Mitigating the gradual change in discharge partitioning at the Pannerdense Kop bifurcation

MSc Thesis

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Master Thesis

Mitigating the gradual change in water partitioning at the Pannerdense Kop bifurcation

By

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in partial fulfilment of the requirements for the degree of

Master of Science
in Civil Engineering - Hydraulic Engineering

at the Delft University of Technology,

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Ministerie van Infrastructuur en Waterstaat

Preface

This thesis is the final requirement for the degree of Master of Science in Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences of Delft University of Technology. For the past months I studied the morphological effects on the main channel of the Dutch Rhine river system and the effects on the discharge partitioning at the Pannerdense Kop of several interventions.

This study is conducted at Rijkswaterstaat. I want to thank Ralph Schielen for giving me the opportunity to execute this research at Rijkswaterstaat. As my daily supervisor he was always available for questions and our meetings really helped me find my way throughout the project.

I would also like to thank Pepijn van Denderen who was a member of my assessment committee. He was interested in the project and was always prepared to help. Our meetings resulted in new helpful insights.

Next, I would like to thank Astrid Blom who was the chair of the assessment committee and the committee members Kifayath Chowdhury and Matthijs Kok. Thank you for your expertise and your critical remarks throughout my thesis.

Furthermore, I would like to thank Birgit de Lange and Eki Liptiay for helping me with the model whenever I got stuck. Lastly, I would like to thank Victor Chavarrías and his colleagues at Deltares who developed the model that I used for my research. They helped me to understand the model and provided me with answers to my questions.

Siebe van den Brand
Teeffelen, March 2024

Summary

It is observed that the bed level development of the Pannerden Canal (PC) and the Waal changed since the peak flows of 1993, 1995 and 1998. Sediment deposited during the peak flows caused the river bed in the Pannerden Canal just downstream of the bifurcation to increase suddenly. Also, the erosion rate of the Pannerden Canal decreased greatly just downstream of the bifurcation to a value of approximately 0.7 cm/year while the erosion rate of the Waal stayed more or less constant. Since the water level at the bifurcation is continuous, this leads to an increasing depth of the Waal relative to the Pannerden Canal and therefore the Waal attracts more discharge.

The model results from this study confirm that without anthropogenic interventions in the future, the erosion speed upstream in the Waal stays larger than the erosion speed upstream in the PC and that therefore also the Waal discharge fraction keeps increasing. The shift in discharge partitioning towards the Waal is an undesired development of the system as for low flows the decreased discharge on the PC, Nederrijn-Lek (NR-Lek) and IJssel can cause problems for navigability and ecology. Also, for low and middle discharges the supply of freshwater throughout the Netherlands becomes more challenging (Barneveld et al., 2022). For high flows the shift in discharge partitioning can become problematic for flood safety. Currently there is a lack of knowledge on how interventions can be used to mitigate the gradual change in discharge partitioning at the Pannerdense Kop (PK). This study aims at filling the knowledge gap by considering several interventions studying their effect on the discharge partitioning at the PK and on the Rhine branches surrounding the PK. The research question that is answered in this study is:

“To what extent can interventions be used to mitigate the change in discharge partitioning at the Pannerdense Kop bifurcation and what is their effect on the bed level of the Dutch Rhine branches?”

To answer the question, firstly an inventory of interventions which could possibly increase the Waal discharge fraction is made. Based on existing studies, a theoretical analysis of the initial and long-term response to the interventions and the grouping of interventions, a selection of interventions is made. The resulting interventions are: A) a side channel from the Boven-Rijn towards the PC, B) fully opening the weirs in the NR-Lek, C) widening on the IJssel, D) directly steering the sediment partitioning at the PK and E) dredging in the PC and dumping in the Waal. These interventions are implemented in a 1D-morphological model of the Dutch Rhine branches.

It is found that the side channel from the Boven-Rijn to the PC (A) is not capable of significantly influencing the discharge partitioning at the PK. The backwater effects due to the water addition counteract the added discharge to the PC.

Furthermore, it is found that for the low Lobith discharges opening the weirs in the NR-Lek (B) can reduce the Waal discharge fraction below the initial value from the reference case for the whole simulated period of 60 years. The opening of the weirs does however lead to significant relative decrease in the IJssel discharge fraction which is unwanted regarding the freshwater supply of the IJsselmeer. For low Lobith discharges the widening on the IJssel (C) initially leads to a significant reduction in Waal discharge fraction of 2.4%. The effectivity reduces throughout the simulation because of aggradation along the widened reach. For high flows the

opening of the weirs and the IJssel widening are less effective. The final relative Waal discharge fraction decrease is respectively 1.1% and 0.7%.

The results of the directly steering the sediment partitioning (D) are similar for high and low flows. The water level is not changed initially and therefore initially the discharge partitioning is not affected. Throughout the simulation the slope of the Waal adjusts to the increased sediment supply and the slope of the PC adjusts to the decreased sediment supply. The relative decrease in Waal discharge fraction reaches a maximum throughout the simulation after approximately 35 years for both high and low flows. For both flows the final relative decrease in Waal discharge fraction is 1.8%.

Dredging and dumping (E) shows similar effects on the bed level and discharge partitioning as steering the sediment partitioning at the PK. Dredging and dumping also does not alter the water level and the discharge partitioning initially. For dredging and dumping however the relative decrease in discharge partitioning does not reach a maximum since the relative bed level difference keeps lowering for the PC and increasing for the Waal throughout the simulation. The relative bed level increase of the Waal is somewhat higher for the dredging and dumping simulation than for the simulation in which the sediment partitioning at the PK is steered. Therefore also the relative decrease in Waal discharge fraction is higher with 2.4% for the low Lobith flows and 2.2% for the high Lobith flows.

Currently the IRM program aims at stopping further skewing of the discharge partitioning of the PK. None of the interventions from this study is capable of realising this on its own. Therefore multiple river interventions will have to be combined to be able to reach the ambitions of IRM. The knowledge on the effect of the interventions on the discharge partitioning at the PK and the bed levels of the Dutch Rhine branches can be used as a basis for further study towards to combined effects of river interventions on the bed level development of the Dutch Rhine branches and the discharge partitioning at the PK.

Contents

1 Introduction

In section 1.1 the context for this study is stated. In section 1.2 the problem which is addressed in this study and the knowledge gap regarding influencing the discharge partitioning are explained. The research objective and research questions can be found in section 1.3. The method is explained in section 1.4 and section 1.5 provides a reading guide for this report.

1.1 Context

Throughout the past river systems have been engineered in order to optimize the performance of the river system for the many different functions it has. Some of the main reasons for human interventions in the river system are protecting the hinterland from flooding, improving navigability of rivers, maintaining sufficient fresh water supply and providing opportunities for nature to thrive. In response to interventions in the river system, the characteristics of a river, such as its planform, width, slope and bed surface texture, can change towards a new equilibrium state (Blom et al., 2016; De Vriend, 2015). Here engineered river systems with fixed planform and width are considered. Engineered rivers can only change their slope and bed surface texture in response to interventions.

An example of a heavily engineered river system is the Rhine river system. The Dutch part of the Rhine river system and a small part of the German Rhine, extending approximately 50 km upstream from Lobith, will be considered in this study, see Figure 1.1. In the past centuries meander cut-offs and many river training works for flood protection and navigation have been carried out on the Rhine (Havinga, 2020; Visser, 2000; Van Til, 1979; Ylla Arbós et al., 2021). The rivers have been made shorter, straighter and narrower. This has led to a higher flow velocity and an increased sediment transport capacity in the Rhine. As a result the river is moving towards a situation in which it has a lower slope, as this suffices to transport the supplied sediment downstream (Blom et al., 2016; Blom et al., 2017a). In order to reach the equilibrium state, the channel bed started incising and this is still happening in the Dutch Rhine river branches (De Vriend, 2015; Frings et al., 2009; Quick et al., 2020; Ylla Arbós et al., 2021). Next to channel bed incision, the channel bed is also coarsening with time (Frings et al., 2009; Ylla Arbós et al., 2021). This is likely a result of the movement and flattening of the Rhine gravel-sand transition (GST) and the German sediment nourishments. It is hypothesised by Ylla Arbós et al. (2021) that the German sediment nourishments in the Niederrhein have sped up the movement and flattening of the Rhine GST.

Next to anthropogenic interventions in the river system, the Rhine river system is also influenced by climate change (IPCC, 2013; KNMI, 2015; Sperna Weiland et al., 2015). As a result of climate change the upstream and downstream boundary conditions will change (IPCC, 2013; KNMI, 2015; Sperna Weiland et al., 2015; Ylla Arbós et al., 2023). Different climate scenarios have been developed by the IPCC (2013) and the KNMI (2015) where the latter developed climate scenarios specifically for the Netherlands. For the different climate scenarios changes in climate variables such as temperature, precipitation and sea level are computed. Implications are that downstream the sea level will change and due to changes in precipitation the upstream hydrograph will change. The change in precipitation for the different climate scenario's has been translated to changes in future hydrographs for the Rhine river by Sperna Weiland et al. (2015) and Ylla Arbós et al. (2023). Also the grain-size specific sediment supply from upstream can change (Ylla Arbós et al., 2023).

Anthropogenic interventions and climate change can lead to changes in the discharge partitioning at bifurcations. The study area contains two bifurcations, the Pannerdense Kop and the IJsselkop. A bifurcation is the part of a river where the discharge and sediment are partitioned from the main branch into two separate branches. Whether the distribution of water and sediment discharge over the downstream branches changes in time depends on whether or not the bifurcation is in equilibrium. Theoretical studies about bifurcation stability show that, in simplified cases, equilibria exist for bifurcations in which the water and sediment discharge are equally distributed, unequally distributed or completely favored towards one branch where the other one is completely filled up with sediment (Bolla Pittaluga et al., 2003; Bolla Pittaluga et al., 2015; Schielen & Blom, 2018; Wang et al., 1995). Schielen & Blom (2018) showed that the initial conditions and pertubations thereof can determine to which equilibrium a bifurcation will develop. So for example, a change in water depths of the downstream branches at the bifurcation can lead to the development towards a new equilibrium where one of the branches might eventually close.

Bifurcations are important parts of the river system. In a treaty from the 18th century it is written that the Waal should accomodate approximately 2/3 of the water from the Boven-Rijn (Chowdhury et al., 2023). However, as explained above, the morphological equilibrium of bifurcations can shift which means that the discharge partitioning over the bifurcation starts changing (Bolla Pittaluga et al., 2003; Kleinhans et al., 2013; Wang et al., 1995). This can lead to unwanted effects as the safety of the structures in the downstream branch with the higher discharge can get in danger for too high discharges. Furthermore the low discharge in the other branch can cause hindrance for navigation and it can cause problems for freshwater supply and ecology. Bifurcation stability can be influenced by interventions in the river system which lead to morphological changes to the river. Morphological changes can lead to a shift in the bifurcation equilibrium (Bolla Pittaluga et al., 2003; Bolla Pittaluga et al., 2015; Schielen & Blom, 2018; Wang et al., 1995).

The ongoing bed degradation, due to the narrowing and straightening of the rivers, and climate change impact the functioning of the river system. After the peak flows of 1993 and 1995 the Dutch river management realized that the rivers were too narrow and that increasing the dike heights over and over again was not the best method to protect the hinterland from floods. Therefore the ‘Room for the River’ program was set up. More space for the rivers to flow has been created leading to lower water levels (van Vuren et al., 2015). Following the ‘Room for the River’ program the ‘Integrated River Management’(IRM) program was set up. The goal of the IRM program is to obtain future proof Meuse and Rhine river systems. This should be realized through integrated solutions which tackle multiple problems and take into account multiple functions of the river systems at the same time. One of the goals for the IRM program with respect to the bed level of the Rhine branches is to obtain a sufficiently stable and maintainable bed level which contributes to a proper water distribution across the Netherlands during low discharges (Ministerie van Infrastructuur en Waterstaat, 2023). It is not mentioned what the proper water distribution should be but by preventing further erosion of the Rhine branches the discharge partitioning at the bifurcation remains approximately equal to its current state. For high flows, the goal of IRM is to have sufficient capacity to deal with the more frequent high flows in the future (Ministerie van Infrastructuur en Waterstaat, 2023). The IRM program has amongst other things led to a study of the development of the Rhine and Meuse river systems (Klijn et al., 2022) and a report on possible policy options (Nota Realistische Beleidsopites).

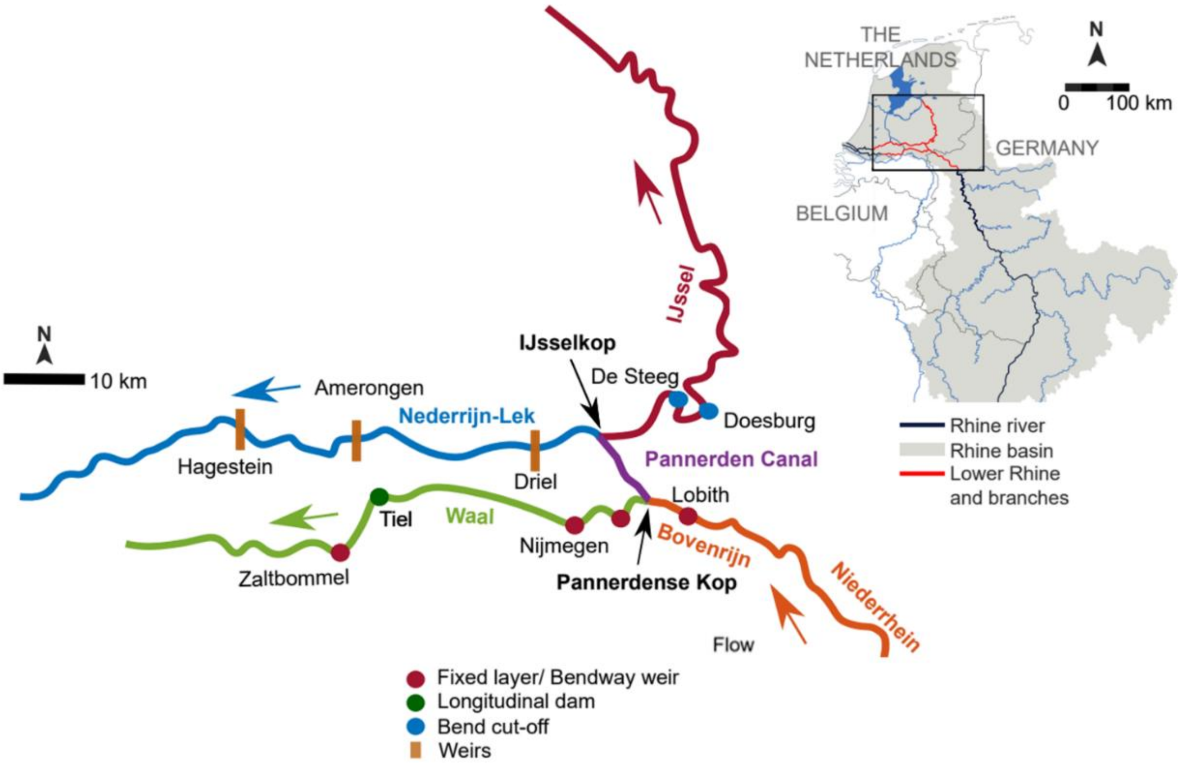

Figure 1.1: Study area containing the Dutch Rhine branches and a part of the German Rhine ((Chowdhury et al., 2023)

1.2 Problem analysis

It is observed that since the peak flows of 1993, 1995 and 1998 in the Rhine river system, the discharge partitioning over the Pannerdense Kop is shifting towards the Waal, see Figure 1.2 (Chowdhury et al., 2023). In Figure 1.2 the relative Waal discharge is shown in case the Driel weir is opened or closed. As can be seen in Figure 1.1, the Driel weir is the most upstream weir of the Nederrijn-Lek. For the closed Driel weir, the relative Waal discharge is higher than for the opened Driel weir, as a result of the backwater curve which arises when the Driel weir is closed. The weirs are necessary to direct more water towards the IJssel under low flow conditions.

The shift in discharge partitioning towards the Waal is an undesired development of the system as for low flows the decreased discharge on the Pannerden Canal, Nederrijn-Lek and IJssel can cause problems for navigability and ecology. Also, for low and middle discharges the supply of freshwater to the west through the Nederrijn-Lek, to the east through the Twentekanalen and to the largest freshwater buffer, the IJsselmeer, through the IJssel becomes more challenging (Barneveld et al., 2022). For high flows the shift in discharge partitioning can become problematic for flood safety. For extremely high flows the distribution of water over the Dutch Rhine branches is established in policy. Regulating structures at Pannerden and the IJsselkop exist to ensure the agreed discharge partitioning during extremely high flows. The regulating structure at Pannerden can be closed to limit the flow in the floodplains of the PC during high flow. Rozier and Asselman (2019) mention that research shows that almost the full control range of the regulating structures should be used to partition Boven-Rijn discharges of 16,000 and 18,000 m^3/s. The regulating structure at Pannerden should almost be completely open to attract more discharge towards the PC and minimize the diversion of discharge towards the

Waal through water level set-up as a result of the regulating structure. The shift in discharge partitioning could therefore become problematic in the future as more water is diverted towards the Waal and there is only limited control range to counter this shift in discharge partitioning to obtain the agreed discharge partitioning under high flow conditions.

The trend in discharge partitioning is a result of the changes in the river bed which have taken place since the peak flows. It is hypothesized that sediment deposited during the peak flows caused the river bed in the Pannerden Canal just downstream of the bifurcation to rise, see Figure 1.3 (Chowdhury et al., 2023). Also, the erosion rate of the Pannerden Canal decreased greatly just downstream of the bifurcation to a value of approximately 0.7 cm/year while the erosion rate of the Waal stayed more or less constant, see Figure 1.3 (Chowdhury et al., 2023). Since the water level at the bifurcation is continuous, this leads to an increasing depth of the Waal relative to the Pannerden Canal and therefore the Waal attracts more discharge.

