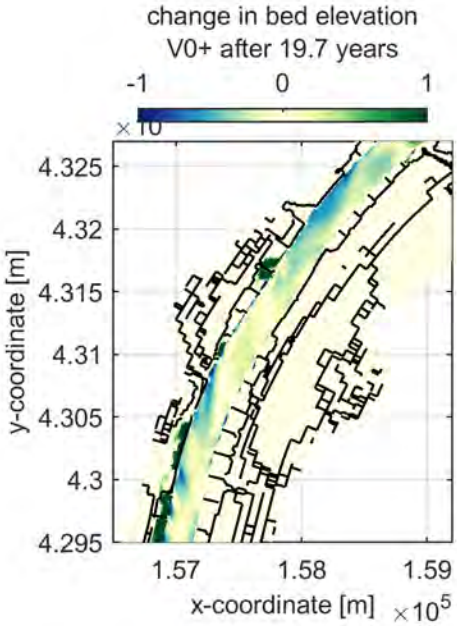

Figure C.98 Change in bed elevation at Dreumel after the last high flow event for the case without longitudinal training walls without dredging.

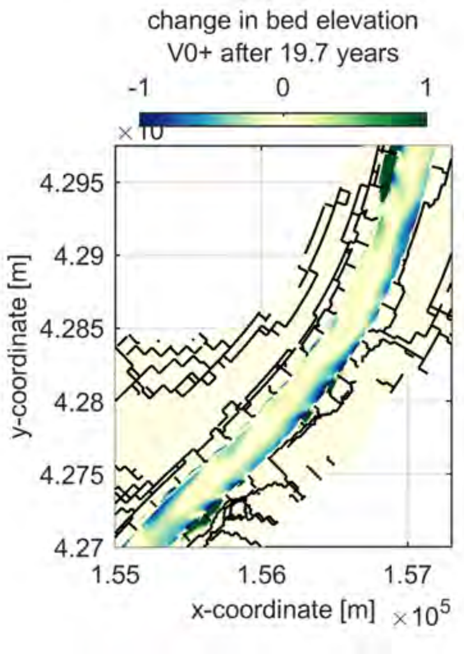

Figure C.99 Change in bed elevation at Ophemert after the last high flow event for the case without longitudinal training walls without dredging.

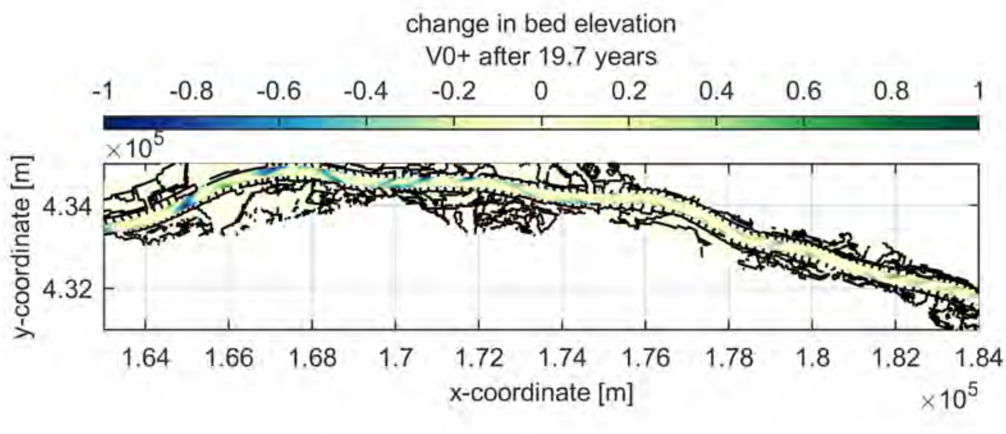

Figure C.100 Change in bed elevation upstream from Wamel after the last high flow event for the case without longitudinal training walls without dredging.

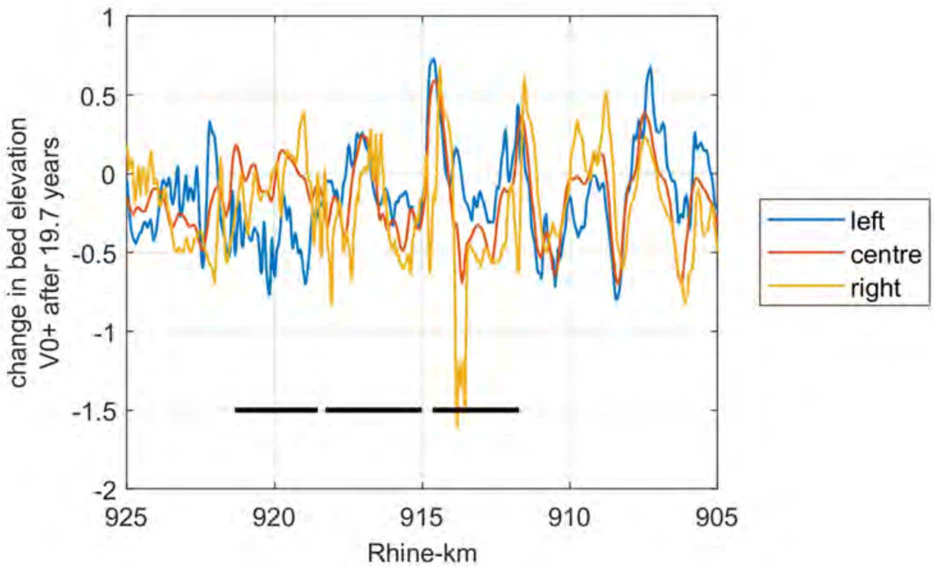

Figure C.101 Longitudinal profile of the change in bed elevation after the last high flow event for the case without longitudinal training walls without dredging.

C.2 Case with as-built longitudinal training walls

C.2.1 With dredging

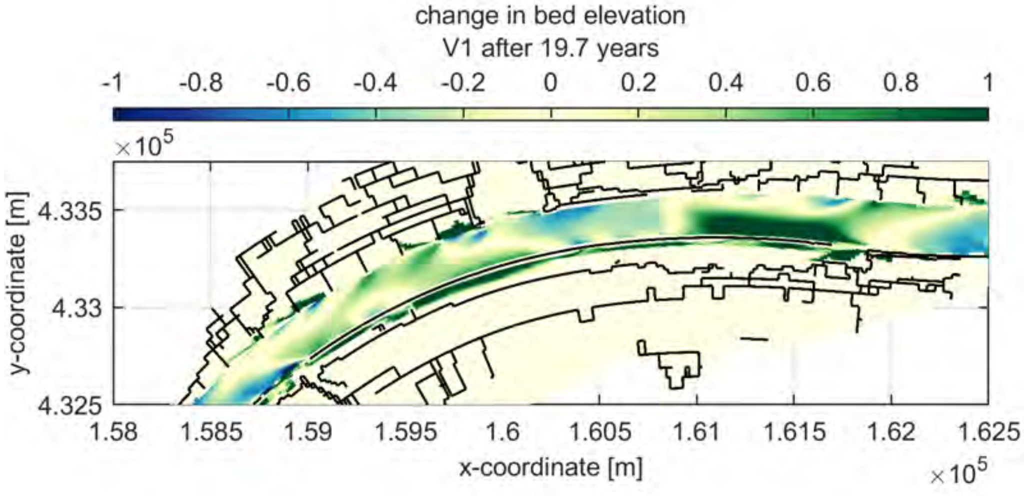

Figure C.102 Change in bed elevation at Wamel after the last high flow event for the case with as-built longitudinal training walls with dredging.