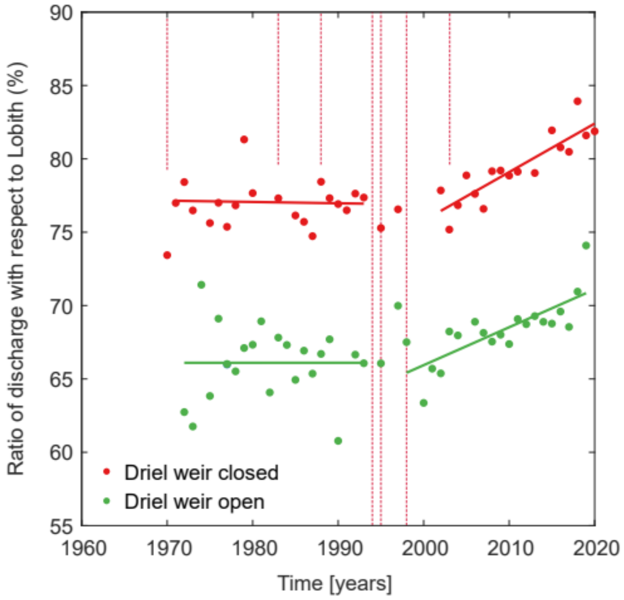

Figure 1.2: Relative discharge of the Waal with respect to the discharge at Lobith as a function of time. The vertical red dotted lines indicate the peak flows where the three full lines indicate the 1993, 1995 and 1998 peak flows (Chowdhury et al., 2023).

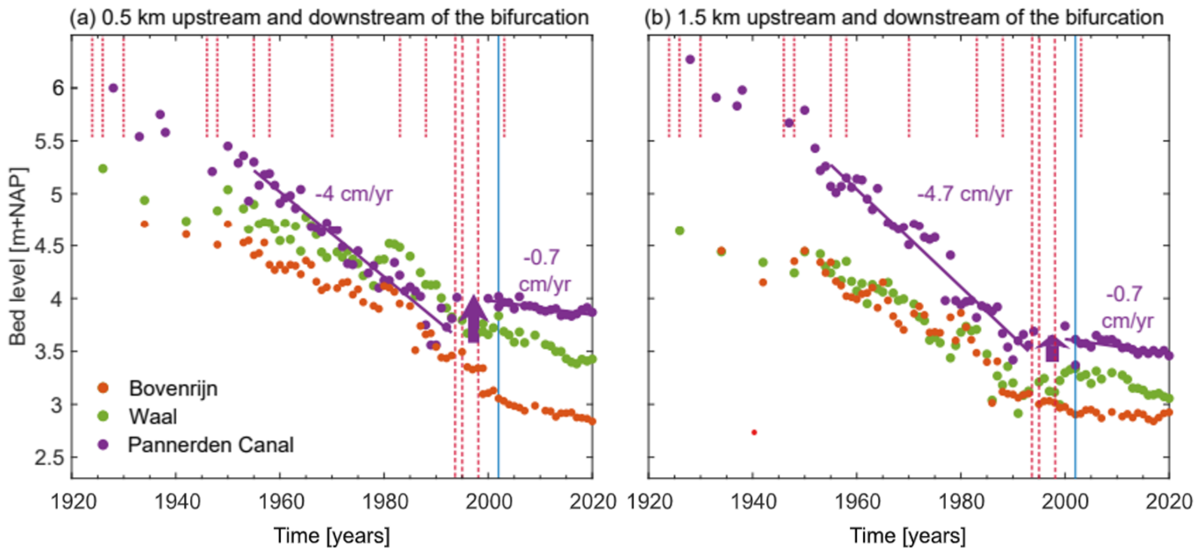

Figure 1.3: Bed level just upstream and downstream of the Pannerdense Kop bifurcation as a function of time. The red dotted vertical lines indicate peak flows. The full vertical lines indicate the peak flows of 1993, 1995 and 1998 (Chowdhury et al., 2023).

Two modelling studies of the Dutch Rhine branches provide insight into the future development of the discharge partitioning over the Pannerdense Kop. They show that the change in discharge partitioning keeps increasing slowly in favor of the Waal in the future (Asselman, et al., 2022; Paarlberg & Van Lente, 2021). Paarlberg and van Lente (2021) used the Rijntakken 1D morphological model developed by Deltares and showed that the Waal discharge fraction increases approximately 5% the next 100 years. Asselman et al. (2022) used a 2D hydraulic D-HYDRO model with an expected river bed level for the year 2050 and showed that especially for the low discharge regimes the partitioning trend keeps increasing until the year 2050. This means the problem is expected to remain present in the future which highlights the necessity to intervene.

Chowdhury et al. (2023) provided several hypotheses on why the river system responded differently from other peak flows to the peak flows of 1993-1995-1998. For the first hypothesis it is important that a coarsening of the bed has been observed over the past decades (Frings et al., 2009; Ylla Arbós et al., 2021). This coarsening of the bed is partly related to a coarsening of the upstream sediment supply since this influences the bed surface grain size distribution (Blom et al., 2016; Blom et al., 2017a). The hypothesis is that the temporal coarsening of the bed and the sediment supply together with the bend upstream, which causes coarse sediment to be deflected towards the Pannerden Canal (PC), have led to a larger coarse sediment supply compared to the transport capacity in the upstream part of the PC at the time of the peak flows from 1993-1995-1998. This led to the aggradation in the upstream part of the canal. The second hypothesis is that the rapid succession of the peak flows or the total duration have caused a different response compared to the peak flows prior to 1993. There might have been too little time for the river to disperse the deposited sediments in between the peak flows. A third hypothesis is that both phenomena occurred simultaneously.

Several studies indicate that the discharge partitioning at the Pannerdense Kop can be influenced by interventions in the surrounding Rhine branches. Studies have been done into the effect of sediment nourishments in the Waal (Becker, 2021; De Lange, 2022; Huthoff & Vieira da Silva, 2019). In all studies the sediment was not continuously dumped but only dumped once. The results show that single nourishments can change the discharge partitioning at the

PK and that the effect dampens with time. Becker (2021) found that single nourishments can lead to maximally 10 and 20 m^3/s extra discharge towards the PC for respectively Lobith discharges below and above 5000 m^3/s. De Lange (2022) found that the relative difference in discharge in the Waal and PC as a result of a single nourishment was respectively 0.65% and 1.80%. Huthoff and Vieira da Silva (2019) found that filling the erosion hole behind the fixed layer at Nijmegen can increase the discharge in the Pannerden Canal by 5 m^3/s for Lobith discharges from 1020 to 2000 m^3/s.

Furthermore, studies have been done to determine the effects of longitudinal training walls (LTW's) (Paarlberg et al., 2021; Sloff et al., 2023). 2D morphological and hydraulic models were used in these studies. Paarlberg et al. (2021) simulated the pilot where LTW's have been placed along the reach from Wamel to Ophemert (rkm 911.5 to 921.5) and Sloff et al. (2023) studied implementation of LTW's on a larger scale along the Waal. They found that LTW's can increase the discharge into the PC for low discharges. Sloff et al. (2023) found that for the Agreed Low Discharge (ALD) (1020 m^3/s) the LTW's can lead to 15-20 m^3/s more discharge to the PC. For discharges equal to or higher than 2250 m^3/s the water level at the upstream end in the Waal drops which leads to more discharge being attracted by the Waal in the order of 100 m^3/s (Sloff et al., 2023). Paarlberg et al. (2021) found that 20-30 m^3/s extra discharge is diverted towards the Waal for a discharge of 16000 m^3/s.

For the project 'Room for living rivers', Barneveld et al (2019) calculated the effects of large scale widening interventions on the bed degradation of the Waal. They modelled flood plain lowering along the Boven-Waal and Midden-Waal and lowering of groynes along the Boven-Waal. They used Sobek-RE to run the simulations. The effect on the discharge partitioning was also calculated. They found that no changes in the discharge partitioning occur for Lobith discharges below 2000 m^3/s. For Lobith discharges above 2000 m^3/s the discharge fraction of the Waal is increased ranging from 2 m^3/s for a Lobith discharge of 2000 m^3/s to 890 m^3/s for a Lobith discharge of 18000 m^3/s.

It should be noted however, that the aim of these studies is to solve problems related to the degradation and the water level of the Waal. The change of discharge partitioning is often regarded as a side effect but is not the main objective in these studies. Therefore in the existing studies, the interventions are not designed to influence the discharge partitioning as effectively as possible. Also, the discharge partitioning at the Pannerdense Kop may be positively influenced by interventions which do not actively decrease the erosion in the Waal and therefore have not been studied in detail yet. This study aims at increasing the general knowledge on how the discharge partitioning at the Pannerdense Kop can be influenced through interventions in order to break the current trend.

To conclude, the discharge partitioning at the Pannerdense Kop (PK) is slowly changing in favor of the Waal. This can become problematic with regard to freshwater supply, navigation, ecology and flood safety. Currently there is a lack of knowledge regarding the possible interventions for changing the discharge partitioning at the PK and their effect on the discharge partitioning. This study aims at filling the knowledge gap by considering several interventions studying their effect on the discharge partitioning at the PK and on the Rhine branches surrounding the PK.

1.3 Objective and research questions

The objective of the research is to get insight into which interventions can mitigate the gradual change in discharge partitioning over the Pannerdense Kop to obtain a stable situation in the long term. Also, the aim is to get insight into the behavior of the river bed in the Dutch Rhine branches in response to the interventions.

The main research question

To what extent can interventions be used to mitigate the change in discharge partitioning of the Pannerdense Kop and what is their effect on the bed level of the Dutch Rhine branches?

Sub questions

- Which interventions could decrease the water discharge fraction into the Waal or increase the sediment discharge fraction into the Waal in order to mitigate the gradual change in discharge partitioning over the Pannerdense Kop?

- What are the effects of the selected interventions on the discharge partitioning over the Pannerdense Kop and on the morphology downstream of the bifurcation?

1.4 Method

Inventory and selection of interventions

The first step towards answering the first sub question will be exploring different interventions which could potentially mitigate the current trend in discharge partitioning over the Pannerdense Kop. Interventions mitigate the change in discharge partitioning if the sediment supply of the Waal starts increasing with respect to its sediment transport capacity, or if the sediment transport capacity of the Pannerden Canal starts increasing with respect to its sediment supply, or when both processes occur.
A selection of interventions is made from the inventory of interventions. This is done through 1) the grouping of interventions. 2) Some interventions are left out based on existing studies to the effect of some interventions on the discharge partitioning at the Pannerdense Kop. 3) Furthermore, the initial hydraulic and morphodynamic effects and the long term morphological effects of the inventorized interventions are analyzed and this analysis is used for the selection of interventions.

Modelling the interventions

The remaining selection of interventions will be modelled to be able to answer both sub questions. First a model has to be chosen. For this study, a 1D numerical model is preferred over a 2D or 3D numerical model. The goal is to do multiple analyses to capture the large-scale and long-term effects of the different interventions. This is still difficult to realize using a 2D or 3D numerical model due to the required computational resources (Paarlberg & Van Lente, 2021). Using a 1D-model, a first insight into the response of the river system to river engineering interventions can be found. Since the aim of the study is to get a first insight into the response of the river system to the different interventions, a 1D-model is used.

An existing 1D model of the Dutch Rhine branches will be used since it will be too time-consuming to develop a new model. The model which will be used is the Rijntakken 1D model of Deltares which was recently developed with the 1D version of the D-HYDRO Suite (Chavarrías et al. 2020). The model has been developed for the Integral River Management program (IRM) as a tool to evaluate long-term and large-scale morphological effects of interventions in the Rhine river system in the Netherlands (Chavarrías et al. 2020). The model description and the model set-up are described in Chapter 3.

Analysis of the results

In order to answer the research questions the results will be visualized and the effects of the interventions on the discharge partitioning and the development of the Rhine branches will be assessed and compared. For the morphological development of the Rhine branches the bed level, the geometric grain size and the sediment transport are considered.

Spatial averaging of the variables of interest will be applied over the river reaches for a concise analysis of the results. The reached over which the results are averaged are the Niederrhein (rkms 815-862), Boven-Rijn (rkms 862-867), Boven-Waal (rkms 867-884), Midden-Waal (rkms 884-930), Beneden-Waal (rkms 930-961), Pannerden Canal (rkms 867-878), Nederrijn-Lek (rkms 878-989) and the IJssel (rkms 878-1001). The Waal is split in three different reaches because the bed level development in the Waal differs across its length. Averaging over the entire Waal would therefore give a distorted view on the bed level development.

The results are presented by either showing the absolute or the relative development of the variables of interest. The relative development is computed in two ways. The first way is to compute the change of the variable of interest with respect to the initial situation. For bed level development ($\Delta z_{b,0}$), positive values indicate net aggradation end negative values indicate net erosion. The second way is to compute the change of the variable of interest with respect to another simulation. When analyzing the bed level development with respect to the reference simulation ($\Delta z_{b,r}$), the effect of interventions is isolated. By comparing changes with respect to another simulation, differences between interventions are found.

The discharge partitioning is determined by calculating the ratio of the discharges in one of the bifurcates and the upstream branch. The results for the effect of the interventions on the discharge partitioning are evaluated in two ways. One way is by computing the difference with respect to the reference case. The other way is by averaging the data yearly and over the discharges in the upstream branch and plotting the resulting data against time. The data is averaged for low flows (Q_{Lobith} < 1650 m^3/s) and high flows (Q_{Lobith} > 2950 m^3/s). For these flows the Driel weir is respectively completely closed and completely opened. The data is analyzed this way in order to able to spot a trend in the data and to be able to evaluate the results with respect to the initial situation. The Driel weir opens for a water level of 8.65 m+NAP at Lobith. Due to bed level changes in the Boven-Rijn the operation of the weir changes. This influences the discharge partitioning for the middle flows where the Driel weir is partly opened. Therefore these are not included in the trend analysis.

Furthermore, in order to compare the discharge distributions for the same upstream discharge, a least square fit (LSF) of a second order polynomial is applied. A discharge of interest would be a Lobith discharge of 1020 m^3/s (ALD) since this discharge is used as a guideline in various practices. However too little data is available for this discharge. A Lobith discharge of 1400 m^3/s is selected as this is better represented by the data. Only the low flows are included in the LSF since a knickpoint is present in the discharge partitioning curve when the Driel weir starts opening, see Figure 6.12.

1.5 Report outline

Firstly, chapter two provides the most important theoretical background for this research. In chapter three the model and its set-up are described. In chapter four an inventory of interventions is made, the initial and long-term hydraulic and morphodynamic response to those interventions is computed and eventually a selection of interventions is made. In chapter 5, the schematization of the selected interventions is described. Chapter 6 provides the modelling results for the reference simulation and the simulations with the interventions. In chapter 7 the methodology, the obtained results and the potential of the interventions related to IRM are discussed. Finally, chapter 8 contains the answer to the research question, the main conclusions from this research and the recommendations for further study.

2 Theoretical background

This chapter provides the relevant theoretical background for this study. The schematization of a river is explained in section 2.1 and the physics of the river bed response are explained in section 2.2.

2.1 Schematization of a river

River morphology is complex, since the interaction between the movement of water and sediment in rivers takes place in all directions (De Vries, 1975). For modelling morphology in engineered rivers three interconnected processes are important: The transport of sediment, the discharge of water and the development of the river bed, where the bed level and the bed sediment composition are the parameters of interest (Blom, 2021). The transport of sediment is influenced by the upstream inflow of sediment and the water discharge is influenced by the upstream flood regime.

The three processes also influence each other. Sediment may be entrained or deposited due to the flow of water. As a result of the deposition and erosion of sediment, the bed level and the bed composition change. This influences the flow of water and the bed friction it experiences and therefore also the sediment transport capacity of the river. This is summarized in a morphological feedback loop, see Figure 2.1.

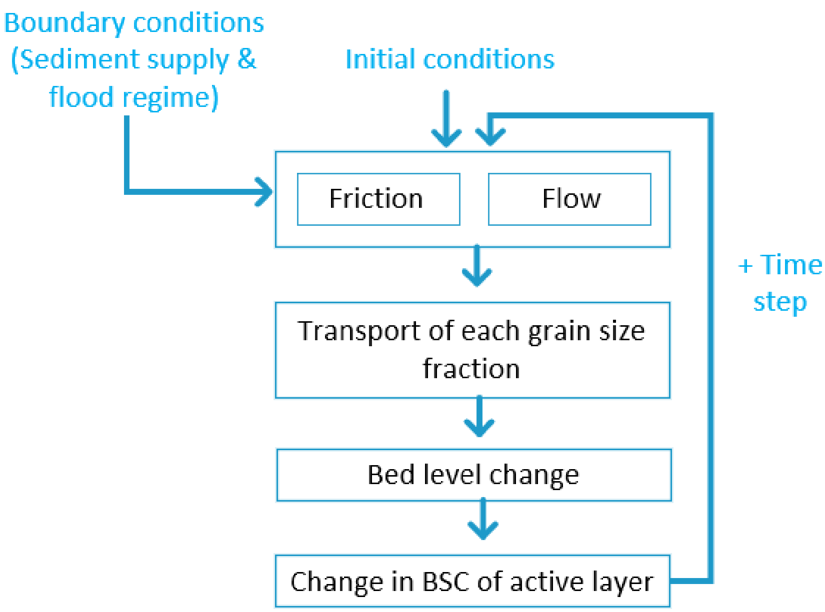

Figure 2.1: The morphodynamic feedback loop (adapted from Blom, 2021). BSC refers to the bed sediment composition

Due to the complex geometries and river morphology, simulating the three-dimensional behavior of rivers is computationally expensive and not always necessary. Therefore rivers are often simplified to 1D or 2D models. 1D models are used to study long-term and large scale morphological developments and 2D models are more fit for studying local morphological phenomena. How rivers are schematized is treated below for the lateral and longitudinal directions.

2.1.1 Schematization in lateral direction

In lateral direction, the cross-section of a river is often schematized as a compound channel consisting of multiple elements. These consist of floodplains, groynes and the main channel. Each element has its width, depth and bed roughness. A 1D schematization is obtained by averaging the relevant quantities (water levels, velocities, sediment transport) over the entire cross-section. A 2D schematization is obtained by averaging the cross-section over the width or the depth.

2.1.2 Schematization in longitudinal direction

For a river with a varying discharge, three different flow segments are identified in the longitudinal direction. The upstream boundary segment (UBS), the quasi-normal flow segment and the backwater segment, see Figure 2.2. The UBS is the adaptation zone for the sediment supply to adjust to the sediment transport capacity. It arises when the instantaneous sediment supply and sediment transport capacity are different, even though the time averaged values may be the equivalent (Arkesteijn et al., 2019). Due to this mismatch fluctuations in bed elevation, slope and bed surface texture arise and migrate downstream (Wong & Parker, 2006). These fluctuations dampen while travelling downstream (Parker et al., 2007). The backwater segment forms when the downstream water level does not match the equilibrium flow depth. The part of the river reach in between is the quasi-normal flow segment. For this segment, the equilibrium equations hold, see appendix A. The UBS and backwater effects are present at the upstream and downstream ends of a reach and at bifurcations, amongst other locations (Blom et al., 2017a). This implies that upstream from the Pannerdense Kop bifurcation, the Boven-Rijn is a backwater segment and the upstream parts of the Waal and the Pannerden Canal are upstream boundary segments.

2.2 Physics of river bed response

In this section the general physics of the river bed response to interventions is explained. The response is separated in an initial and equilibrium response. The limitations of applying the theory to a bifurcation are also discussed.

2.2.1 Initial response

For the short-term morphodynamic response of the river system to interventions only hydrodynamic changes and no morphological changes have occurred. The short-term morphodynamic response is analyzed by first looking at the hydrodynamic changes as a result of the interventions. The hydrodynamic changes which are studied are the change in specific discharge, flow depth, equilibrium flow depth and flow velocity. These are then related to changes in sediment transport rates and bed level changes through a sediment transport relation and the Exner equation. The method to derive the initial response and the corresponding equations can be found in Appendix A.

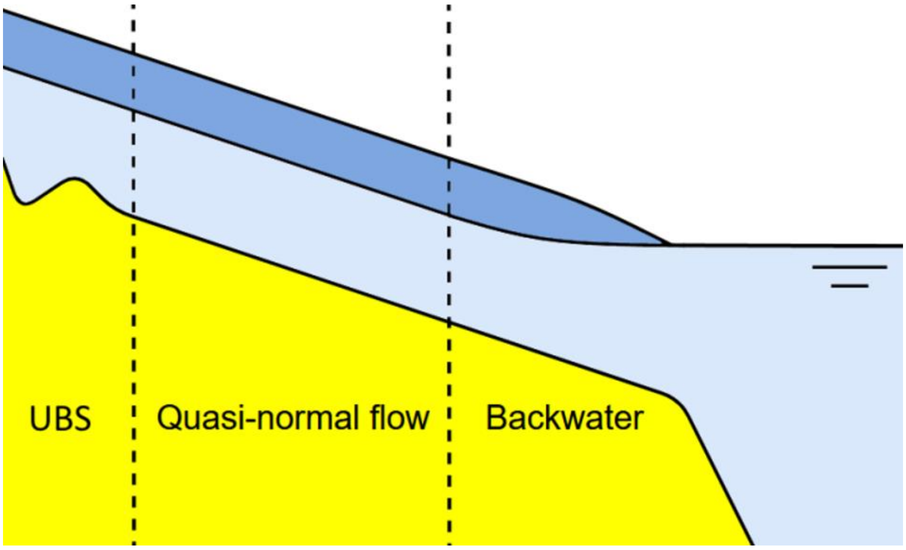

Figure 2.2: The different river segments in a river reach with a hydrograph during base and peak flow (Blom et al., 2017)

2.2.2 Equilibrium response

The long-term effect is analyzed by applying the concept of grade or equilibrium (Mackin, 1948) which means that the channel adjusts its slope such that it can transport the supplied sediment downstream. It is assumed that the river will eventually reach a new equilibrium state. For the quasi-normal flow segment this leads to a simplification of Saint Venant equations to the normal flow equation. Combining this with the Exner equation and the conservation of water mass leads to a set of equilibrium equations for the flow velocity, flow depth and the slope. This is explained in detail in appendix A.
These equations are valid for a constant discharge and for unisize sediment. However, the discharge is varying. When a varying discharge is taken into account this leads to small changes in the equations. The sediment load changes to a mean load, the discharge changes to the dominant discharge and for the flow depth and the flow velocity the discharge is also in the equations as a function of time, see Appendix A (Blom et al., 2017a). The dominant discharge is a constant discharge which, in combination with the mean sediment load, leads to the same morphological equilibrium as the discharge hydrograph.

2.2.3 Limitations theoretical assessment

The equations for the equilibrium response only hold in the quasi-normal flow segments. This should be taken into account when applying the equilibrium response to river segments just upstream and downstream of the bifurcations and downstream in the Waal, the IJssel and the Nederrijn-Lek.

For the long term response the river reaches are assumed to be in equilibrium initially. It should be noted that currently the Rhine river system is not in equilibrium. The upstream part of the Waal and the Pannerden Canal have been eroding the past decades and are still eroding currently (Chowdhury et al., 2023). So if interventions, according the equilibrium theory, lead to a higher bed level in the long term, this could also mean a reduction in degradation on the long term. It depends on the equilibrium the river reach is currently moving towards.

Furthermore, it is uncertain whether and when the equilibrium situation will eventually be reached. It is shown analytically by de Vries (1975) that the morphological time-scale for adaptations of the river bed to sea level rise on the Waal is in the order of centuries for a length of 200 km. The morphological time-scale for adaptations of the river bed to interventions is also dependent on the length of the interventions.

Whether the equilibrium situation will be reached is also uncertain because interventions change the sediment and discharge division over the Pannerdense Kop bifurcation which influence the equilibrium situation. Schielen and Blom (2018) showed that for simplified gravel-sand bifurcations equilibrium situations exist where only one branch is open. The equilibrium situations depend on the ratio of the downstream channel lengths, the ratio of the sand load to the gravel load and the constants in the equations which determine the sediment division over the downstream branches. To which equilibrium the system evolves depends on the initial conditions.

The equilibrium response theory is used as a means to predict the behavior of the river system qualitatively. A quantitative analysis will be done using the Rijntakken 1D model. The model is described in the next chapter.

3 Model description

3.1 1-D Rijntakken model set-up

In this section the model set-up of the 1-D Rijntakken model is described. It starts with a model description. Then the calibration and validation are reviewed critically. Finally the initial and boundary conditions for the reference simulation are provided.

3.1.1 Model description

The Rijntakken 1D model consists of all Dutch Rhine branches and part of the German Rhine, extending approximately 50 km upstream from Lobith. The upstream boundary is located at the confluence of the Lippe and the Rhine, near Wesel. The downstream boundaries for the Waal, the Lek and the IJssel are respectively located at Hardinxveld, Krimpen and Keteldiep and Kattendiep. The model domain is shown in Figure 3.1.

Figure 3.1: The model domain of the Rijntakken 1D model developed by Chavarrías et al. (2020). In brackets the river kilometers are shown. Adapted from de Lange (2022).

The model numerically solves the shallow water equations. The resulting hydrodynamics are used to compute the sediment transport and bed level development. The equations which are solved by the model are given in Appendix B (Chavarrías et al., 2020).

The sediment in the model is divided in 16 grain size fractions ranging from fine sand to coarse gravel. The characteristic grain size and the sediment type of the grain size fractions are shown in Table 3.1. For the sand fractions the Engelund and Hanssen (1967) sediment transport formula is used. For the gravel fractions the Meyer-Peter and Müller (1948) sediment transport formula is used, see Appendix B. All sediment transport is modelled as bed load transport

(Chavarrías et al., 2020). The model only simulates the morphodynamics of the main channel which means that sedimentation and erosion in the flood plains do not occur in the simulations.

Table 3.1: Characteristic grain sizes for the sediment size fractions (Chavarrías et al., 2020).

Fraction	Grain size (mm)	Type	Fraction	Grain size (mm)	Type
1	0.0753	Sand	**9**	2.37	Gravel
2	0.106	Sand	**10**	3.35	Gravel
3	0.150	Sand	**11**	5.66	Gravel
4	0.212	Sand	**12**	11.3	Gravel
5	0.298	Sand	**13**	22.6	Gravel
6	0.421	Sand	**14**	45.3	Gravel
7	0.707	Sand	**15**	90.5	Gravel
8	1.41	Sand	**16**	181	Gravel

In the model, morphodynamic changes in the bed are modelled with the active-layer model for mixed-size sediment of Hirano (1971). The active layer is the part of the bed that interacts with the flow and is set to a thickness of 1.0 m. A value of 1.0 m is chosen as this is an estimate for the height of the bedforms during high-flow events and the active layer thickness represents the scale of the bedforms. Since the model has been calibrated with an active layer thickness of 1.0 m it is chosen not to change this value.

By default the river bed is divided into 10 layers. The top layer has a thickness of 0.5 m and the lower layers all have a thickness of 0.4 m. As no information is available about the sediment composition of the substrate layers, it is assumed that the sediment composition of the substrate layers is the same as the initial sediment composition of the top layer (Chavarrías et al., 2020). For fixed layers the thickness of the substrate layers is set equal to 0. For long-term simulations the combination of morphology and weir operation leads to unstable simulations. Therefore the bed level and compositions around the weirs are fixed. The physical interpretation of this is that the bed around the weirs is continuously nourished or dredged to prevent erosion and sedimentation.

3.1.2 Model calibration and validation

The main aim of this study is to assess the effects of interventions on the discharge partitioning at the Pannerdense Kop. In order to model this correctly, the model has to be able to properly model at least three processes. It should properly model the bed level development upstream in the Waal and the Pannerden Canal and the discharge distribution at the Pannerdense Kop. The bed level development is of importance since it determines the development of the discharge distribution over time.

An analysis is made of the calibration and validation of the Rijntakken 1D model performed by Chavarrías et al. (2020) and it is assessed to what extent their approach is suitable for this study.

The model calibration is performed by Chavarrías et al. (2020) where the following initial and boundary conditions are used: Upstream the discharge time series for the period of 1995-2019 at Lobith is used; Downstream h-t relations are used to prescribe the water level; Lateral in and outflows are included in the model; The bathymetry and the initial bed sediment composition from 1995 are used. The model is run for the period of 1995-2010. The model was first calibrated hydraulically and morphodynamically afterwards.

Hydrodynamic calibration took place through comparison with WAQUA data as this is assumed to be the most reliable information available for the hydrodynamics. The model results are compared with the WAQUA data where in order of importance the following variables are considered: flow velocities, discharges and water levels. These choices would be the same for this modelling study as flow velocity is important for correctly modelling aggradation and erosion and therefore also for the bed level development in the long term. In this step the manning coefficient has been calibrated. One manning coefficient has been chosen which applies to all branches. The manning coefficient has been calibrated such that the flow velocities, discharges and water levels correspond well with the WAQUA data for the whole model domain. For this study the focus for matching the hydrodynamic model results with the WAQUA data should preferably be on be on the Pannerdense Kop area. Furthermore, it would be preferred to calibrate the manning coefficient of the Rijntakken separately and to even treat the downstream part of the Boven-Rijn and the Boven-Waal separately. However this is not possible in a model which contains morphodynamic development since sudden changes in friction also lead to sudden changes in sediment transport.

The morphodynamics calibration is based on two different data sets, namely the sediment transport rates estimated by Frings et al. (2019) and the bed elevation of 2011 as present in the SOBEK-3 model. The calibration parameters are the calibration coefficients from the Engelund and Hansen and Meyer-Peter and Müller sediment transport relations for the different branches and the calibration coefficients from the nodal point relations for the sand and gravel fractions for both bifurcations in the model domain. Chavarrías et al. (2020) chose not to include the active layer thickness as a calibration parameter in order to prevent overcomplicating the calibration. Also, the sediment transport parameters give more control of the simulation results than the active layer thickness (Chavarrías et al., 2020).
The goal of the morphodynamic calibration is correctly modelling the sediment transport and the bed level development in the river branches. The calibration is done in steps and it is an iterative process starting upstream. Therefore the focus was firstly on getting the calibration parameters right for the Boven-Rijn, then for the Pannerdense Kop bifurcation and then for the bifurcates of the Pannerdense Kop. Again, it would be preferred to treat the downstream part of the Boven-Rijn and the Boven-Waal separately. The resulting calibration coefficients can be found in Appendix B.

So for this study, some steps in the calibration procedure would have been taken differently. In order to check whether the model calibrated by Chavarrías et al. (2020) is suitable for the purpose of this study, the results for the discharge partitioning at the Pannerdense Kop for the calibration run are compared to measurement data and the bed level development of the calibration run is thoroughly analyzed.

Discharge Partitioning

In Figure 3.2 the model results as well as the measurement data are shown for the discharge division at the Pannerdense Kop (PK). The measurements were done with Ott current meters until 1999 and with acoustic Doppler current profiler (ADCP) since 2000 (Chowdhury, et al., Bifurcation response to peak flow events in an engineered river, 2023). To obtain the plots, the same methodology as applied by Chowdhury et al. (2023) to show the trend in discharge partitioning at the PK, is applied. The data is separated in two discharge regimes: (1) high flows at Lobith for which the Driel weir is fully open ($Q_{Lobith} > 2500\ m^3/s$), and low flows at

Lobith for which the Driel weir is entirely closed ($Q_{Lobith} < 1500\ m^3/s$). The data has been yearly averaged to filter out the high variability of the measured data.

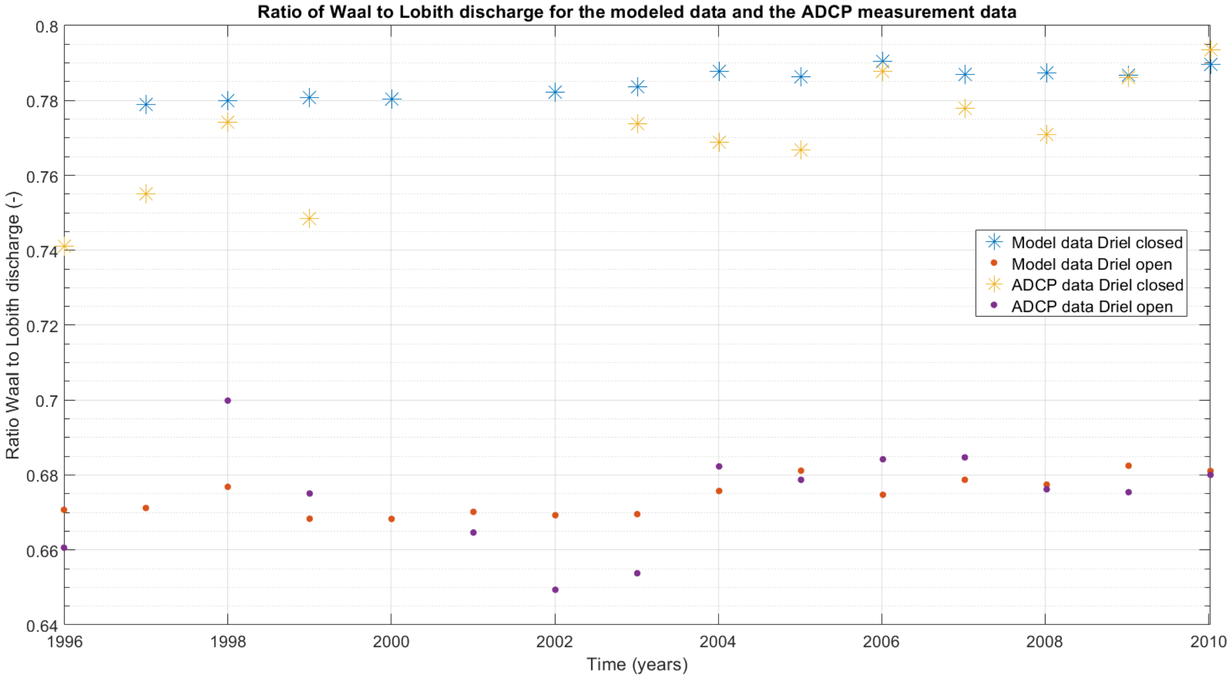

Figure 3.2: Ratio of the Waal to Lobith discharge for the modeled data and the ADCP measurement data for the calibration run.

For the Rhine branches surrounding the PK, the prediction uncertainty of the ADCP ranges from 4.6% - 6.0% expressed in relative standard deviations and the prediction uncertainty of the Ott current meter ranges from 5.3% - 7.8%, see Appendix C.1. The prediction uncertainty consists of the seasonal variation, hysteresis and measurement error (Twijnstra, 2020). The measurement error is attributed to several causes, namely: Uncertainty in the measurable zone, uncertainty in the unmeasurable zones and uncertainty of instrumental errors (Twijnstra, 2020).

As a result of the prediction uncertainty the measurements show strong variability. In order to compare this to the model data, the standard deviation and the mean of the measurement data from Figure 3.2 have been computed. By assuming the data is normally distributed, 95% confidence intervals are plotted, see Appendix C.2. It is seen that for both the low and the high discharges the model data fall within the 95% confidence intervals.
It should be noted that the input to the model is not the discharge obtained from measurements with the Ott current meter and the ADCP, but the discharge time series obtained from rating curves. This gives extra uncertainty, see Appendix C.3. Using the discharge time series obtained from rating curves also introduces a systematic error, since the ADCP data used to construct the rating curve contain a water balance error (Gensen, 2021). The discharges of the bifurcates do not add up to the discharge in the Boven-Rijn. In recent years there has been a positive bias. The water balance error may propagate towards discharge predictions (Gensen, 2021).

Bed level development

The results of the calibration run for the bed level development for the Waal and the Pannerden Canal (PC) are shown in Figure 3.3 and Figure 3.4. The figures also show the measured bed level development. It is seen that upstream in the Waal the model results correspond well with the measurements. After approximately 35 km the model results start to deviate from the

measurements. The measurements predict more degradation than the model results. This is attributed to the absence of dredging activities in the model. The mismatch downstream is maximally in the order of 0.75 m. It is uncertain to what extent this might be attributed to the exclusion of dredging activities. The mismatch occurred over a period of 15 years. The model will eventually be run for 60 years. Throughout this simulation time the error may develop further. Even though the mismatch is not in the upstream part of the Waal this can still influence the water level at the PK due to backwater curves.
In the calibration results for the PC there also appears to be a mismatch between the measurement data and the model data as the model predicts degradation halfway the Pannerden Canal which is not present in the measurement data. However, in the validation run of 2011-2019 the degradational pattern is present in both the model data and the measurements, see Appendix C.4. It is argued by Chavarrías et al. (2020) that this might mean that the model results are realistic and that the degradational pattern is missing in the data of 2011 due to the timing of the measurements. This reasoning is supported by a comparison of the bed level measurements from 1994 and 2010, see Appendix C.4. It is seen that also here the degradational pattern is visible in the middle of the PC. However, in the downstream part of the PC the model shows oscillatory behavior of the bed for the calibration and the validation run while the measurements show a more uniform bed level for the downstream part of the PC. This might also lead to unwanted backwater effects at the Pannerdense Kop bifurcation.

Concluding remark

The modelled discharge ratio’s for the PK seem to fall within the variability of the measured discharge ratio’s. A detailed analysis is complicated due to the mismatch between the rating curve data used as input for the model and the ADCP/Ott current meter measurements and due to the high variability of the measurement data. The model performs reasonably for modelling the bed level development upstream in the Waal and the PC. Downstream a mismatch occurs which, for the Waal, is partly attributed to the absence of dredging. Even though the upstream bed level development is the most important for correctly modelling the discharge division the downstream mismatch may still influence the water level at the PK due to backwater curves. It will be reflected upon in the discussion what this means for the results.