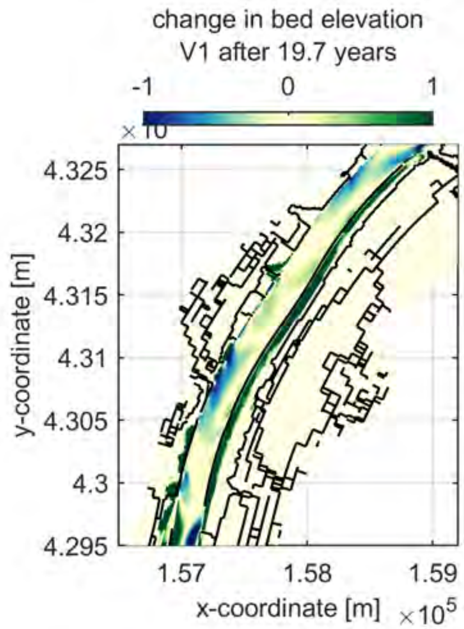

Figure C.103 Change in bed elevation at Dreumel after the last high flow event for the case with as-built longitudinal training walls with dredging.

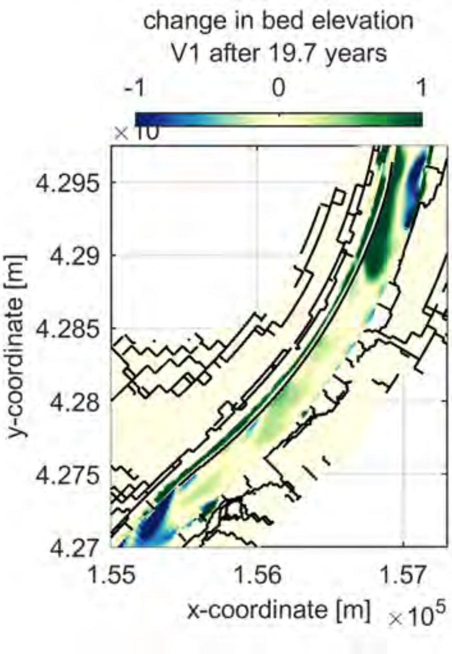

Figure C.104 Change in bed elevation at Ophemert after the last high flow event for the case with as-built longitudinal training walls with dredging.

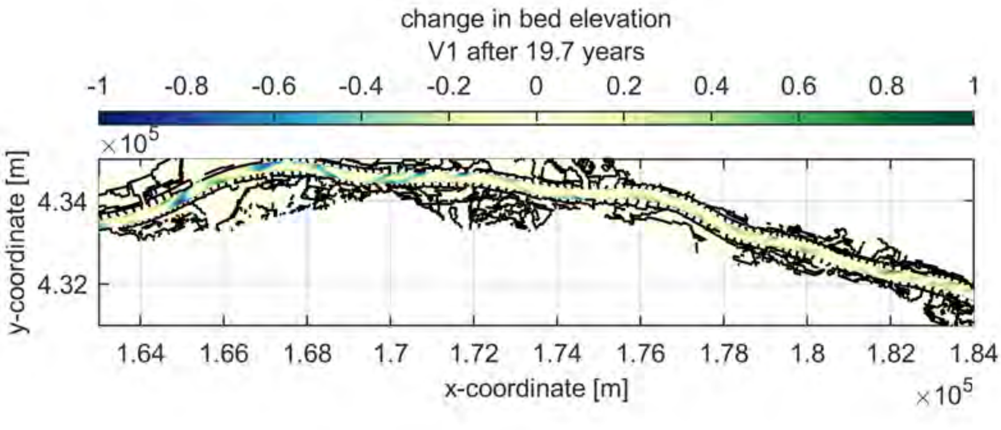

Figure C.105 Change in bed elevation upstream from Wamel after the last high flow event for the case with as-built longitudinal training walls with dredging.

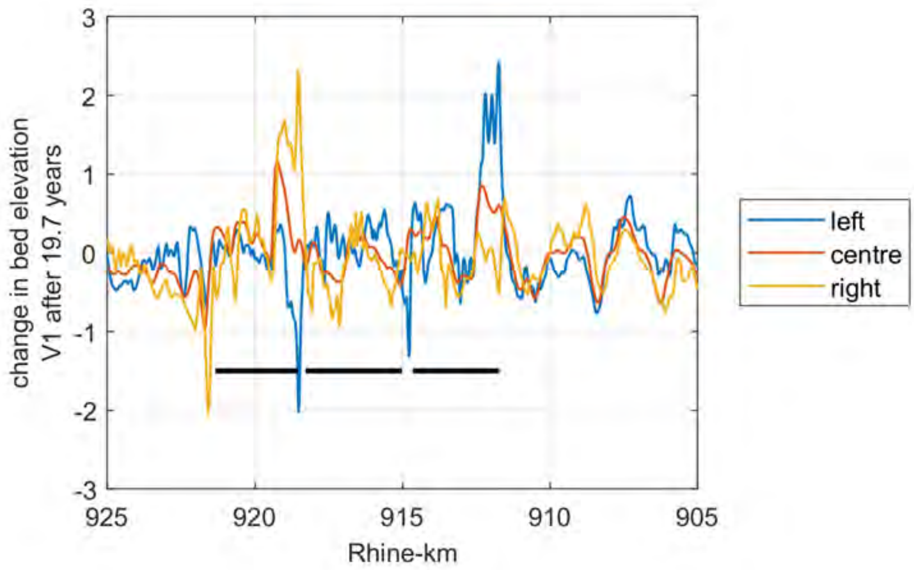

Figure C.106 Longitudinal profile of the change in bed elevation after the last high flow event for the case with as-built longitudinal training walls with dredging.

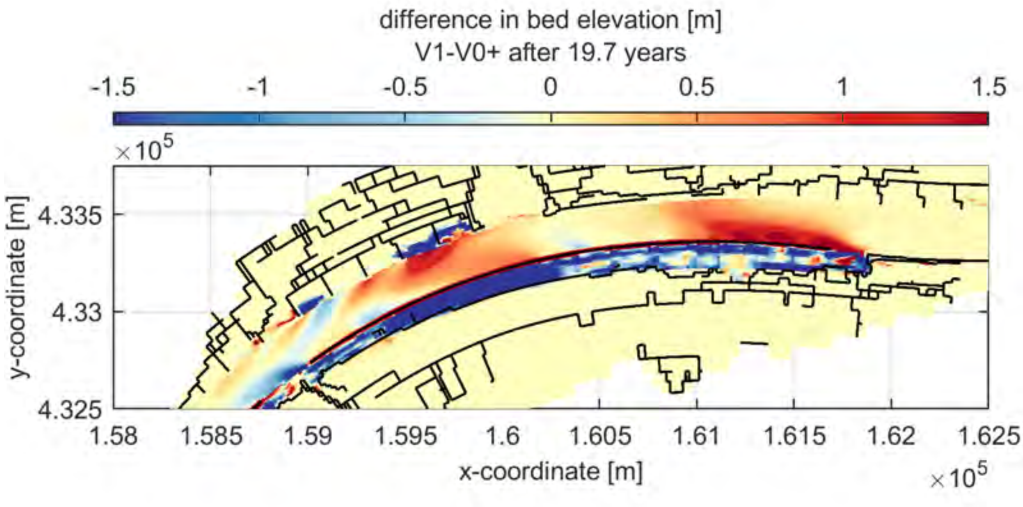

Figure C.107 Difference in bed elevation at Wamel after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls with dredging.

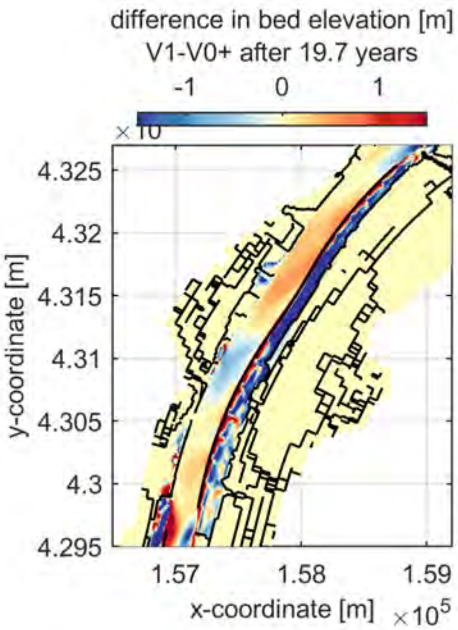

Figure C.108 Difference in bed elevation at Dreumel after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls with dredging.

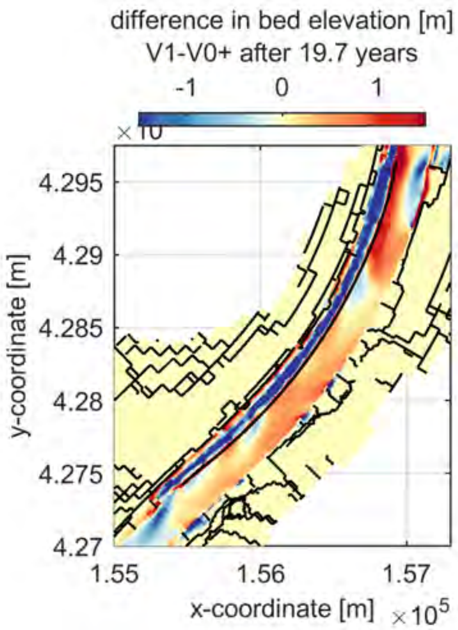

Figure C.109 Difference in bed elevation at Ophemert after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls with dredging.

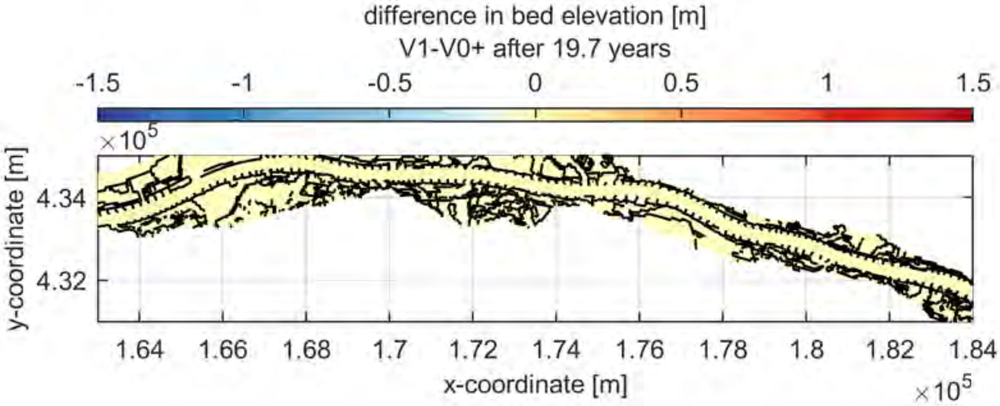

Figure C.110 Difference in bed elevation upstream from Wamel after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls with dredging.

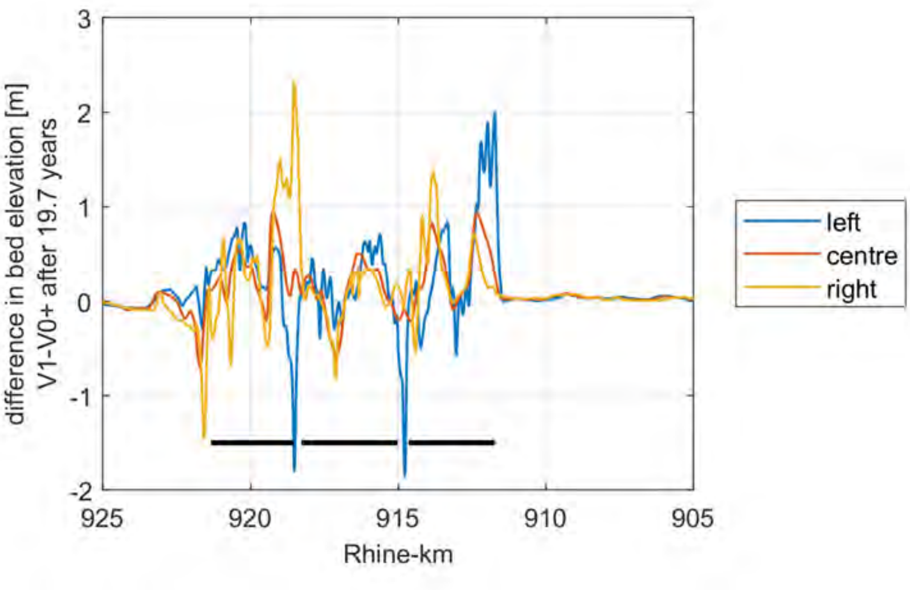

Figure C.111 Longitudinal profile of the difference in bed elevation after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls with dredging.

C.2.2 Without dredging

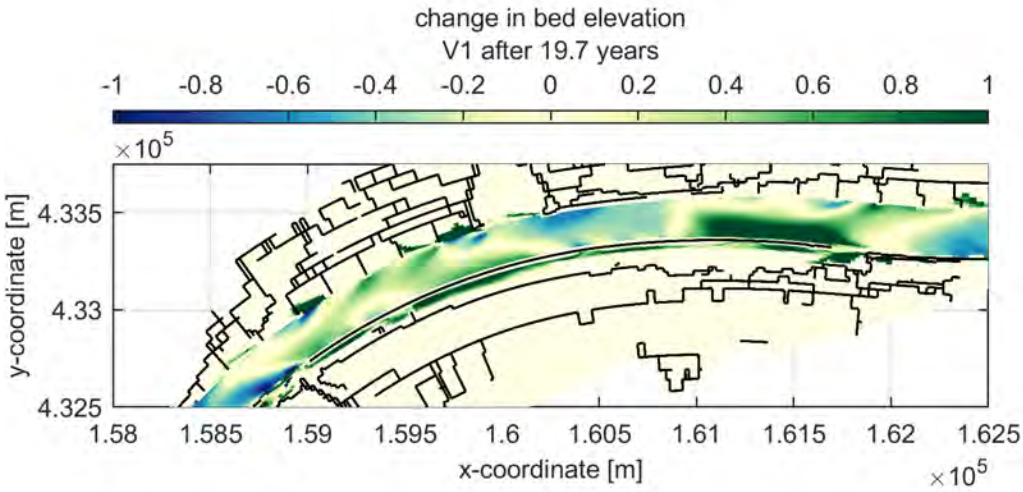

Figure C.112 Change in bed elevation at Wamel after the last high flow event for the case with as-built longitudinal training walls without dredging.

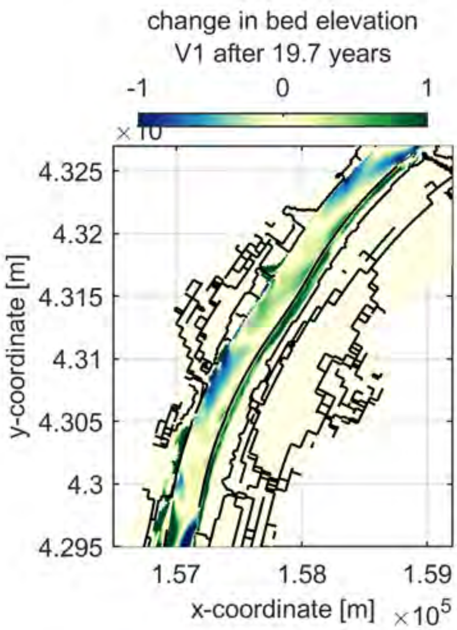

Figure C.113 Change in bed elevation at Dreumel after the last high flow event for the case with as-built longitudinal training walls without dredging.

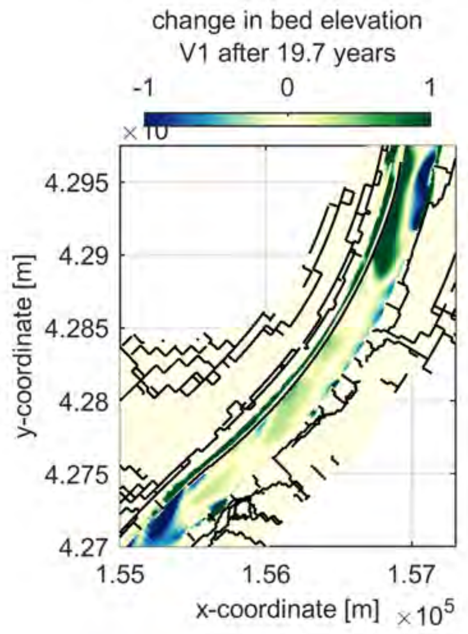

Figure C.114 Change in bed elevation at Ophemert after the last high flow event for the case with as-built longitudinal training walls without dredging.