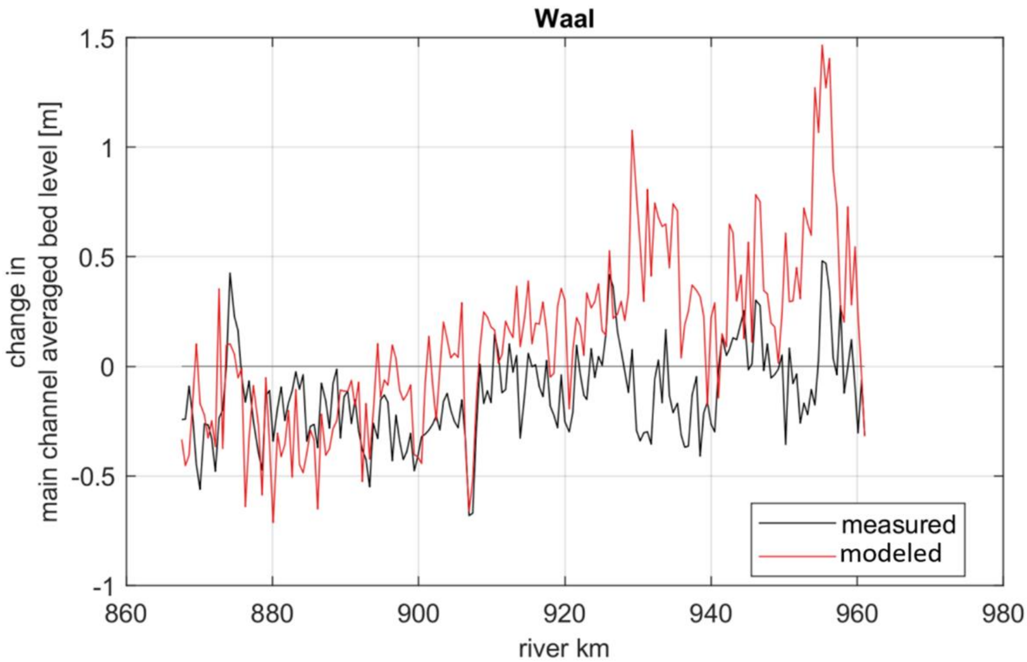

Figure 3.3: Measured and modeled bed level changes for the Waal for the period 1995-2010. The 2010 bed level is subtracted from the 1995 bed level (adapted from Chavarrías et al., 2020).

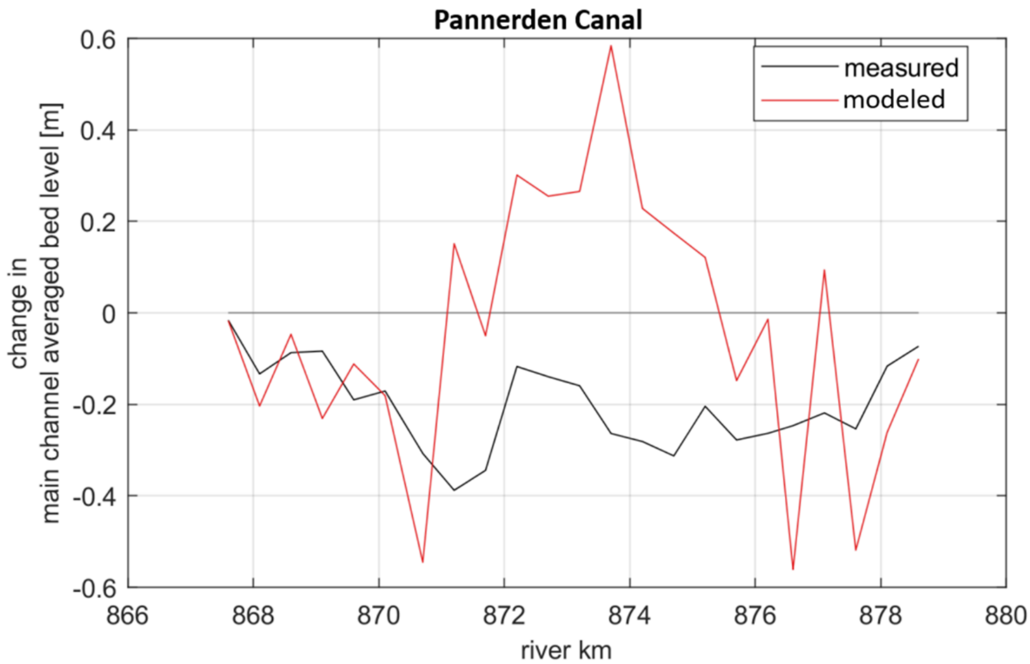

Figure 3.4: Measured and modeled bed level changes for the Pannerden Canal for the period 1995-2010. The 2010 bed level is subtracted from the 1995 bed level (adapted from Chavarrías et al., 2020).

3.1.3 The base case – initial conditions

The initial conditions in the model are the initial bed level and the initial bed sediment composition. The initial bed sediment composition in the model is from schematizations by Sloff (2006), which are based on measurements from 1995. In the model from Chavarrías et al. (2020) the bathymetry is taken from SOBEK-3 schematizations which represent the situation of 2019 for the Dutch parts of Rhine and of 2012 for the German parts.

The SOBEK-3 schematizations for the friction values and the profiles are used. The SOBEK-3 schematizations are converted to D-FLOW FM 1D. Before conversion to D-FLOW FM 1D, first simplifications have to made to the SOBEK-3 schematizations.

The model domain has been straightened. D-FLOW FM 1D uses a 2D numerical solver which leads to energy losses due to curvature of streamlines. In order to minimize these losses the grid cell size should become very small which leads to a large computational time. So to keep the energy losses to a minimum and to prevent a small space step, the domain has been straightened. Also, the storage area in the cross sections is removed. The storage area is removed because it led to problems in combination with the advections scheme which is used in D-FLOW FM 1D.

3.1.4 The base case – boundary conditions

Two boundary conditions are present at the upstream boundary. One for the water discharge and one for the sediment discharge. For the water discharge the discharge time series of the discharge at Lobith from 1916–2016 is used, see Appendix B. As climate change effects are not accounted for in this study, this discharge time series is assumed to be representative for the coming 100 years. The discharge time series is for Lobith but we impose it at Wesel. This is justifiable since the model is intended for morphological developments and individual flood events with a timescale in the order of days are not withing the scope of the model. The interest is not on the exact timing of a flood wave.

For the upstream sediment discharge, the bed level and the sediment composition at the upstream boundary are fixed. This seem to be reasonable assumptions since Ylla Arbos et al. (2020) showed that the Niederrhein has mostly been stable since 1975, partly because of the sediment nourishments which have been carried out in the Niederrhein. The amount and the composition of the sediment which enters the model domain is such that the sediment composition and the bed level at the upstream end of the model domain remain unchanged.

At the downstream boundaries the water levels are prescribed. Initially in the model of Chavarrías et al. (2020) this was done through h-t relations. For the models in this study Q-h relations are used since the measurements of the water depth at the downstream locations are not continuous for the duration of the upstream discharge time series. The Q-h relations are taken from Paarlberg and Van Lente (2021), see Appendix B.

The lateral in and outflows are set to zero. This is common practice in morphological calculations as explained by Paarlberg and Van Lente (2021) since lateral in and outflows only have a small effect on the morphology which is not visible in the model results.

4 Interventions and response of the system

In this chapter the first research sub-question is answered: *"Which interventions could decrease the water discharge fraction into the Waal or increase the sediment discharge fraction into the Waal in order to mitigate the gradual change in discharge partitioning over the Pannerdense Kop?* First an inventory of interventions is made which could restore the discharge partitioning at the Pannerdense Kop. Then the initial hydraulic and morphodynamic effects and the long term morphological effects of the inventorized interventions are analyzed. This analysis is combined with existing studies to the effect of some interventions on the discharge partitioning at the Pannerdense Kop, to obtain a selection of interventions.

4.1 Inventory of interventions

Interventions in the bifurcates can change the discharge partitioning in two ways. 1) In the short term the discharge partitioning is influenced by changing the water levels at the upstream ends of the Pannerden Canal (PC) or the Waal through backwater effects. Since the water level at the bifurcation is continuous, increasing the water level at the upstream end of the PC or lowering the water level at the upstream end of the Waal means that the water level at the upstream end of the Waal has to go up as compensation and this can only happen through an immediate increase of the discharge in the Waal. This is the initial hydraulic response. The discharge partitioning can also change due to morphodynamic changes in the short term. The sediment transport capacity of the Waal should be reduced with respect to its sediment supply such that the current erosion is limited or aggradation starts and the sediment transport capacity of the PC should increase with respect to its sediment supply such that the erosion increases.
2) In the long term interventions can change the discharge partitioning through changes in the bottom elevation. At the moment the upstream part of the Waal is eroding faster than the upstream part of the Pannerden Canal. If interventions can turn this around such that the upstream part of the Waal erodes less fast than the PC, or even starts aggrading, then the bed level of the Waal is raised compared to that of the PC. This means that the flow depth of the Pannerden Canal increases with respect to the flow depth of the Waal which leads to a change in flow partitioning where more discharge enters the PC (Chowdhury et al., 2023).
Interventions in the Boven-Rijn change the discharge partitioning over the PK by changing the sediment or the water discharge partitioning over the Pannerdense Kop. This should be done such that the sediment supply to the Waal starts increasing with respect to its sediment transport capacity, or the sediment transport capacity starts decreasing with respect to the sediment supply, or both processes occur. The opposite is true for the Pannerden Canal.
Based on the reasoning mentioned above, an inventory of different possible interventions is in the Boven-Rijn and the bifurcates is made, see Table 4.1. In the table the interventions are categorized into three types. Namely interventions in the bifurcates, and interventions in the Boven-Rijn which either influence the sediment or the discharge partitioning at the Pannerdense Kop.

Table 4.1: Inventory of interventions

Intervention	Type	Description
Bottom vanes[1]	Sediment diversion	Placement of bottom vanes in the Boven-Rijn to influence the helical flow.
Sill	Sediment diversion	Placement of a sill in the Boven-Rijn upstream of the entrance of the Pannerden Canal and thereby forming an obstacle for the bed load sediment.
Dredging	Sediment diversion	Dredging of the Boven-Rijn such that the transverse slope of the river bed is reduced.
Flow screens	Water discharge diversion	Bandal-like structures which consist of flow screens attached to poles to divert the upper part of the flow which only contains suspended sediment.
Water offtake channel from the BR to the bifurcate	Water discharge diversion	A channel with an inlet step to divert water from the Boven-Rijn towards one of the bifurcates of the Pannerdense Kop.
Dredging	Bifurcates	Dredging a part of the main channel.
Widening	Bifurcates	Widening a part of the main channel.
Groyne lowering	Bifurcates	Lowering the groynes in order to reduce the friction during high flows.
Nourishments	Bifurcates	Sediment nourishments in the main channel.
Longitudinal training wall	Bifurcates	Placement of longitudinal training walls to separate a river section into the main and the side channel.
Groyne heightening	Bifurcates	Heightening the groynes in order to increase the friction during high flows.
Change weir settings	Bifurcates	Changing the weir settings such that the weirs are always fully opened.
Interventions that lower the water level at the IJsselkop	Bifurcates	Lowering of the water level at the IJsselkop in order to influence the water level at the PK. This is realized through widening a part of the main channel of the IJssel.
Regulating structure[2]	Other	Placement of a regulating structure based on the Old River Control Structures which control the discharge which flows from the Mississippi to the Atchafalaya River.

1. Bottom vanes have originally been designed to flatten the bed level in the river cross sections in bends. Bottom vanes in the outer bend placed under a small angle with respect to the main flow should generate a spiraling flow which counteracts the helical flow which is generated in the river bend, see Appendix D (Majoor, 1995). The helical flow pushes the sediment towards the inner bend and therefore towards the Waal. So the original application of bottom vanes is unwanted here. The bottom vanes should strengthen the helical flow instead. Whether bottom vanes are capable of doing this should be studied in detail. This is outside the scope of this research and therefore this intervention will not be dealt with further on.
2. The idea for a regulating structure is based on the Old River Control Structure (ORCS) which controls the discharge which flows from the Mississippi to the Atchafalaya River. With the ORCS the discharge entering the Atchafalaya River is controlled (Wang & Jun Xu, 2016). This concept may also be applied to the Pannerdense Kop bifurcation to completely control the discharge into the Waal or the Pannerden Canal. However, this would require the placement of structures inside the main channel which causes hindrance for navigation and might also damage the ecology of the river. So for this measure the question is not so much whether it could be effective but whether it is feasible. This is outside the scope of this research and therefore this intervention will not be dealt with further on.

4.2 Initial and long-term response to interventions

4.2.1 Initial and long-term response for the affected bifurcate

The theory from section 2.2 on the initial hydraulic and morphodynamic effects and the long term morphological effects of interventions is applied to the interventions from the inventory. An example for the widening intervention is shown below. The analysis for the other interventions is in Appendix D. The results from the analysis are summarized in Table 4.2.

Table 4.2: Overview of the initial and long-term effect of the interventions

Intervention [2]	Initial water level influence	Initial morphodynamic influence	Long-term bed level influence	Influential for (high/ low/ all flows)	Branch
Sill	0[1]	+	+	All	Boven-Rijn
Dredging	0	+	+	All	Boven-Rijn
Flow screens	0	0	0	All	Boven-Rijn
Water offtake channel from the BR to bifurcate	+	+	0	All	Boven-Rijn/PC
Dredging	-	-	-	All	PC
Widening	-	-	+	All	PC
Groyne lowering	-	-	-	High	PC
Nourishments	+	+	+	All	Waal
Longitudinal training wall (low flow/high flow) [3]	+/-	+/-	-/+	All	Waal
Groyne heightening	+	+	+	High	Waal
Change weir settings	-	0	+	Low	NR-L
Interventions that lower the water level at the IJsselkop	-	-	+	All	IJssel

1. +/-/0 indicate increase/decrease/no change in water and bed level. For the interventions in the Boven-Rijn the effect on the bifurcate to which sediment or discharge is diverted, is considered.
2. For the interventions in the Boven-Rijn the effect on the bifurcate to which sediment or discharge is diverted, is considered. So for example, for the sill the initial water level upstream in the Waal is not influence. Furthermore, as a result of the sill, both initially and In the long-term the bed level upstream in the Waal is increased.
3. Response for longitudinal wall is different for different flows.

Widening of the main channel

Initially widening lowers the equilibrium water depth which leads to a lower water level over the widened section through a M1 backwater curve. The water level just downstream of the Pannerdense Kop is also lowered through a M2 backwater curve, see Figure 4.1.

As widening lowers the upstream water level, widening in the IJssel will lead to a lower water level at the IJsselkop. Therefore widening in the IJssel will be considered for the intervention where the water level is lowered downstream in the Pannerdense Kop. The initial effect for this intervention can also be obtained from Figure 4.1 where the IJsselkop would be located at the transition point between the M1 and M2 backwater curves.

The initial morphodynamic response due to the backwater curves is aggradation in the widened section and degradation upstream of it. An aggradation wave starts at the upstream end of the widened section and a erosion wave starts at its downstream end. For widening in the IJssel this means that for the whole Pannerden Canal erosion will take place.

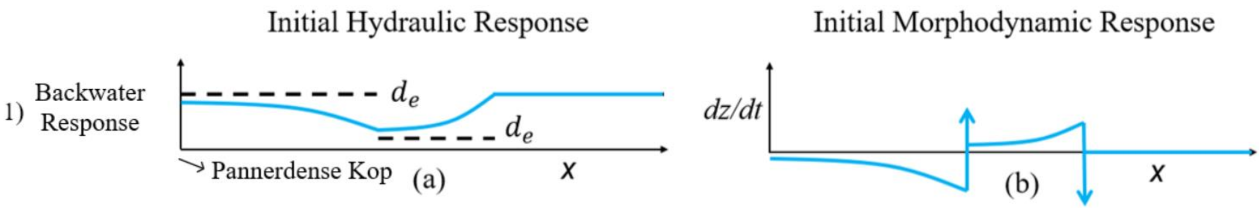

Figure 4.1: Initial hydraulic (a) and morphodynamic (b) response. The Backwater response due to a widened section is shown (a and b).

Initially the widening intervention attracts more discharge into the branch in which it is located. On the long term the widening solution is expected to decrease the discharge into the branch in which it is located. The sediment transport capacity of the widened section is lowered as the velocity is lowered in the widened section. The sediment supply from upstream remains the same which means that aggradation will start until the reach has a higher slope to be able to transport more sediment downstream. Due to the increased slope of the widened section the bed level upstream of this section will also move up. The long-term effect is shown in Figure 4.2. This eventually leads to a higher water level at the Pannerdense Kop (PK). Estimates of the initial water level lowering and the long-term bed level rise are computed using the formula's from Appendix A. When comparing the two it is concluded that the initial effects of the widening intervention are larger than the long-term effects and therefore widening might be successful on the PC or the IJssel.

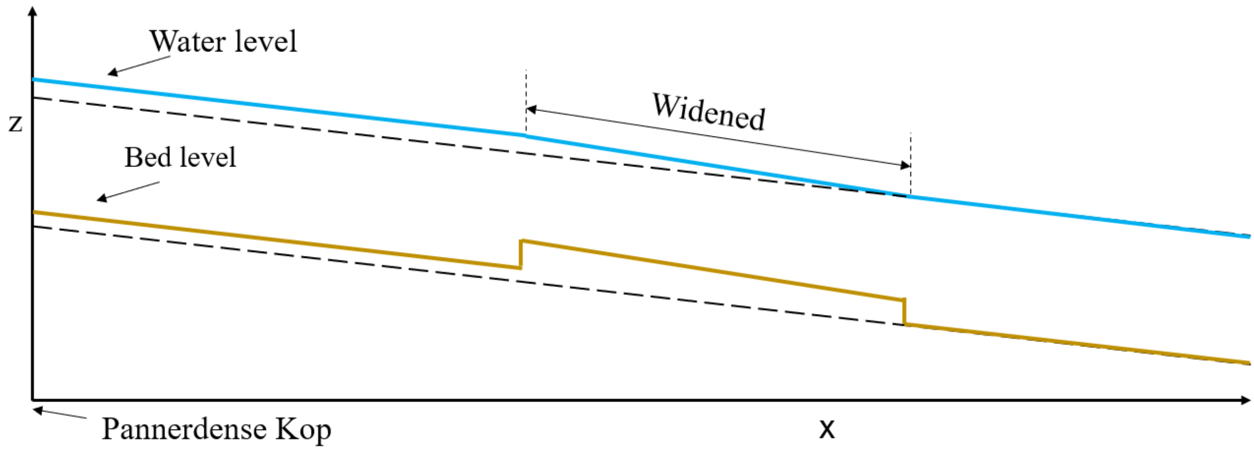

Figure 4.2: Long-term effect of widening a river section

4.2.2 Initial and long-term response for the Boven-Rijn and the untouched bifurcate

The analysis above shows the effect in the branch in which the intervention is applied. In order to get a better insight into how the system will respond, we extend the initial hydraulic and morphodynamic effects of interventions across the PK bifurcation. The interventions are split in two categories. Namely interventions which initially increase the water level at the upstream part of the Waal and interventions which decrease the water level at the upstream part of the Pannerden Canal. For the first group of interventions, the initial response is seen in Figure 4.3. A M1 type backwater curve is seen in the Boven-Rijn which leads to aggradation. In the PC initially the water level rises. For the analysis it is assumed that the sediment at the PK is partitioned according to the nodal point relation described below in equation 4.1.

$$\frac{Q_{sk1}}{Q_{sk2}} = \beta \frac{Q_1}{Q_2} \tag{4.1}$$

where, Q_{skj} = the sediment transport rate of size fraction k on the outgoing branch j (m^3/s). With this assumption an erosion and aggradation wave arise at the upstream part of the PC. The erosion wave arises as a result of the increased water discharge into the PC. Due to the increased water discharge, also the sediment discharge into the PC increases which leads to an aggradation wave.