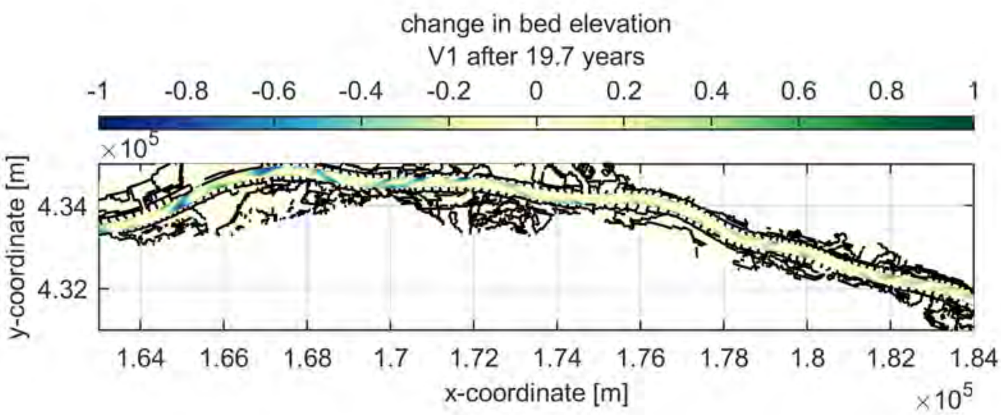

Figure C.115 Change in bed elevation upstream from Wamel after the last high flow event for the case with as-built longitudinal training walls without dredging.

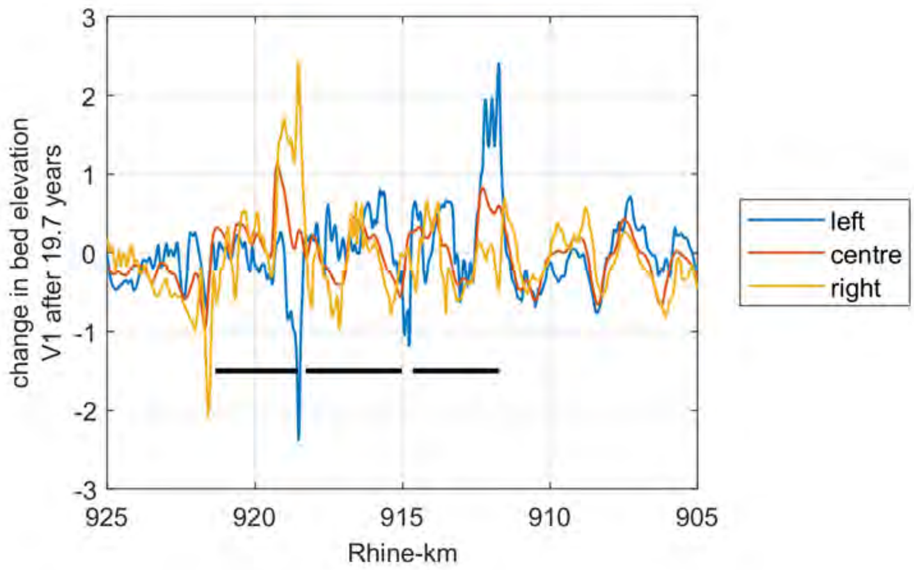

Figure C.116 Longitudinal profile of the change in bed elevation after the last high flow event for the case with as-built longitudinal training walls without dredging.

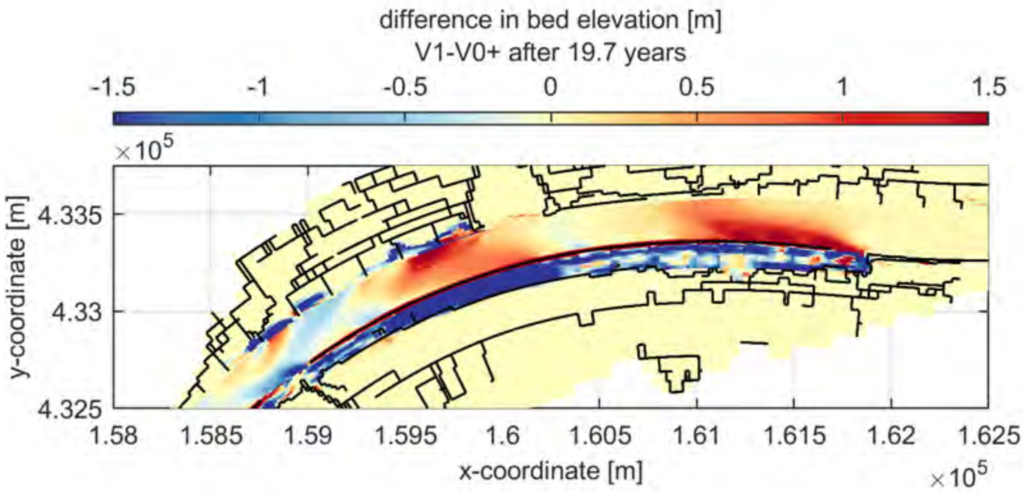

Figure C.117 Difference in bed elevation at Wamel after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls without dredging.

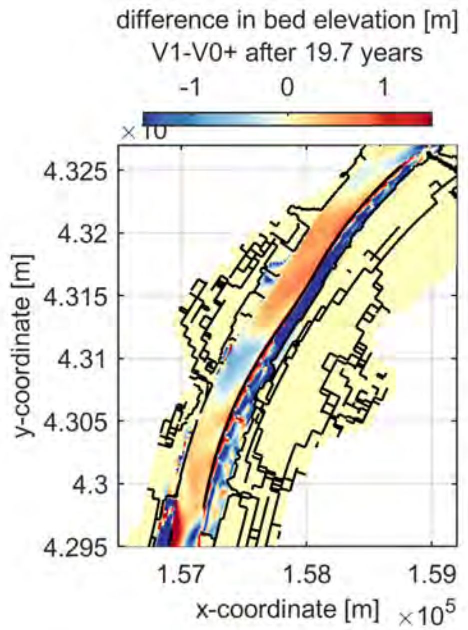

Figure C.118 Difference in bed elevation at Dreumel after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls without dredging.

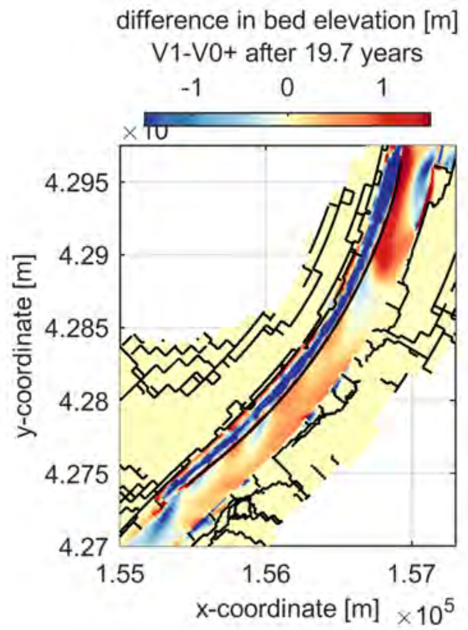

Figure C.119 Difference in bed elevation at Ophemert after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls without dredging.