The initial response for the group of interventions which decrease the water level at the upstream end of the Pannerden Canal is seen in Figure 4.4. A M2 type backwater curve is seen in the Boven-Rijn which leads to degradation. In the Waal the water level drops but no morphological changes are seen along the reach. At the upstream part of the Waal an erosion and aggradation wave arise as a result of respectively the decreased sediment and water discharge into the Waal.

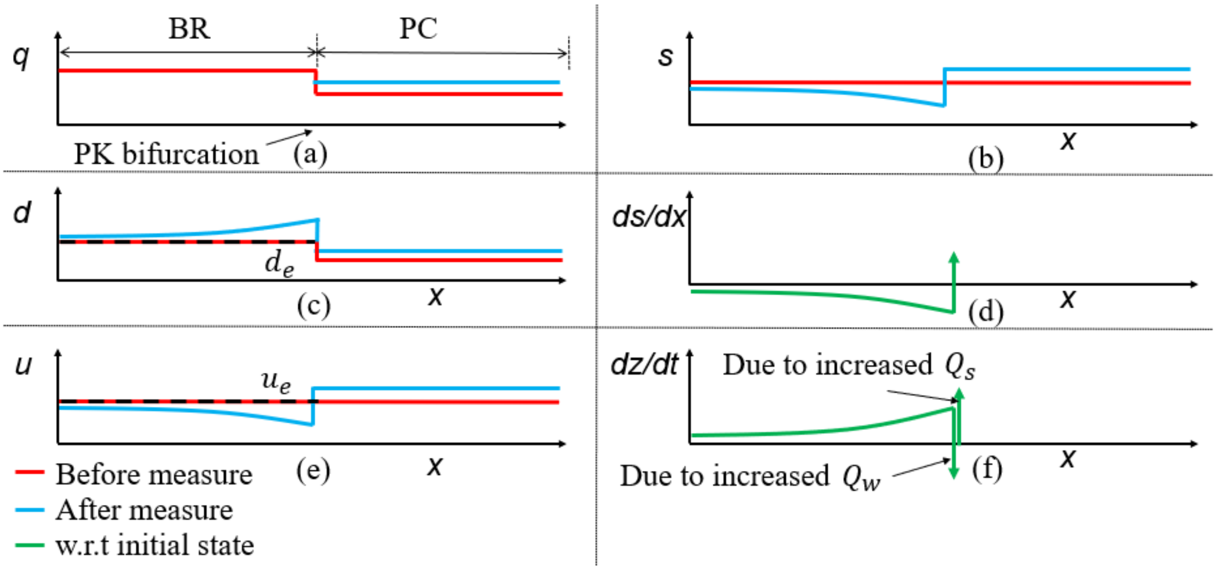

Figure 4.3: The initial hydraulic and morphological response of the downstream part of the Boven-Rijn and the upstream part of the Pannerden Canal to a water level increase at the upstream end of the Waal.

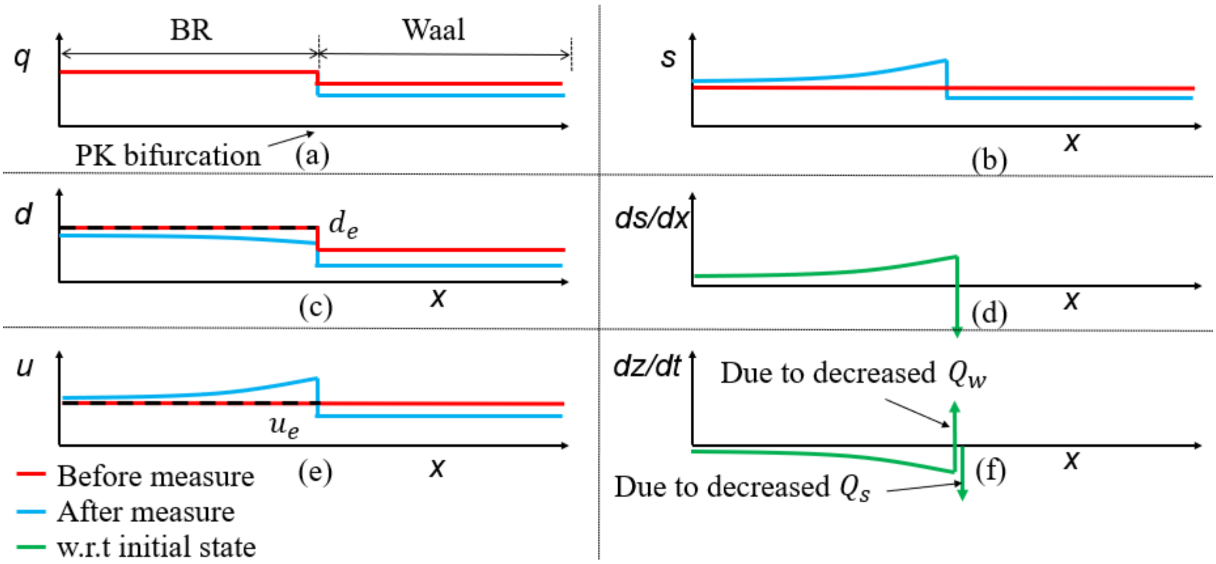

Figure 4.4: The initial hydraulic and morphological response of the downstream part of the Boven-Rijn and the upstream part of the Waal to a water level lowering at the upstream end of the Pannerden Canal.

In Figures 4.3 and 4.4 the flow velocity and therefore also the sediment transport capacity are assumed to be uniform across the bifurcation. This assumption does not hold for the majority of the time. However, we are not interested in the initial or final flow velocity and sediment transport capacity along the river reaches but in the difference with respect to the initial situation. The plots for the change in sediment transport capacity along the river and the change in bed level in time therefore show the change with respect to the initial situation.

From the initial response it remains uncertain whether or not an aggradation or erosion wave occurs in the untouched bifurcate. Therefore a quantitative analysis is made where the change in sediment transport capacity is compared to the change in sediment supply for the untouched bifurcate. The analysis is in Appendix E. It is found that after a water level increase in the Waal, the sediment transport capacity in the Pannerden Canal increases relatively more than its sediment supply. Therefore, assuming that the sediment is divided over the bifurcates according to the nodal point relation of equation 4.1, an erosion wave is expected in the PC after a water level increase on the Waal. After a water level decrease in the PC, the sediment transport capacity in the Waal decreases relatively more than its sediment supply. Therefore an aggradation wave is expected in the Waal after a water level decreases on the PC.

An estimate for the long term effect of the interventions in the unaffected bifurcate is also made. As a result of the interventions more water, and therefore also sediment, is expected to flow to the PC and less tot the Waal on the long term. As is seen from Appendix A, the change in water and sediment discharge have opposing effects on the long term bed slope.

The nodal point relation and the powers in the equation for the bed slope determine which effect will be dominant. Since the nodal point prefactor in front of the water discharge ratio is larger than 1 ($\beta = 1.79$), the relative change in the water discharge is larger than the relative change in the sediment discharge. In the equation for the equilibrium bed slope, the water discharge has no power and the sediment discharge has the power 3/n, where n is equal to 5. Lower relative changes for the sediment discharge compared to the water discharge combined with a lower power result in a dominant effect of the changed water discharge in the bifurcates on the long term bed slope. For the Waal this would mean a higher slope and therefore aggradation and on the PC this would mean a lower slope and degradation. This result is based on the assumption that the sediment is divided over the bifurcates according to the nodal point relation of equation 4.1which is a simplification of reality.

4.3 Selection of interventions

The research sub question that is answered by this chapter is: *"Which interventions could decrease the water discharge fraction into the Waal or increase the sediment discharge fraction into the Waal in order to mitigate the gradual change in discharge partitioning over the Pannerdense Kop?"*.

Not all interventions from the inventory will be modelled. A selection of the interventions is made resulting in the final set of interventions which are shown in Table 4.3. The set of interventions is narrowed down through grouping of interventions and by considering the results from the theoretical analysis and what has been studied already.

First of all, groyne lowering and heightening are respectively comparable to widening and narrowing of a river section. Widening and narrowing the river with the width of the groynes is regarded as the maximum effect possible by respectively lowering and heightening the groynes. Therefore groyne lowering and heightening are not considered separately. Widening should take place on the PC or the IJssel and narrowing should take place on the Waal. Since narrowing in the Waal will contribute to the ongoing bed degradation in the Waal this intervention is not selected. The PC is too short to successfully apply a widening intervention so therefore the widening will be done on the IJssel. Widening on the IJssel also falls into the category of interventions which lower the water level at the IJsselkop.

From the theoretical analysis it follows that flow screens do not alter the discharge partitioning at bifurcations. Even though the flow screens change the flow in the cross-section upstream from a bifurcation, nothing changes to the water levels or geometry of the bifurcation. This means that the discharge diversion of the flow screens will be counteracted by the bifurcation leading to no net discharge difference in the bifurcates. Therefore flow screens are not considered.

Some interventions have been studied in more detail in other studies already, see section 1.2. Since the influence of longitudinal training walls on the discharge partitioning at the PK and the bed level development has been the subject of previous studies (Paarlberg et al., 2021; Sloff et al., 2023), it is decided not to select LTW's for this study. It is found that for low flows, the LTW's could increase the PC discharge fraction (Paarlberg et al., 2021; Sloff et al., 2023). Paarlberg et al. (2021) simulated the pilot where LTW's have been placed along the reach from Wamel to Ophemert (rkm 911.5 to 921.5) and Sloff et al. (2023) studied implementation of LTW's on a larger scale along the Waal. Also studies have been done into the effect of one-time sediment nourishments in the Waal (Becker, 2021; De Lange, 2022). Since the effects of one-time nourishments diminish in time, it is chosen to nourish continuously. In order to keep the sediment in the river system balanced, the nourishment intervention is combined with dredging. Dredging takes place in the PC and all dredged material is dumped upstream in the Waal. This leads to the following list of selected interventions.

Table 4.3: Selection of interventions

	Intervention
A	Side channel from the Boven-Rijn to the PC
B	Fully opening of the weirs in the NR-Lek
C	Widening on the IJssel
D	Directly steering the sediment partitioning at the PK
E	Dredging in the PC and dumping in the Waal

5 Schematization of interventions

In this section the locations, dimensions and the implementation in the Rijntakken 1D model of the interventions are discussed. An overview of the locations of the interventions is shown in Appendix B.

Two simple tools have been developed to aid with the schematization. The tools are explained in more detail in Appendix E. The tools help in determining the dimensions of the widening and the side channel interventions. One tool determines the initial water extraction or addition to the main channel as a result of the interventions and the other tool determines the initial water level difference at the PK as a result of the interventions. The tools provide an extraction curve and a water level lowering curve at the Pannerdense Kop (PK). In order to be able to use the tools, the water level lowering at the PK should first be converted to an effect on the discharge partitioning at the PK. This is done using the method in Appendix F, where for two discharges the required water level drop at the PK for changing the Waal to BR discharge ratio by 5% is calculated. The reduction by 5% indicates the situation before the peak flows of 1993-1998 as since then the Waal to Boven-Rijn discharge ratio has approximately increased by 5% (Chowdhury et al., 2023). This does not serve as a goal to be obtained by the interventions but it serves as a first estimate to aid in the schematizations of the interventions. The results are highly sensitive to the chosen water level slopes and for the high discharge the result is likely overestimated, since the floodplains are neglected. The obtained water level differences as a result of the intervention are presented in Table 5.1.

Table 5.1: The required water level differences as a result of the intervention for the two different Lobith discharges.

	Δd (m)
$Q_0 = 1.85*10^3$ (m^3/s)	0.24
$Q_0 = 6.43*10^3$ (m^3/s)	0.44

5.1 Side channel from the Boven-Rijn to the Pannerden Canal

The length of the side channel is chosen to be approximately 5 km as this is in the same order as interventions of this type in the field. The entrance of the side channel is located in the Boven-Rijn (BR), 3 km upstream from the PK and the outlet of the side channel is located in the PC 2 km downstream of the PK. The width is set at 50 m as it follows from the tool that this leads to reduction of 5% in the discharge through the BR, see Figure 5.1. The discharge through the side channel is calculated for a pre-determined range of BR discharges with the extraction tool. Through interpolation the discharge through the side channel is then calculated for the BR discharges which are in the model. The obtained discharge through the side channel is then added to the model as water extraction in the BR and addition in the PC.

In the extraction tool the side channel is schematized as another part of the compound channel with the same friction value as the main channel. An important assumption that is made by schematizing it this way is that it is assumed that the side channel has the same bed slope as the Boven-Rijn. However, in reality the bed slope of the side channel will be smaller since it connects the BR to the PC and there is a bed level step at the PK bifurcation. Therefore the water extraction and addition which are added to the model actually belong to a somewhat larger side channel than one with a length and width of respectively 5 km and 50 m and the results obtained for the change in discharge partitioning will be overestimated.

Another assumption which is made is that only water flows through the side channel and no sediment enters the side channel. To be able to justify this assumption, an inlet step is present at the entrance of the side channel. This is schematized in the extraction tool by letting the side channel start to contribute to the flow when the discharge in the BR exceeds 1500 m^3/s, see Figure 5.1.

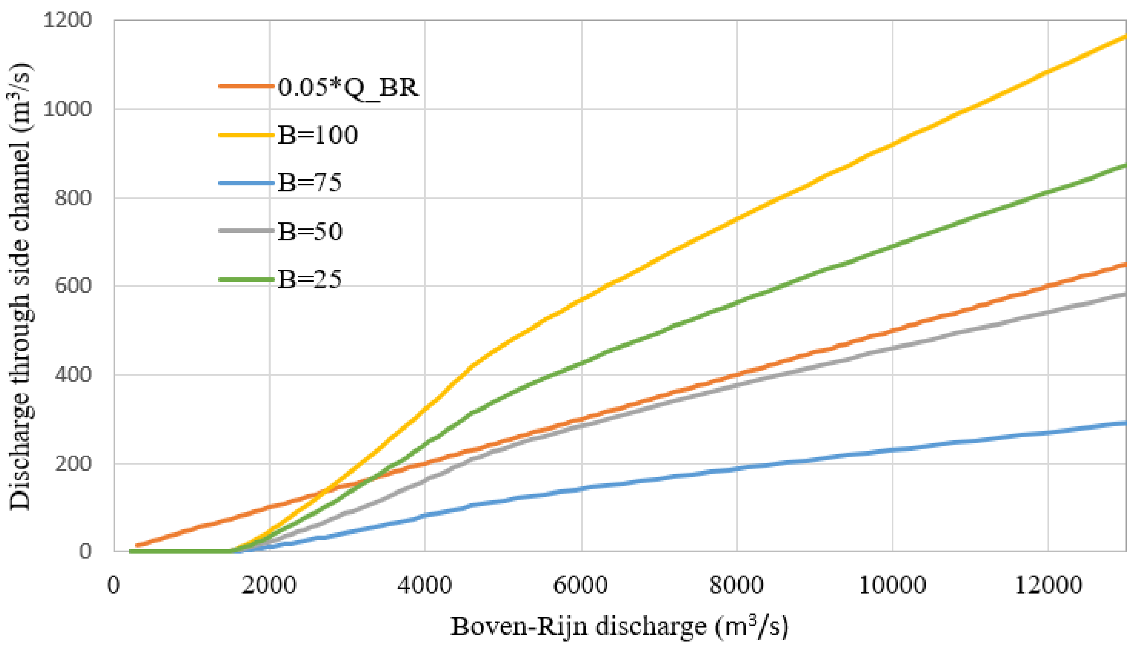

Figure 5.1: Discharge through the side channel as a function of the Boven-Rijn discharge for different side channel widths

5.2 Fully opening the weirs

For this intervention the weirs at Driel, Amerongen and Hardinxveld in the Nederrijn-Lek are completely opened in order to get insight into the maximum effect which can be obtained by changing the weir settings. The bed level around the weirs stays fixed such that it is modeled as if the structures of the weirs are still present and the weirs are always fully opened.

5.3 Widening on the IJssel

Widening on the IJssel is schematized by changing the width of the main channel in the cross sections. Values for different parameters have to be chosen, namely: the location upstream and the length and width of the widened section. The upstream location of the interventions is set rather arbitrarily at 3 km. From satellite imagery it is observed that in some locations buildings or the winter dike are close to the main channel. However, this is not taken into account in the schematization since the nature of this study is exploratory and the goal is to assess the general effects of different interventions. With the extraction and water level tool different combinations of added withs and lengths of the widened section have been tested. For these combinations the water addition curve and the water level lowering curve are plotted, see Figure 5.2 and Figure 5.3. It follows that a significant widening interventions is needed in order to alter the discharge partitioning at the PK and that the 5% reduction in the Waal to Boven-Rijn discharge ratio will likely not be reached, since the maximum change of water level at the PK is 0.25 m instead of 0.45 m. The selected dimensions for the widening interventions are unrealistically large. This way, an indication of the potential effects of the widening on the

IJssel is obtained. The added width and the length of the widened section are respectively 60 m and 17 km.