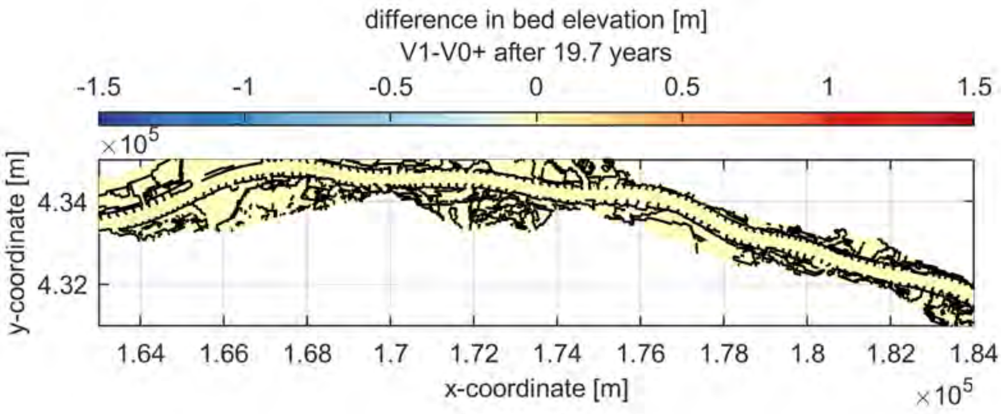

Figure C.120 Difference in bed elevation upstream from Wamel after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls without dredging.

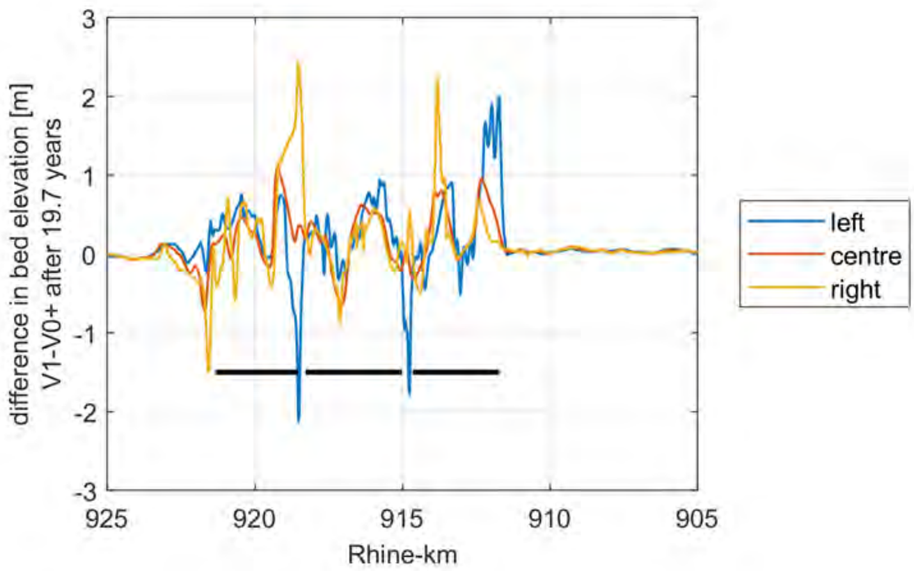

Figure C.121 Longitudinal profile of the difference in bed elevation after the last high flow event between the case with as-built longitudinal training walls and the case without longitudinal training walls without dredging.

C.3 Case with longitudinal training walls with closed sills

C.3.1 With dredging

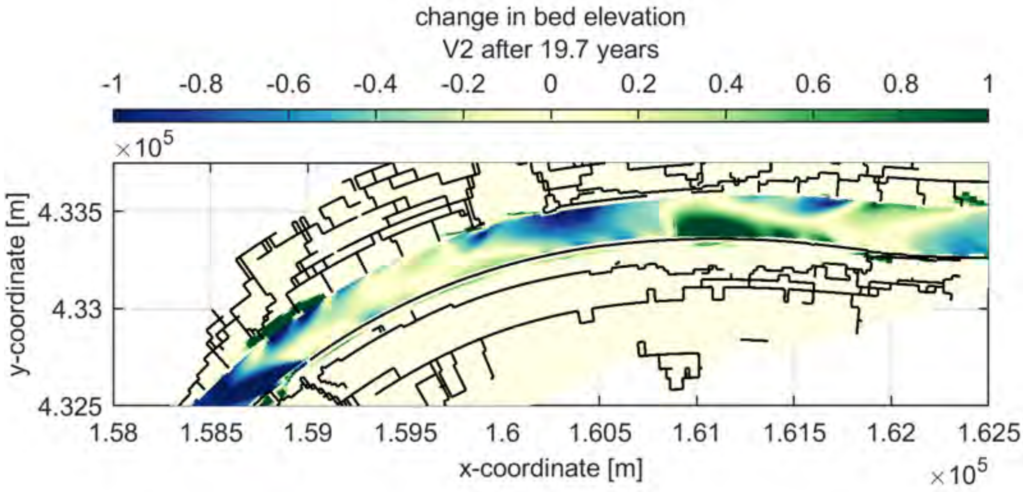

Figure C.122 Change in bed elevation at Wamel after the last high flow event for the case with longitudinal training walls with closed sills with dredging.

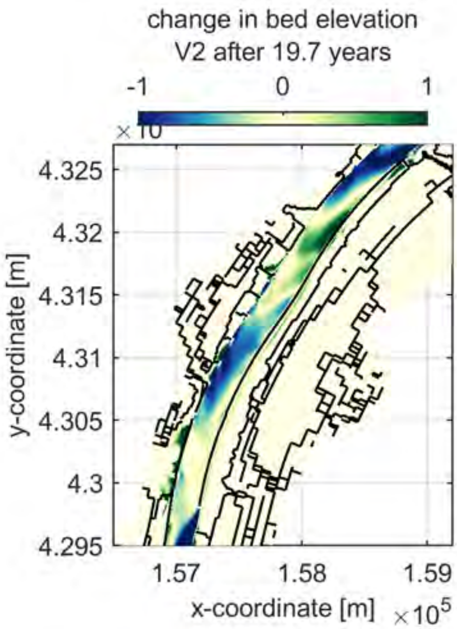

Figure C.123 Change in bed elevation at Dreumel after the last high flow event for the case with longitudinal training walls with closed sills with dredging.

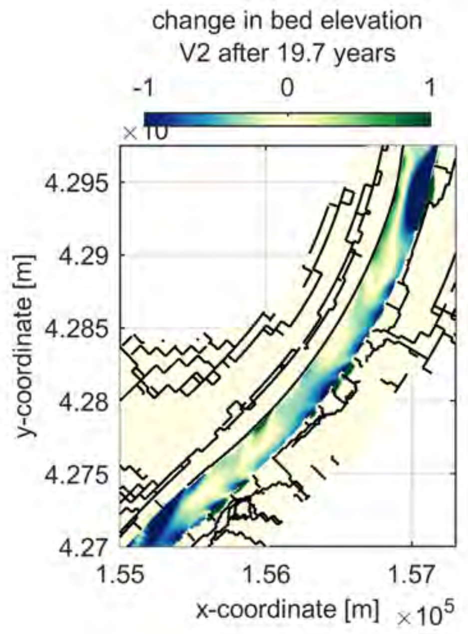

Figure C.124 Change in bed elevation at Ophemert after the last high flow event for the case with longitudinal training walls with closed sills with dredging.

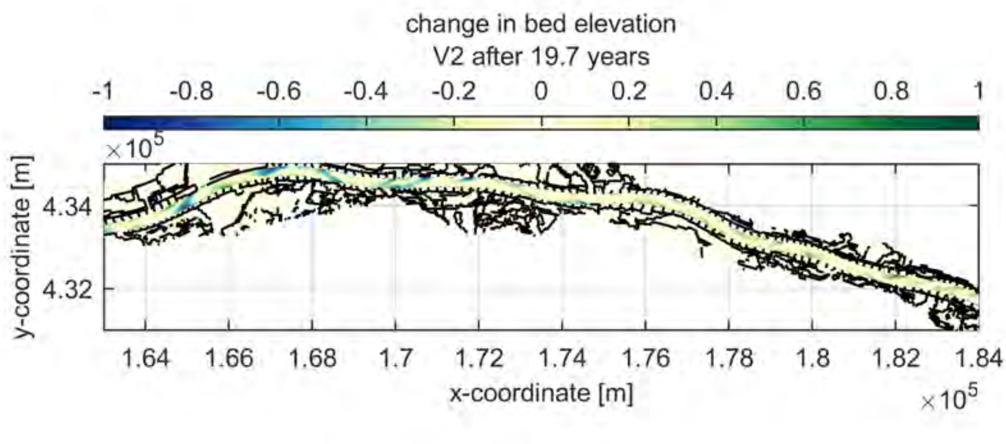

Figure C.125 Change in bed elevation upstream from Wamel after the last high flow event for the case with longitudinal training walls with closed sills with dredging.

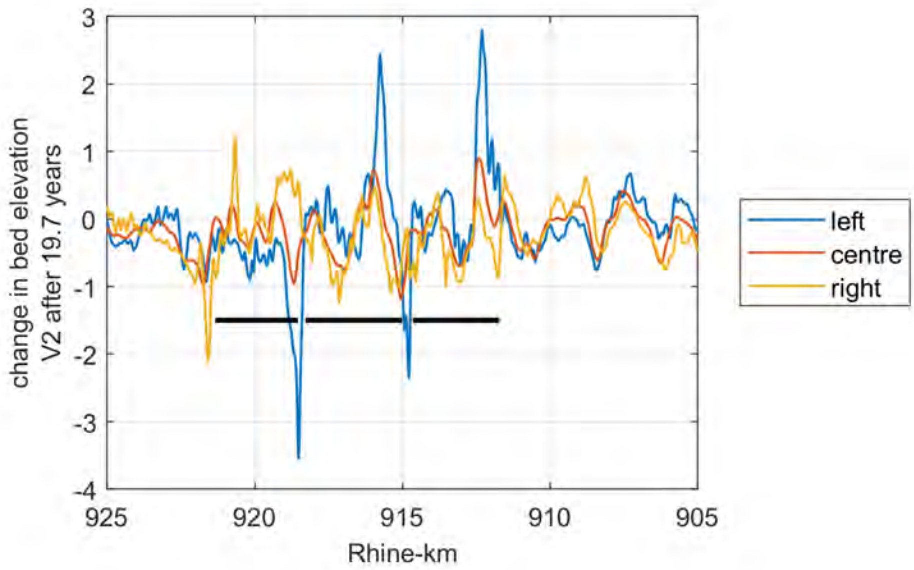

Figure C.126 Longitudinal profile of the change in bed elevation after the last high flow event for the case with longitudinal training walls with closed sills with dredging.

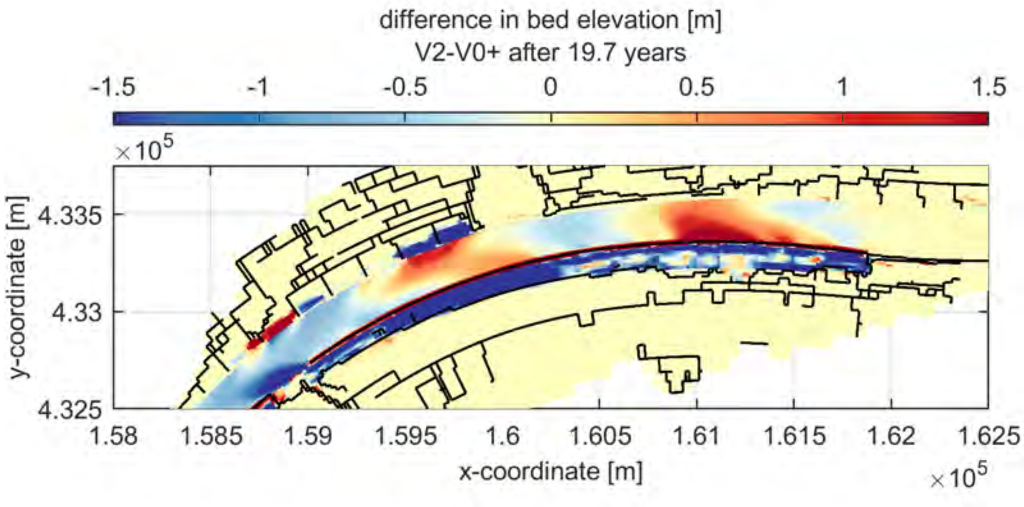

Figure C.127 Difference in bed elevation at Wamel after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls with dredging.

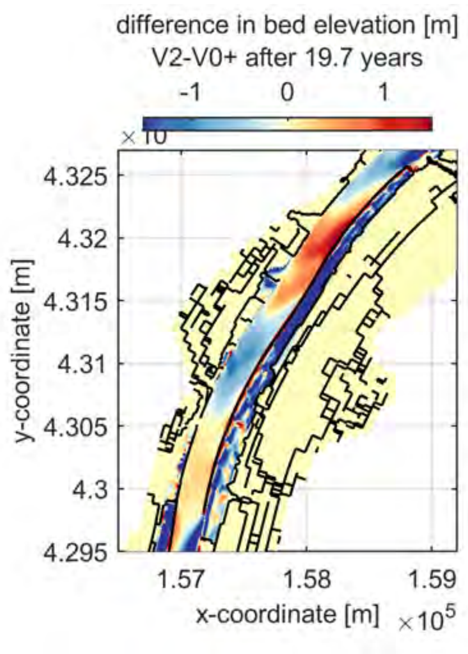

Figure C.128 Difference in bed elevation at Dreumel after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls with dredging.

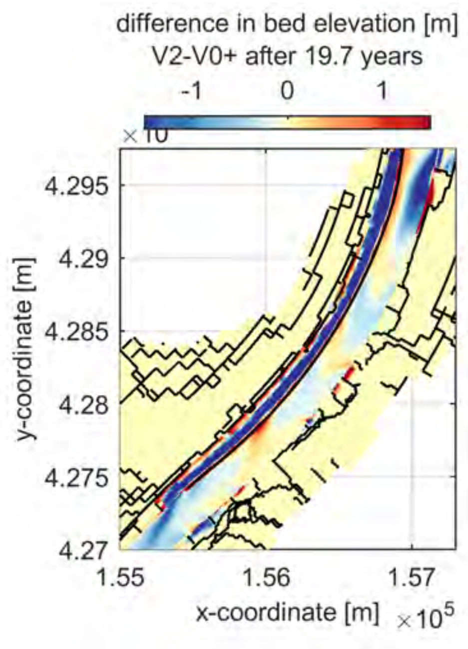

Figure C.129 Difference in bed elevation at Ophemert after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls with dredging.

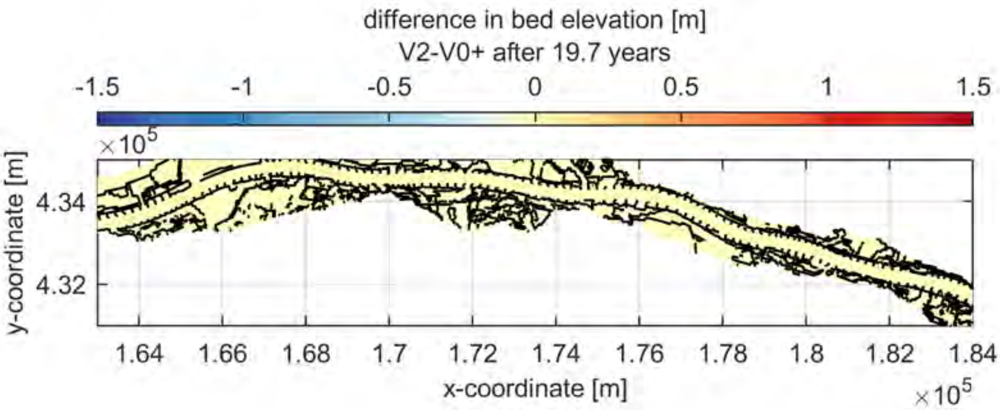

Figure C.130 Difference in bed elevation upstream from Wamel after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls with dredging.