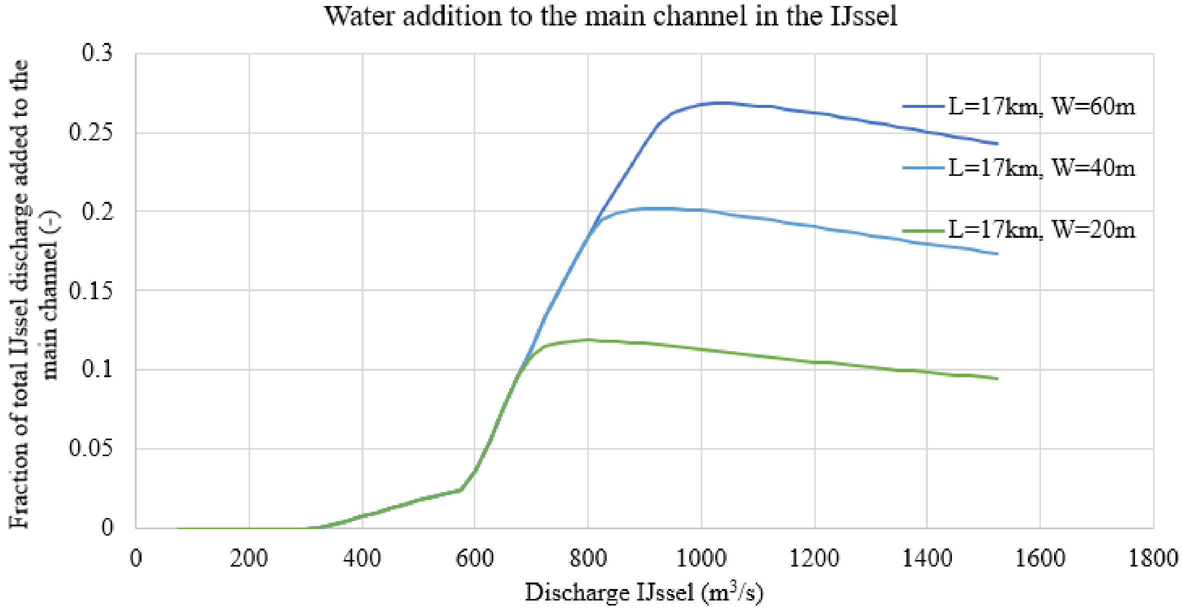

Figure 5.2: Water addition to the main channel in the IJssel due to the widening intervention

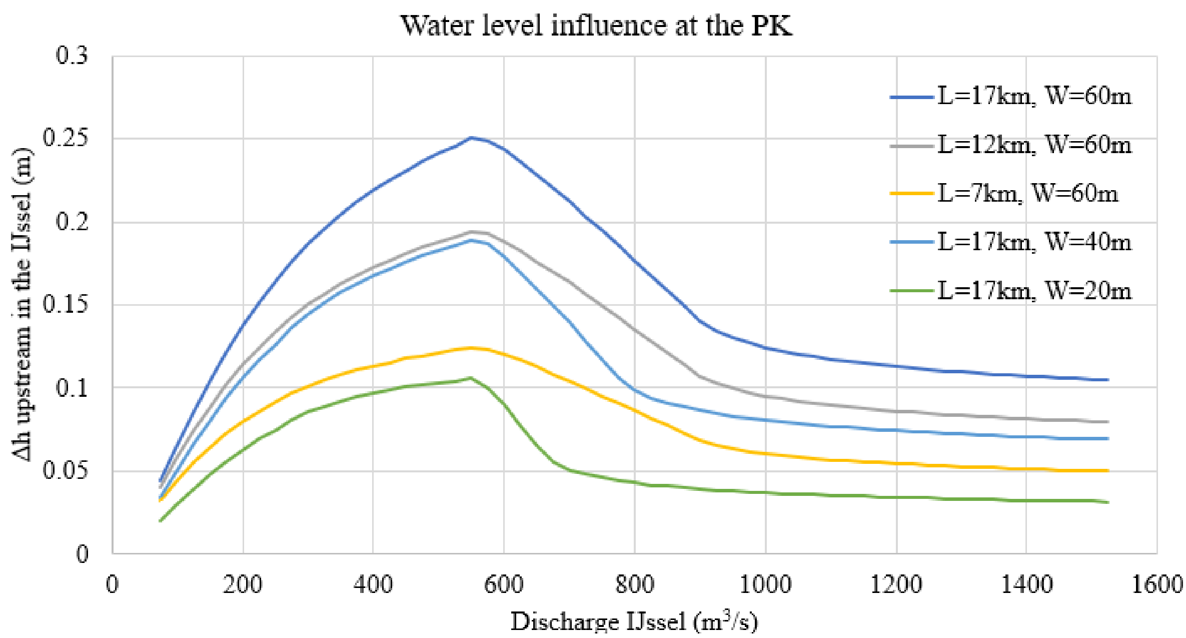

Figure 5.3: Water level difference at the Pannerdense Kop as a result of the widening intervention on the IJssel

5.4 Directly steering the sediment partitioning at the Pannerdense Kop

The interventions in the Boven-Rijn which aimed at changing the sediment partitioning at the PK are grouped together. These interventions change the sediment partitioning through two dimensional processes which can not be modeled in 1D. Therefore this group of measures is modeled by changing the nodal point relation, see equation 4.1. Only the calibration coefficient of the nodal point relation, β, is changed. By modelling the interventions this way no information about the effectivity of the specific interventions is obtained. However, changing the nodal point relation does give us insight into what the effects of interventions aimed at diverting sediment at the PK are on morphology and the discharge partitioning at the PK. A large volume of sediment is diverted towards the Waal in order to obtain an indication of the potential effects of steering the sediment partitioning at the PK. The nodal point relation is changed such that 20% extra sand and gravel are diverted towards the Waal, see Table 5.2. The decrease in bed load towards the PC will lead to additional erosion on the PC. For this study, 1.5 m is chosen rather arbitrarily as the upper boundary of additional erosion on the PC. Through trial and error it is found that diverting 20% extra sand and gravel towards the Waal corresponds to an additional erosion on the PC of 1.5 m.

Table 5.2: Nodal point calibration coefficients for the runs for the changed sediment partitioning at the PK intervention

	Reference	20% increase
β_{sand}	1.79	3.78
β_{gravel}	1.79	3.78

5.5 Dredging in the Pannerden Canal and dumping in the Waal

Dredging and dumping is implemented in D-FLOW FM by using the dredge and dump module. A different D-FLOW FM version is used to execute this simulation since the D-FLOW FM version used in the simulations for the other interventions is not capable of running the dredge and dump module. The results of the dredge and dump simulation are compared to a reference run with the same DFLOW-FM version. The differences between both reference runs are shown in Appendix G. The bed level differences are small local differences which are approximately 0.2 m maximally except for the downstream end of the Niederrhein and the upstream end of the Boven-Rijn. This is outside the region of influence for the discharge partitioning at the PK, which differs maximally 0.3%. The differences between both reference simulations complicates direct comparison of the results of the simulation with the dredge and dump intervention and the results of the simulations with the other interventions. However, the small differences do allow for a comparison of differences between the simulations of the interventions and their reference simulation.

In the dredge and dump module the dredging speed and duration, the dredge and dump location and the dredge and dump distribution need to be specified. The dredging and dumping activities are repeated every 2.5 years. During the dredging the highest deposits are removed firstly and for the dumping the sediment is distributed based on the dump capacity. The dredging and dumping activities are executed in one day. The dredging volume is determined by a dredging rate which is defined in m^3/year. The first dredging and dumping activities are carried out between days 9 and 10. This time window is chosen because the morphological developments in the model are only started after a week since the model needs this time to fill with water.

The dredging and dumping should take place upstream in the PC and the Waal in order to effectively affect the discharge partitioning at the PK. Upstream in the Waal, at Erlecom (rkm 874.5) bendway weirs are present. In practice the bendway weirs at Erlecom cause problems due to insufficient depth for navigation during low flows. So nourishing at this location is unwanted. Therefore the nourishment will be placed upstream from the bendway weirs at Erlecom. The upstream part of the Waal has many bends. Therefore it is not possible to not locate the nourishment in a river bend. Bend effects are not captured in this 1D-model so the behavior of nourishments in the bends is not modelled. This is discussed in more detail in the Discussion. For the Waal the dumping is located immediately downstream of the bifurcation to maximize the effect on the discharge partitioning, see Appendix B. From the reference simulation it is found that the bed level development in the PC is different for the upstream part than for the downstream part, see Figure 6.9. Upstream more erosion is observed than downstream. To prevent aggravating the unequal bed level development the dredging activities are located 4 km downstream of the PK, see Appendix B.

The length over which dumping takes place is taken from De Lange (2021) where the length of nourishments was set to 2.5 km. Since the main channel width of the Waal is approximately twice the main channel width of the PC, dredging along the same length as the nourishment length would lead to a larger erosion pit in the PC compared to the height of the aggradation hump in the Waal. Therefore the dredging length is scaled with the ratio of the widths leading to a dredging length of 5 km. For the volume of the nourishment the scour hole depth in the PC is normative. As a result of the repeated dredging the bed in the PC starts eroding. Through trial and error it is found that setting the maximum dredging speed to $2.5 \cdot 10^7$ m^3/year limits the added erosion in the PC to 1.5 m which is deemed acceptable for this study.

6 Modelling results reference simulation

In this chapter the morphological development and the development of the discharge partitioning at the PK are analyzed for the reference simulation. Sections 6.1 up until 6.4 provide the morphological development of the Dutch Rhine branches. In section 6.5 the development of the discharge partitioning over the Dutch Rhine branches is presented.

6.1 Niederrhein and Boven-Rijn

Figure 6.1a shows the bed level development of the Niederrhein and Boven-Rijn (BR) for the next 60 years. Figure 6.1b shows the bed level change ($\Delta z_{b,0}$) for both reaches with respect to the initial situation. Erosion is observed. In Figure 6.4a the reach-averaged bed level change throughout time is presented for both reaches. The Niederrhein starts degrading along the majority of its length from the start of the simulation. Between river kilometers 835 and 840 aggradation is observed as a result of a side channel that reduces the sediment transport capacity in the main channel. The degradation takes place during the first 30 years after which the bed level of the Niederrhein stabilizes. The degradation in the Niederrhein locally reaches a maximum of 1.4 m and the reach-averaged degradation during the first 30 years equals 53 cm. During the last 30 years the bed aggrades with 3 cm. The erosion rate during the first 30 years equals 1.7 cm/year.

Initially sedimentation takes place in the Boven-Rijn. After the first two years the erosion starts and after 4.5 years the averaged bed level is at its initial level again. The erosion stops after 45 years when the erosion equals 1.2 m. The erosion rate during this period is 2.7 cm/year. The BR and Niederrhein have degraded in the past but measurements show stable behavior during the past 10 years. Experts have different opinions on the prediction for the bed level development of the Niederrhein and BR as it is not entirely clear whether the reaches have fully adapted to interventions in the river system yet. Furthermore, the bed level development is dependent on the management of the German Rhine as this influences the sediment influx.

The erosion of the Niederrhein and Boven-Rijn is coupled to the development of the bed sediment composition of those branches. The bed sediment composition is shown by the geometric mean grain size. The geometric mean grain size is defined as follows:

$$D_g = \exp\left(\sum_{i=1}^{16} x_i \, ln(D_i)\right) \tag{1.1}$$

Where x_i is the fraction of the grain size D_i present in the active layer. The summation is for all 16 fractions present in the model. From Figure 6.2 it is seen that from the start of the simulation the vast majority of the Niederrhein coarsens. A coarse sediment supply from upstream may cause coarsening but the fact that it takes place from the start along the entire length of the Niederrhein indicates that the boundary condition is not the reason for the coarsening. The coarsening is a direct result of the bed degradation. The bed coarsens since fine sediment is more easily entrained than coarser sediment. In Figure 6.4b the reach averaged geometric mean grain size change (ΔD_g) with respect to the initial situation is presented. It is seen that the coarsening in the Niederrhein takes place during the first 30 years of the simulation after which the mean grain size stabilizes. Initially the Boven-Rijn fines slightly but after a few years the coarsening also starts in the Boven-Rijn. After 45 years the mean grain size of the BR stabilizes.

The reason for the initial fining is deposition of the fine sediment eroded from the Niederrhein. This also explains the slight aggradation at the start of the simulation in the Boven-Rijn.

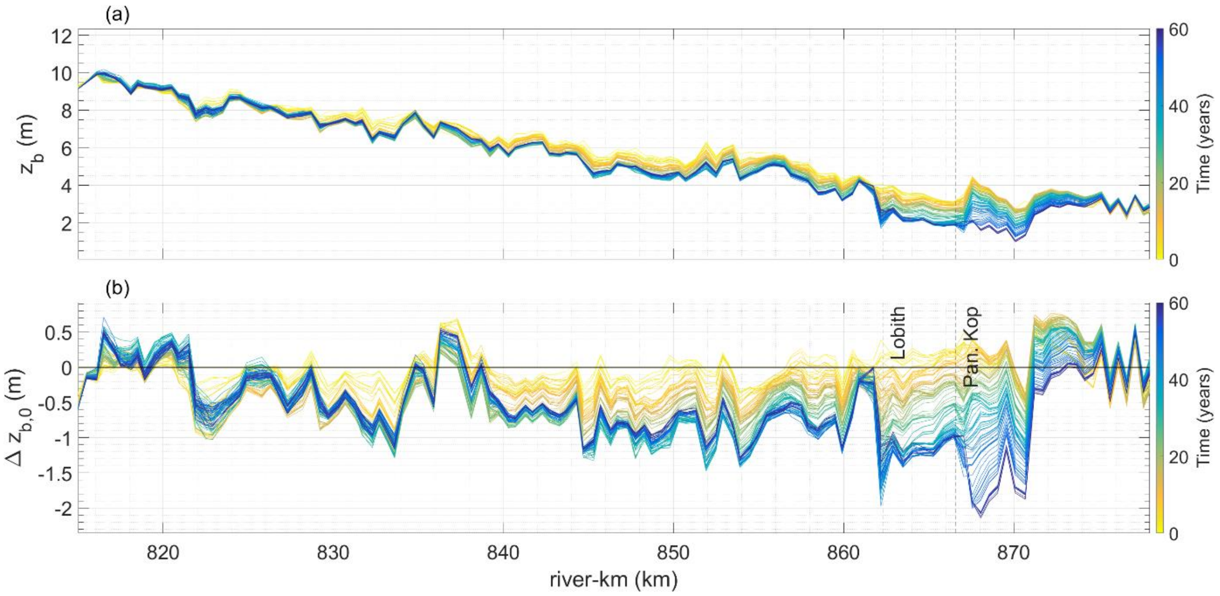

Figure 6.1: a) Main channel averaged bed level development and b) the main channel averaged bed level change with respect to the initial bed level for the Niederrhein and Boven-Rhein for the reference simulation.

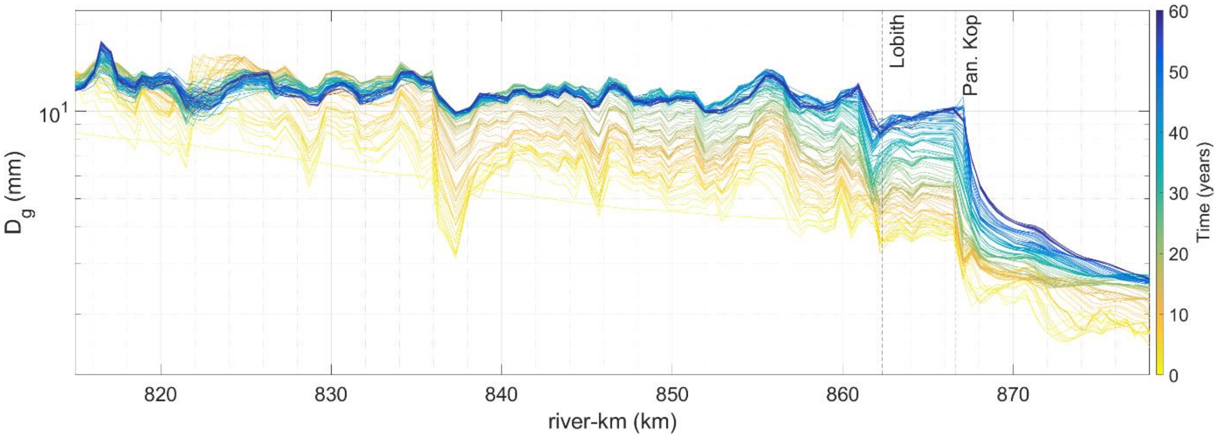

Figure 6.2: Geometric mean grain size development for the Niederrhein, Boven-Rijn and Pannerden Canal for the reference simulation.

The degradation and coarsening of the bed in the Niederrhein and Boven-Rijn is also seen in the sediment transport over this reach. Initially the sediment transport is high and it increases along the Niederrhein and BR, see Figure 6.3. When the bed stabilizes it has coarsened a lot. The sediment transport capacity is lower after the coarsening leading to a decrease in sediment transport as is shown in Figure 6.4c where the reach averaged bed load sediment transport (Q_s) is shown.

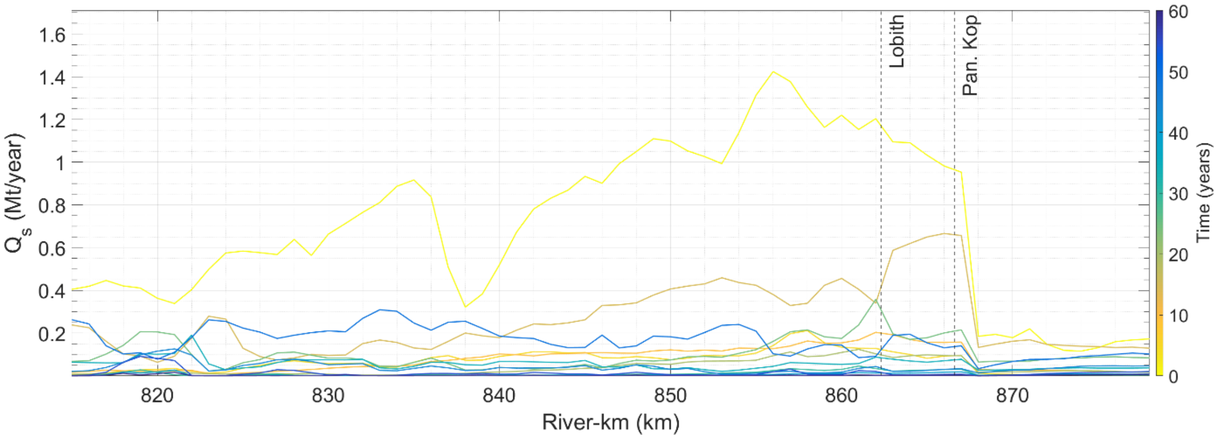

Figure 6.3: Yearly bed load sediment transport in time for the Niederrhein, Boven-Rijn and Pannerden Canal for the reference simulation.