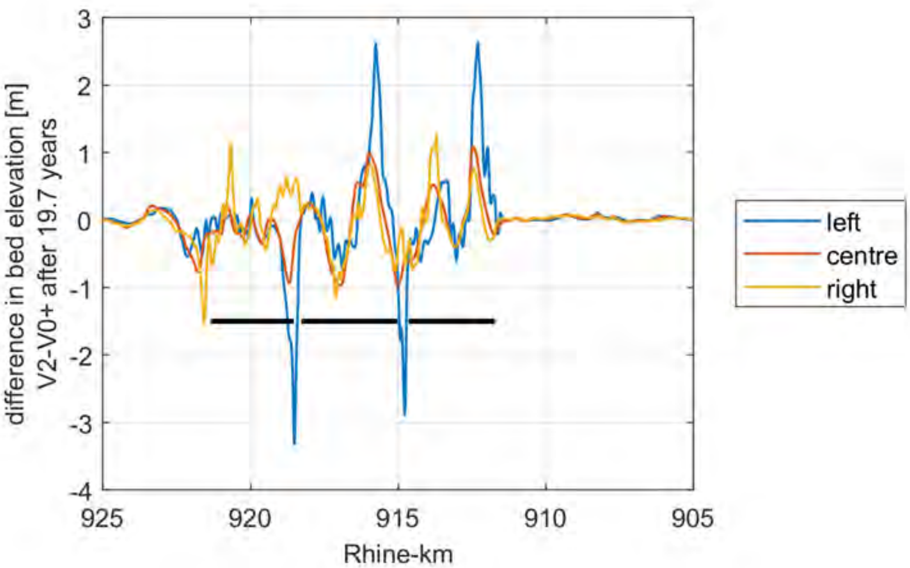

Figure C.131 Longitudinal profile of the difference in bed elevation after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls with dredging.

C.3.2 Without dredging

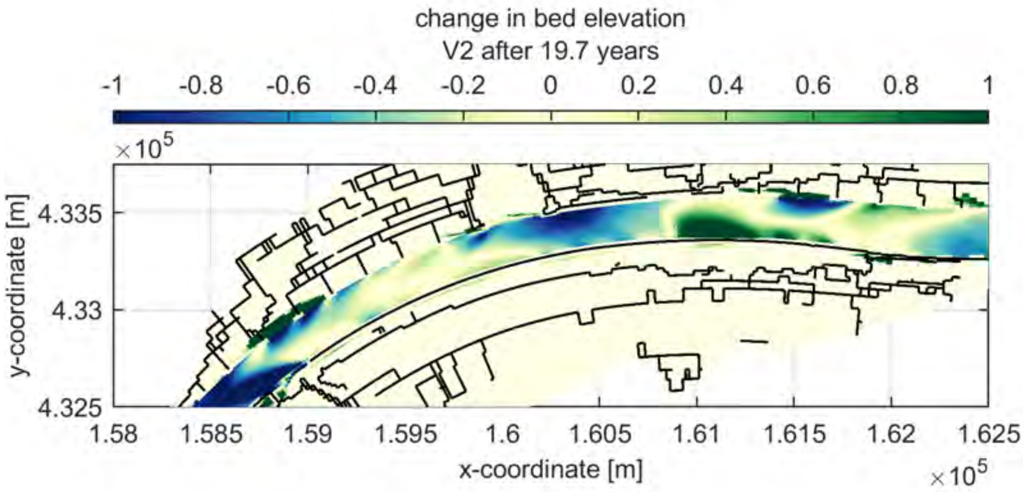

Figure C.132 Change in bed elevation at Wamel after the last high flow event for the case with longitudinal training walls with closed sills without dredging.

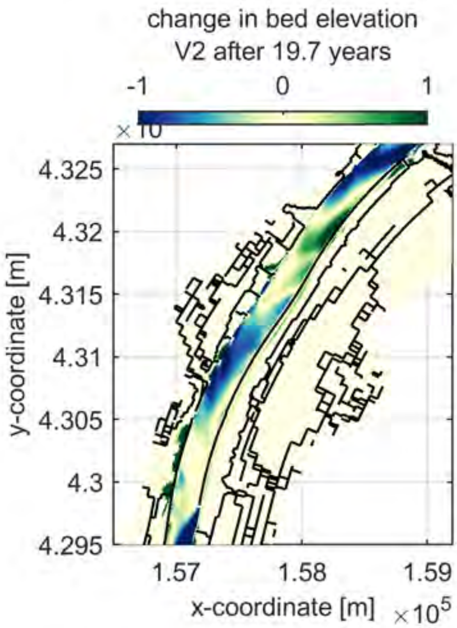

Figure C.133 Change in bed elevation at Dreumel after the last high flow event for the case with longitudinal training walls with closed sills without dredging.

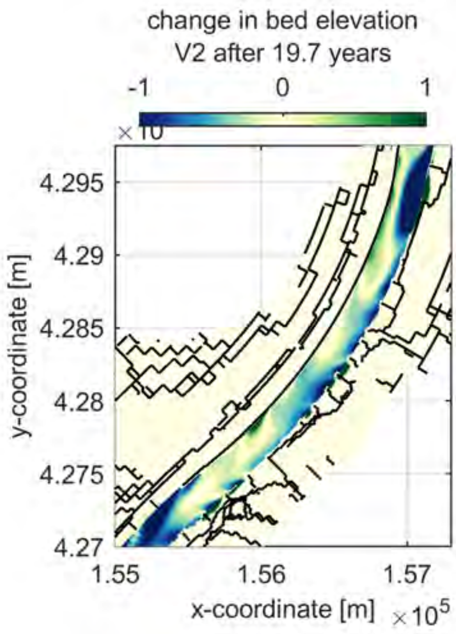

Figure C.134 Change in bed elevation at Ophemert after the last high flow event for the case with longitudinal training walls with closed sills without dredging.

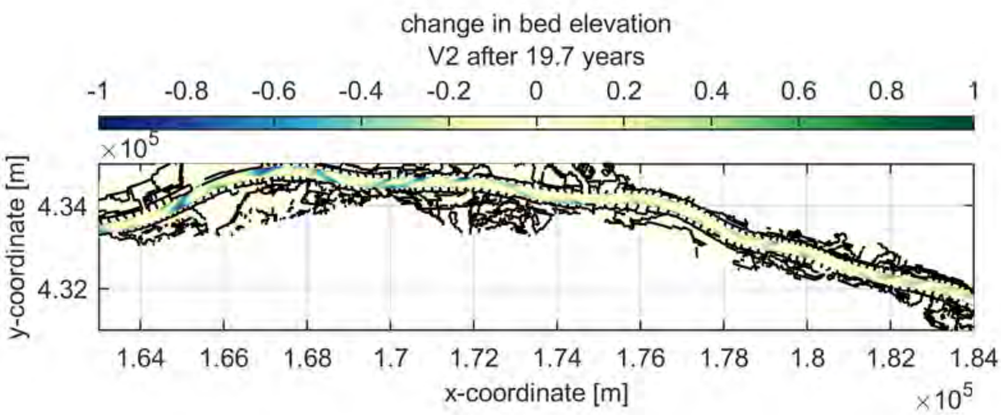

Figure C.135 Change in bed elevation upstream from Wamel after the last high flow event for the case with longitudinal training walls with closed sills without dredging.

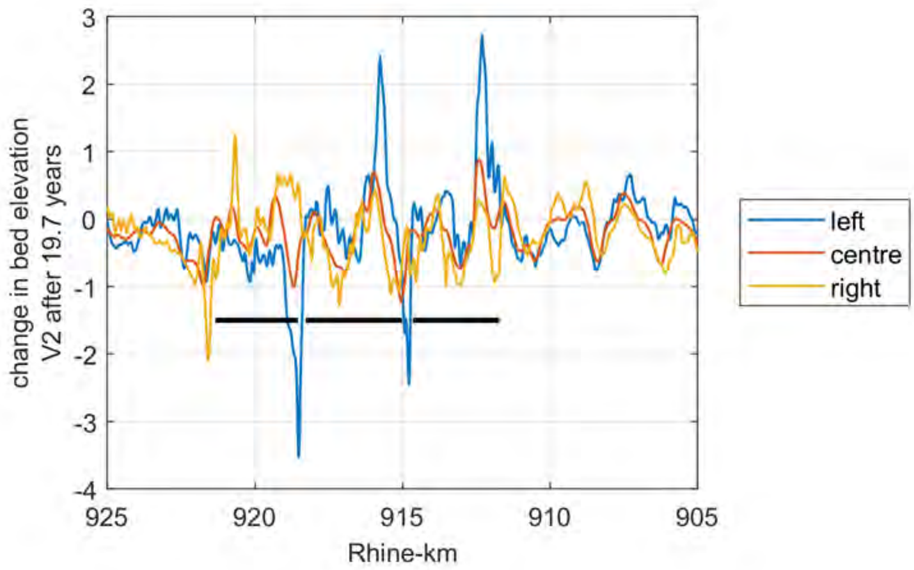

Figure C.136 Longitudinal profile of the change in bed elevation after the last high flow event for the case with longitudinal training walls with closed sills without dredging.

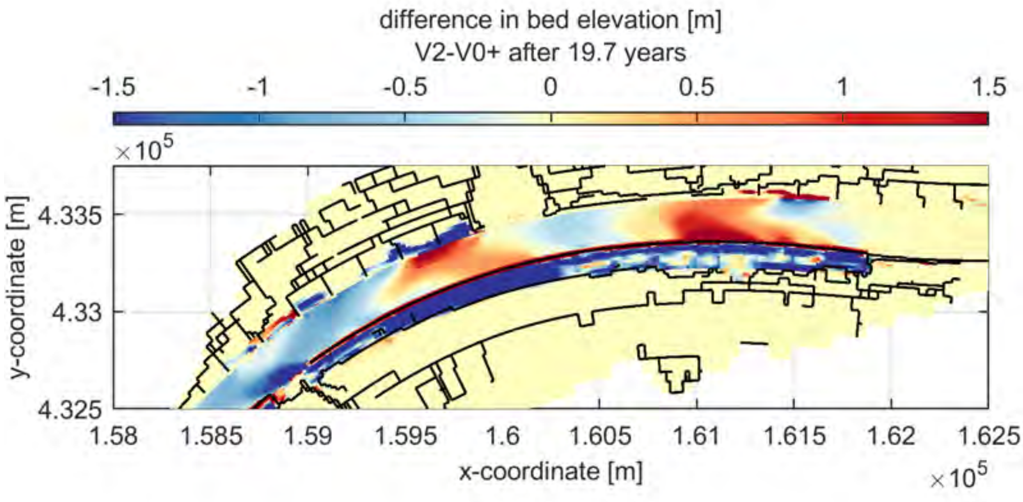

Figure C.137 Difference in bed elevation at Wamel after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls without dredging.

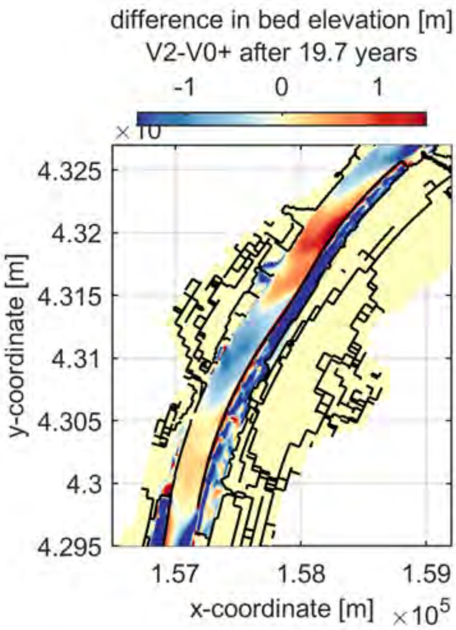

Figure C.138 Difference in bed elevation at Dreumel after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls without dredging.

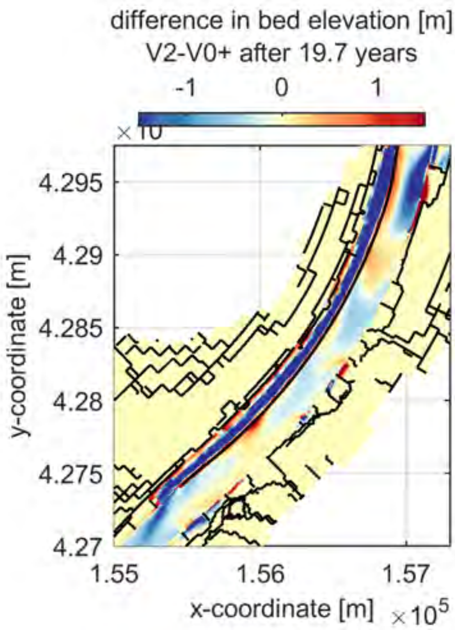

Figure C.139 Difference in bed elevation at Ophemert after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls without dredging.

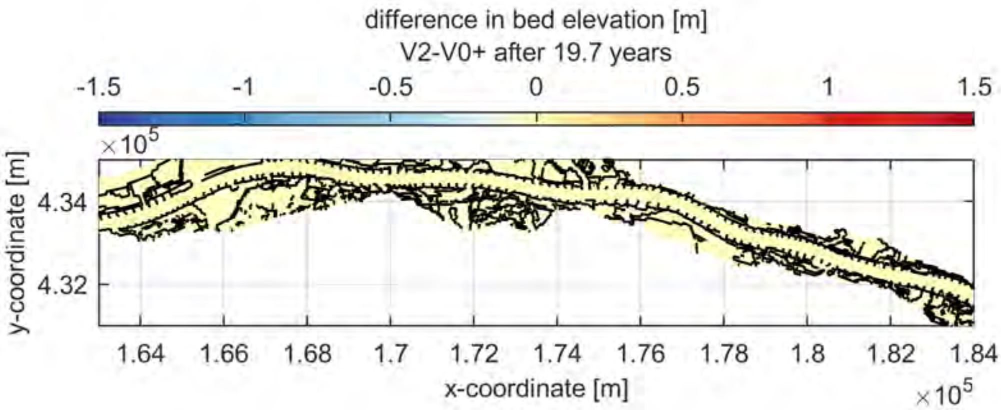

Figure C.140 Difference in bed elevation upstream from Wamel after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls without dredging.

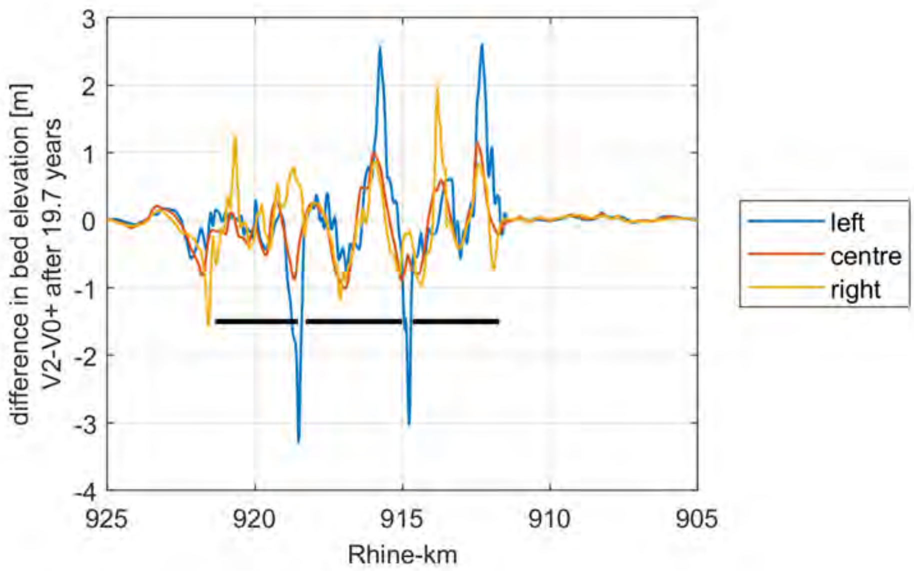

Figure C.141 Longitudinal profile of the difference in bed elevation after the last high flow event between the case with longitudinal training walls with closed sills and the case without longitudinal training walls without dredging.