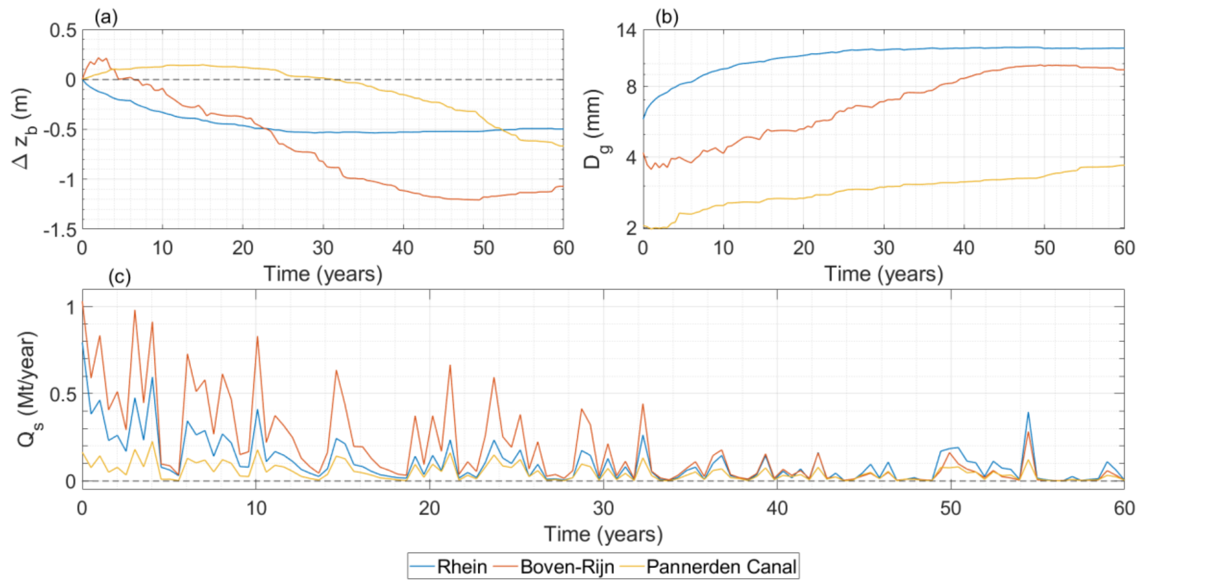

Figure 6.4: a) Reach averaged absolute main channel bed level change, b) reach averaged absolute mean grain size change and c) reach averaged yearly bed load sediment transport in the Niederrhein, Boven-Rijn and Pannerden Canal for the reference simulation.

6.2 Pannerden Canal

The bed level development of the Pannerden Canal (PC) is shown in Figure 6.1 for the reference case. The bed level initially shows aggradation throughout the whole canal. The initial aggradation is present longer and is higher in the downstream part compared to the upstream part of the PC. Figure 6.4a shows that on average the aggradation reaches 0.2 m and the bed starts degrading after 15 years. The reason for the aggradation is the high sediment supply from upstream as is shown in Figure 6.3. The supply of fine sediment from the Niederrhein and Boven-Rijn also leads to a slight fining of the bed upstream initially, see Figure 6.2. The upstream part of the PC degrades 1.2 m on average after 60 years and the downstream part degrades 0.2 m on average after 60 years which is equal to erosion speeds of respectively 2.0 cm/year and 0.3 cm/year. The current erosion speed is 1.5 cm/year which corresponds well to the upstream part and matches less with the downstream part. For the whole PC, the river bed coarsens. From Figure 6.2 it is seen that the coarsening wave from the Boven-Rijn travels into the PC. As a result of the coarsening and the reduced sediment supply from upstream, the sediment transport in the PC drops during the simulation, which is shown in Figure 6.4c.

6.3 Waal

The bed level development of the Waal is shown in Figure 6.5. Along the entire Waal a slope change is observed. Up to rkm 915 the Waal erodes and downstream from rkm 915 aggradation occurs. In Figure 6.8a the mean bed level change with respect to the initial situation is shown for three reaches along the Waal: the Boven-Waal (rkm 867-884), the Midden-Waal (rkm 884-930) and the Beneden-Waal (rkm 930-961). It is seen that the eroded sediment from the Niederrhein and Boven-Rijn also influences the Waal since in the Boven-Waal initially aggradation and fining takes place as a result of the fine sediment eroded from the Niederrhein and Boven-Rhein. After the initial aggradation, erosion starts. In the first 30 years of the simulation the erosion is counteracted by the sediment supplied from upstream. This supply significantly reduces after the first 30 years leading to increased erosion. The erosion in the Boven-Waal during the first 30 years of the simulation equals 0.35 m or 1.2 cm/year and in the remaining 30 years it equals 1.30 m or 4.3 cm/year. In the Midden-Waal the bed only starts eroding after 10 years. This leads to little erosion in the first 30 years. The erosion during the first 30 years equals 0.08 m or 0.27 cm/year. From year 30 to year 60 the erosion equals 0.20 m or 0.67 cm/year. In the Beneden-Waal aggradation occurs. During the first 30 years the aggradation equals 0.73 m or 2.4 cm/year and during the second 30 years it equals 0.31 m or 1.0 cm/year. This is higher than the current rate. The reason for this is that dredging activities in the Beneden-Waal are not included in the model. What is also interesting is that at the fixed layer at Nijmegen and the bottom groynes at Erlecom some erosion takes place. This is possible since an active layer of 1 m is present which can erode.

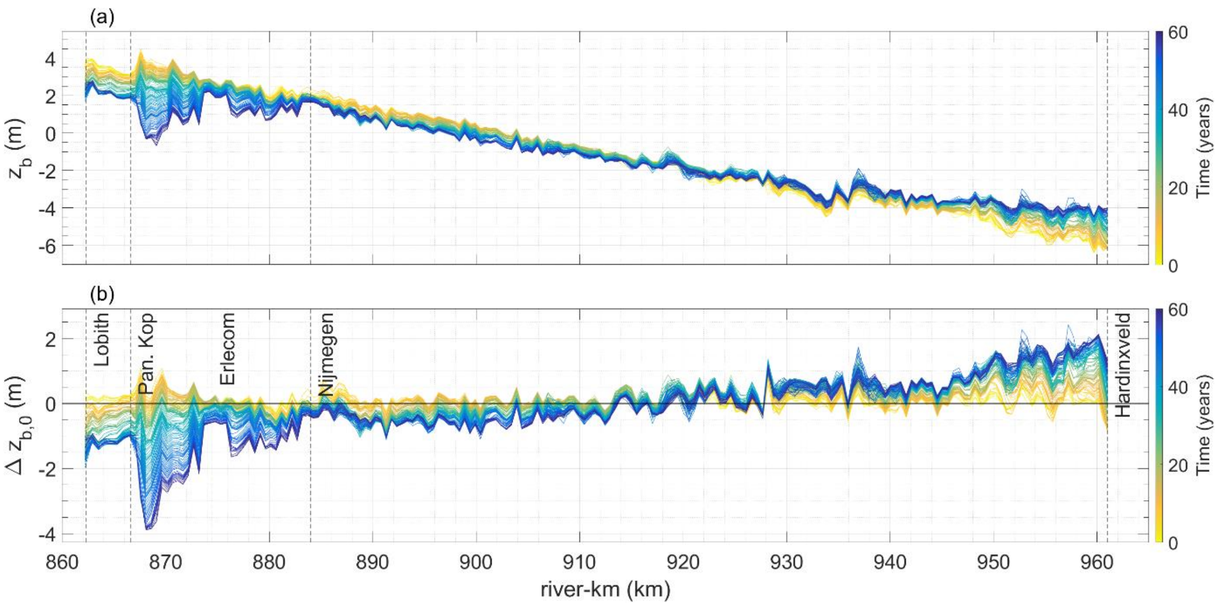

Figure 6.5: a) Main channel averaged bed level development and b) the main channel averaged bed level change with respect to the initial bed level for the Waal for the reference simulation.

From the sediment transport along the Waal reach the erosional and aggradational pattern is visible, see Figure 6.6. The sediment transport increases in downstream direction along the Boven-Waal and Midden-Waal and it decreases in downstream direction along the Beneden-Waal for the majority of the simulation. The sediment transport fluctuates over time as an unsteady hydrograph is used. An overall decrease in the sediment transport rate is observed along the Waal, see Figure 6.8c. From Figure 6.8c it is also seen that from year 25 onwards the average sediment transport increases in downstream direction. This explains the erosion as the slope of the Waal starts decreasing to match the low sediment supply.

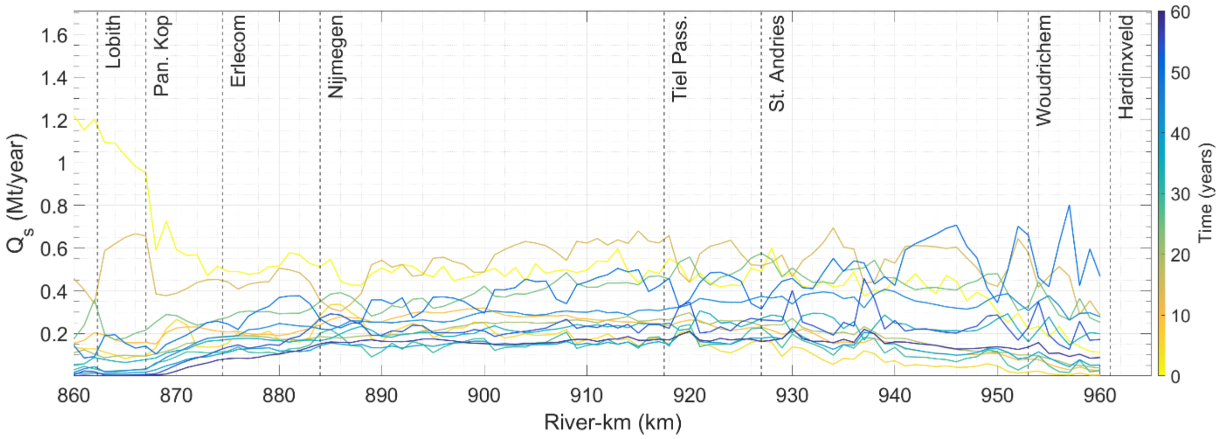

Figure 6.6: Yearly bed load sediment transport in time for the Waal for the reference simulation.

In Figure 6.7 the geometric mean grain size development of the Boven-Rijn and Waal is seen. The changes in bed surface mean grain size in the Waal are small compared to the Boven-Rijn. In general, a coarsening of the bed takes place throughout the Waal. Just as in the Boven-Rijn, during the first few years fining of the bed is observed in the Boven-Waal. After this, during the first 30 years coarsening is observed in the Boven-Waal, see Figure 6.8b. During year 30-60 a fining of the river bed is observed again. During this period the Boven-Waal erodes rapidly. It is expected that the fining is related to the active layer concept, in which the active layer is replenished from the substrate layers. Analysis shows that during the first 30 years the first three substrate layers are emptied and that afterwards the remaining substrate layers are emptied. The composition of the deep substrate layers changes minimally which means that the sediment composition moves towards its initial state and therefore fines.

The Midden-Waal and Beneden-Waal coarsen throughout the simulation, see Figure 6.8b. Furthermore it is seen that the extreme coarsening from the Boven-Rijn only reaches the Waal minimally. The gravel sand transition (GST), which occurs at a mean grain size of 2 mm, only shifts by 1 km in 60 years. This does not match the measurements which indicate the has become les abrupt (Ylla Arbós et al., 2021).

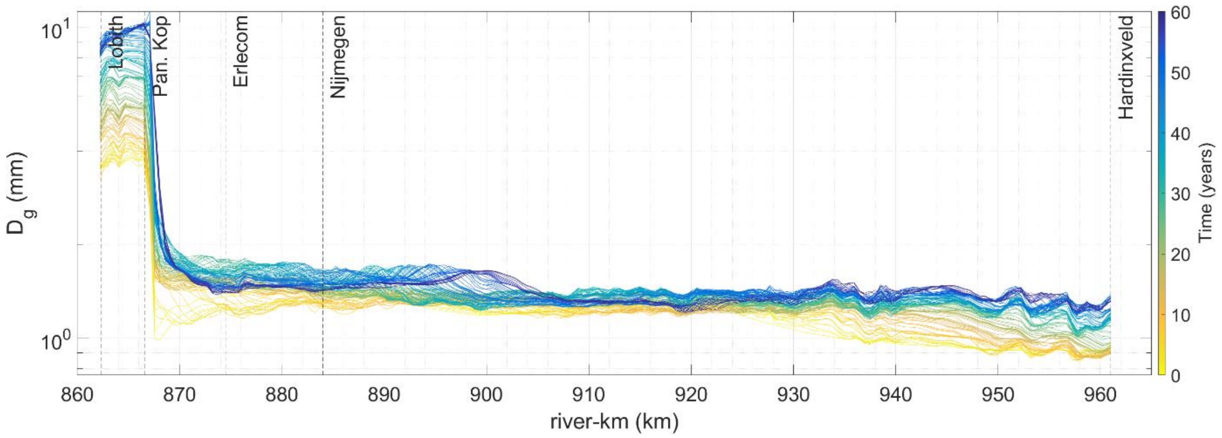

Figure 6.7: Geometric mean grain size development for the Boven-Rijn and Waal for the reference simulation.

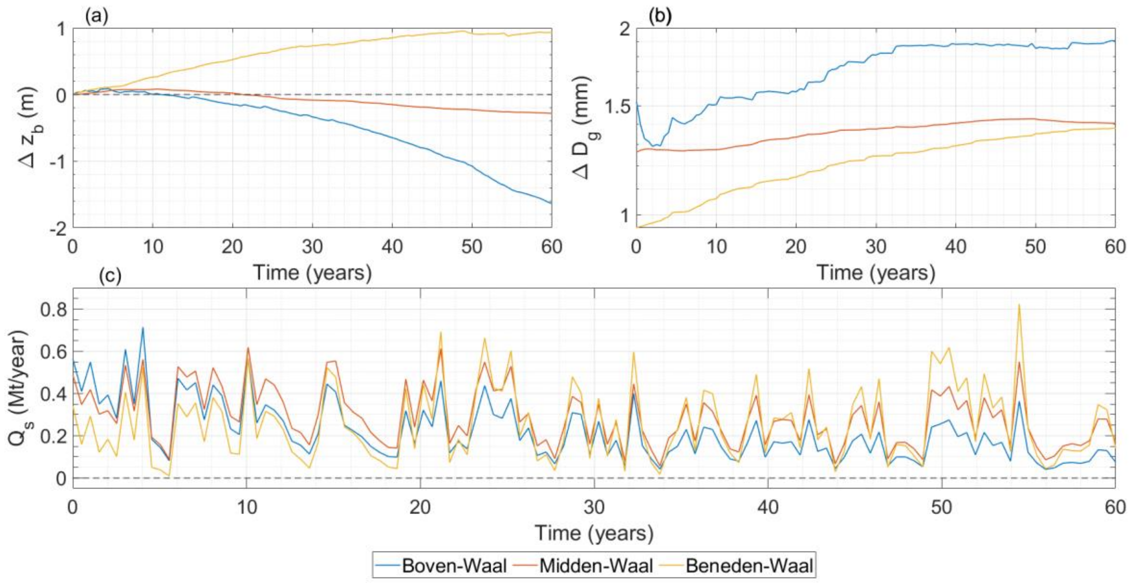

Figure 6.8: a) Reach averaged absolute main channel bed level change, b) reach averaged mean grain size change and c) reach averaged yearly bed load sediment transport in the Boven-Waal, Midden-Waal and Beneden-Waal for the reference simulation.

6.4 IJssel and Nederrijn-Lek

This study focusses on the developments around the Pannerdense Kop, and therefore the IJssel and Nederrijn-Lek (NR-Lek) branches are discussed in less detail. Detailed figures on the development of the mean grain size and the yearly sediment transport are shown in Appendix G. In Figure 6.11 the reach and time averaged mean grain size and yearly sediment transport are shown. From Figure 6.9 and Figure 6.11a it is seen that the Nederrijn-Lek has a slight aggrading trend with a reach-averaged aggradation of 0.16 m or 0.27 cm/year which is in line with the current measured trend. The IJssel is morphologically more stable as is seen in Figure 6.10 and Figure 6.11a. There is degradation upstream of 0.4 to 1.0 m which matches the current trend. Further downstream slight aggradation is found while slight degradation is expected. At the downstream end there is an aggradation hump which is attributed to the summer bed deepening which has taken place over there. From Figure 6.11a it is seen that both river reaches coarsen throughout the simulation.

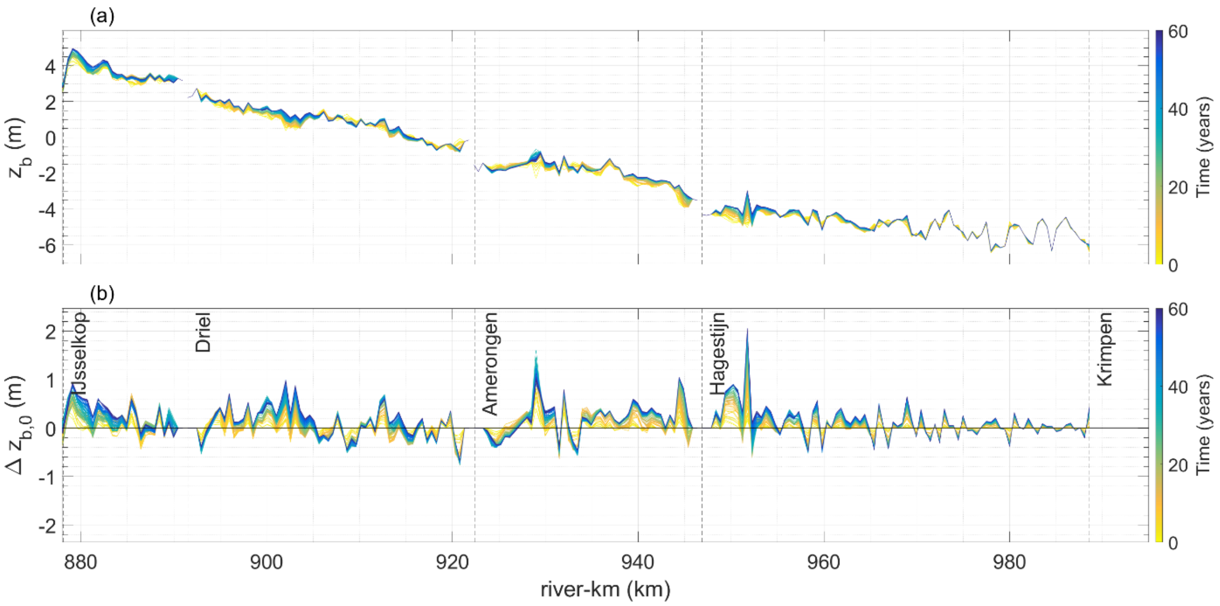

Figure 6.9: a) Main channel averaged bed level development and b) the main channel averaged bed level change with respect to the initial bed level for the Nederrijn-Lek for the reference simulation.

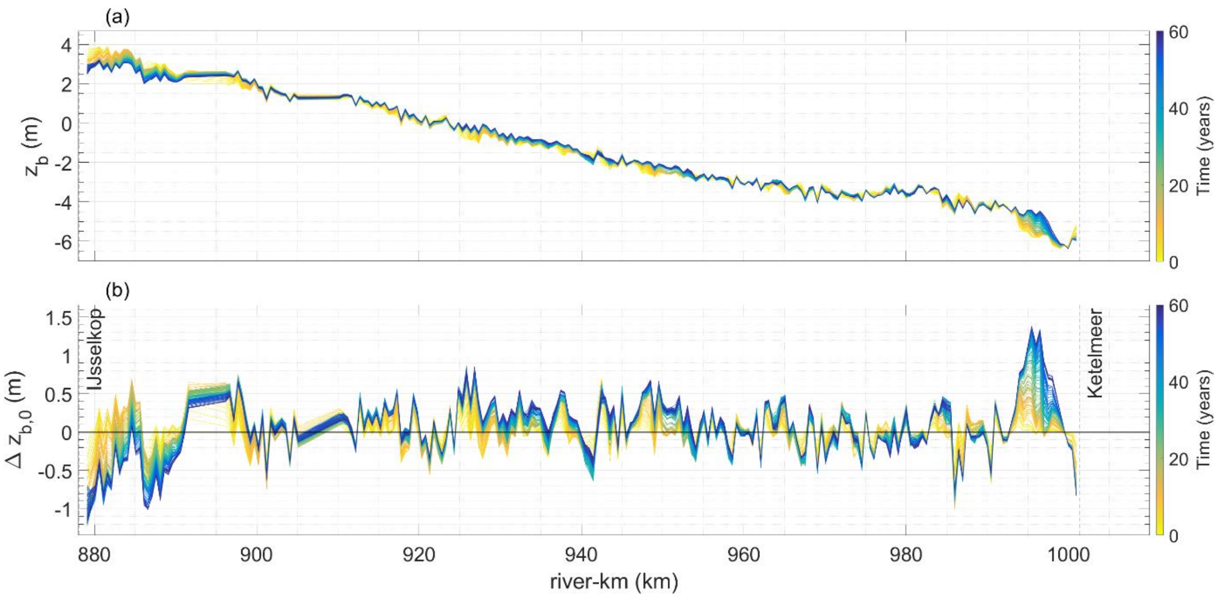

Figure 6.10: a) Main channel averaged bed level development and b) the main channel averaged bed level change with respect to the initial bed level for the IJssel for the reference simulation.

Figure 6.11c and Figure 6.11d show the time averaged sediment transport for respectively the IJssel and the NR-Lek. The aggradational pattern from the NR-Lek is seen from the averaged sediment transport along the reach. The sediment transport gradually decreases downstream indicating aggradation along the whole branch. For the IJssel initially the sediment transport increases after which it decreases a little and it decreases sharply in the end, which explains the initial erosion and the slight aggradation and aggradation hump downstream.

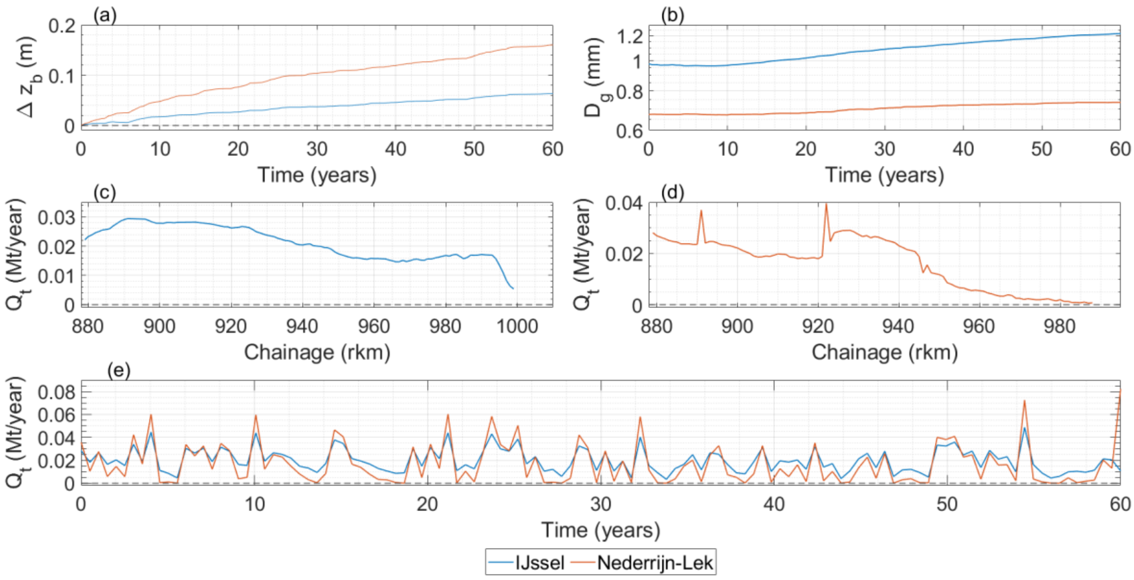

Figure 6.11: a) Reach averaged absolute main channel bed level change and b) reach averaged absolute mean grain size change for the IJssel and Nederrijn-Lek. c) Time averaged mean yearly bed load sediment transport rate for the IJssel and d) for the Nederrijn-Lek. e) Reach averaged yearly bed load sediment transport in the IJssel and Nederrijn-Lek for the reference simulation.

6.5 Discharge distribution

In Figure 6.12 and Figure 6.13 the change in discharge partitioning at the Pannerdense Kop and the IJsselkop is seen for the reference simulation. The changes are a result of the changing bed levels and bed slopes in the downstream branches. In both figures a knickpoint is observed which indicates that the Driel weir starts opening. The weirs open as a function of the water level at Lobith. At a water level of 8.65 m+NAP at Lobith the weirs start opening. From Figure 6.12 it follows that this water level corresponds to a Lobith discharge of approximately 1650 m^3/s at the start of the simulation and 1950 m^3/s at the end of the simulation. The required discharge for opening increases throughout the simulation due to the erosion in the Boven-Rijn. After the first 10 years the Boven-Waal starts eroding more quickly than the Pannerden Canal leading to increased discharge towards the Waal. From Figure 6.12 it is seen that for the entire discharge range of the Boven-Rijn, the Waal receives more discharge. The difference in discharge fraction towards the Waal between the start and the end of the simulation is larger for low flows than for the higher flows. For the high flows the flood plains are inundated which leads to a smaller influence of the changed main channel bed levels on the discharge partitioning. In Figure 6.14a and Figure 6.14b the development of the biyearly averaged Waal discharges and their trends are presented. The difference in discharge partitioning for the low and high flows is obtained from the trends. For the low flows the average Waal discharge fraction increases by 5.3 % and for the high flows this is 3.0 %. In Figure 6.13 it is seen that also for the entire discharge range of the PC, the IJssel discharge fraction increases over time. In Figure 6.14c and Figure 6.14d the development of the biyearly averaged IJssel discharges and their trends are presented. The IJssel discharge fraction increases with 0.4 % for the low flows and 3.6 % for the high flows.

For very low PC flows the discharge ratio of the IJssel exceeds 1 in some cases which indicates water flows from the Nederrijn-Lek towards the IJssel. This is not realistic as a minimum flow of 25 m^3/s towards the Nederrijn-Lek is maintained in reality. Therefore data with NR-Lek discharges below 25 m^3/s are left out in the analysis of the IJssel discharge fraction. The IJssel discharge fraction shown in Figure 6.13 is relative to the Pannerden Canal discharge. This way the influence of the changing discharge partitioning at the Pannerdense Kop is left out and only the changes of the discharge partitioning at the IJsselkop are regarded. Figures of the IJssel and Nederrijn-Lek discharge fractions relative to the Boven-Rijn discharge are included in Appendix G.

In order to compare the discharge distributions for the same upstream discharge, a least square fit (LSF) of a second order polynomial is applied. A discharge of interest would be a Lobith discharge of 1020 m^3/s (ALD) since this discharge is used as a guideline in various practices. However too little data is available for this discharge. A Lobith discharge of 1400 m^3/s is selected as this is better represented by the data. Only the low flows are included in the LSF since a knickpoint is present in the discharge partitioning curve when the Driel weir starts opening, see Figure 6.12. Through a least squares fit the Waal discharge fraction for a Lobith discharge of 1400 m^3/s ($f_{QW,1400}$) is found at the start and end of the simulation. The value at the start of the simulation corresponds to the second year since too little data is available in the first year to perform the LSF. $f_{QW,1400}$ equals 78.2 % at the start of the simulation and 82.5 % at the end. The difference is 4.3% or 60 m^3/s.

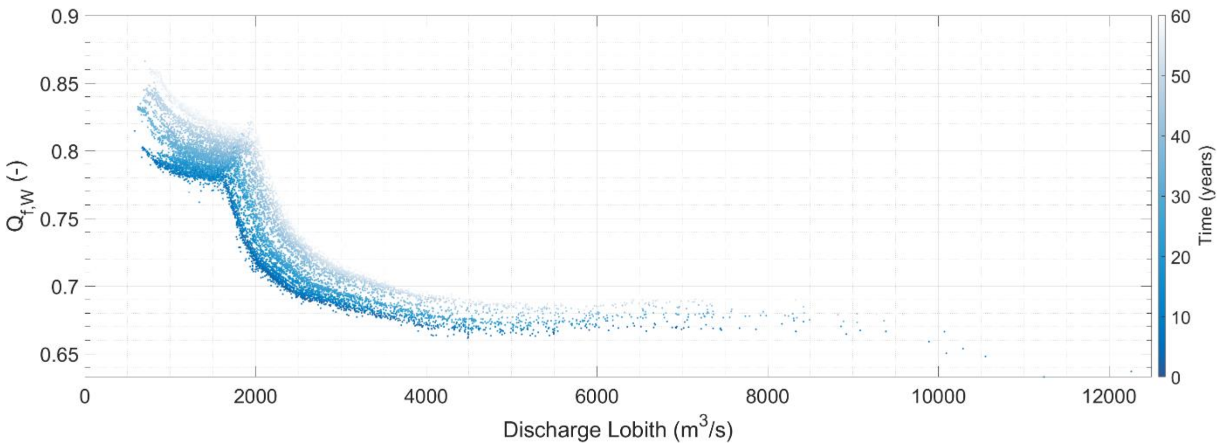

Figure 6.12: Development in time of the Waal discharge fraction as a function of the Lobith discharge for the reference simulation.

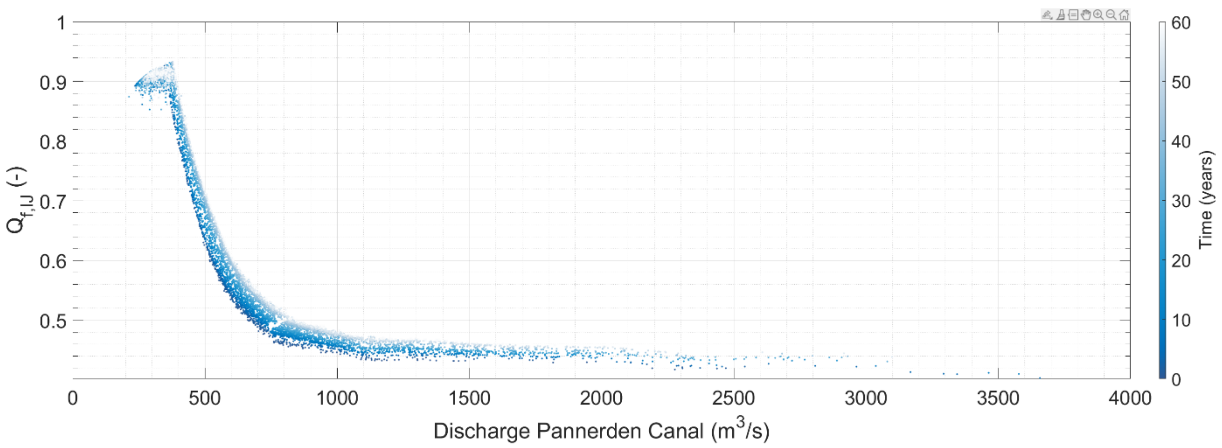

Figure 6.13: Development in time of the IJssel discharge fraction relative to the Pannerden Canal discharge as a function of the Pannerden Canal discharge for the reference simulation.

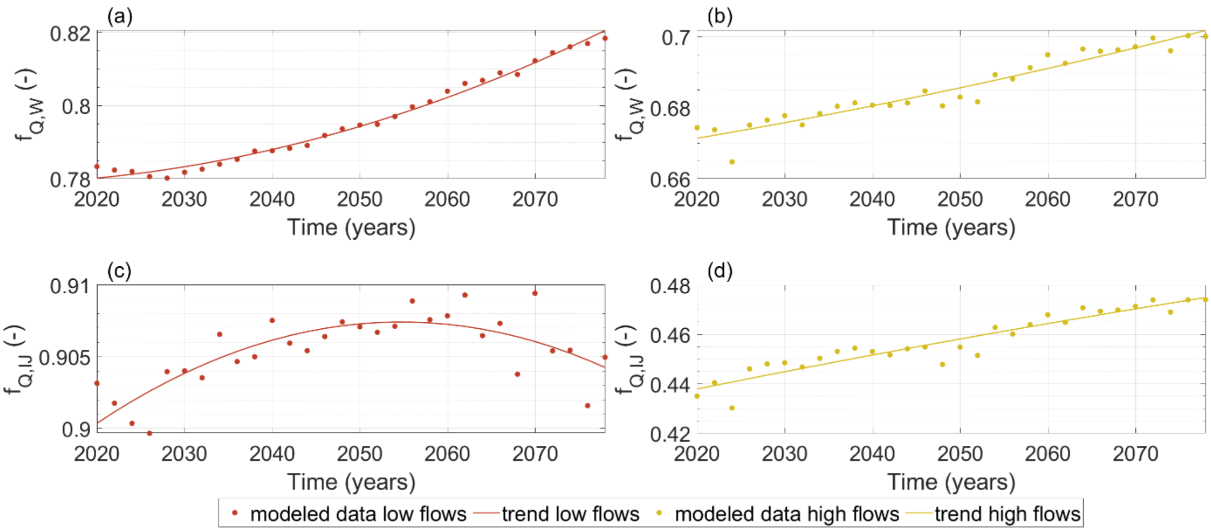

Figure 6.14: Development of the biyearly averaged Waal and IJssel discharge fractions relative to the Lobith and PC discharges respectively and the trends for a) the Waal during low flows ($Q_{Lobith} < 1650$ m^3/s), b) the Waal during high flows ($Q_{Lobith} > 2950$ m^3/s), c) the IJssel during low flows and d) the IJssel during high flows for the reference simulation.

7 Modelling results interventions

This chapter answers the second sub-question "What are the effects of the selected interventions on the discharge partitioning over the Pannerdense Kop and on the morphology downstream of the bifurcation?". Therefore in this chapter the morphological development and the development of the discharge partitioning at the PK is analyzed for the simulations with the interventions as described in the Chapter 5.

The interventions are analyzed separately. The analyses are all structured the same. First, a short recap of the intervention is given. Next, bullet points are listed which give a short overview of the most important effects of the intervention on the morphology and the discharge partitioning. Then the effects of the intervention on respectively the bed level development of the Dutch Rhine branches and the discharge partitioning over them are dealt with extensively. For the effects on the bed level development for all interventions the bed level difference with respect to the reference case is shown for the Dutch Rhine branches. Plots of the mean grain size, sediment transport and the reach averaged bed level difference are included when necessary to understand and explain the bed level development. The reasoning for the bed level development starts from the branches which are directly affected by the interventions.

For the effects on the discharge partitioning first, the difference in Waal discharge fraction with respect to the reference case is shown as a function of the Lobith discharge. This way it is difficult to spot a trend in the data. To enable this, in the next figure the discharge fraction is averaged for low flows ($Q_{Lobith} < 1650$ m^3/s) and high flows ($Q_{Lobith} > 2950$ m^3/s) and then plotted against time. This is done for the relative difference in Waal and IJssel discharge fractions and for the absolute value of the Waal discharge fraction. For the relative difference the data is averaged semi-annually. Semiannually averaging the data for the absolute discharge fraction leads to messy plots since the absolute discharge fraction is more variable. Therefore the absolute discharge fraction data is averaged biyearly. The relative difference in IJssel discharge fraction in the second plot is based on the discharge in the PC. This way the influence of the changing discharge partitioning at the Pannerdense Kop is left out. This however does not show the total effect of the interventions on the discharge in the IJssel and NR-Lek. Therefore, in the last figure the relative difference in IJssel and NR-Lek discharge fractions are shown based on the discharge at Lobith.

7.1 Side channel from the Boven-Rijn to the Pannerden Canal

The side channel connects the Boven-Rijn to the Pannerden Canal. The side channel is 5 km long and 50m wide. It is assumed that only water enters the side channel and that the sediment remains in the Boven-Rijn. To be able to justify this assumption, an inlet step is present at the entrance of the side channel.

Overview effects

- Downstream of the water extraction point the Boven-Rijn shows reduced erosion.
- Upstream of the water addition point the PC shows reduced erosion and downstream of it the PC shows enhanced erosion.
- Upstream of the water extraction point the PC initially shows reduced coarsening. Downstream of the water extraction point this changes to enhanced coarsening. Throughout the simulation this changes and the PC shows enhanced coarsening upstream of the water extraction point and reduced coarsening downstream of it.
- The development of the Waal discharge fraction is hardly influenced. Throughout the simulation the Waal discharge fraction decreases slightly relative to the reference case.

Bed level difference

In Figure 7.1 up to Figure 7.3 the bed level development with respect to the reference case is shown for the Boven-Rijn , Pannerden Canal, Nederrijn-Lek and the IJssel. The Boven-Rijn shows reduced erosion from the water offtake point onwards. This response also followed from the theoretical analysis as a water offtake point is expected to lead to a hump at the water offtake point and a water addition point leads to aggradation upstream of it. Upstream from the offtake point enhanced erosion is expected as a result of the arising M2 backwater curve. From Figure 7.1 it is seen that this takes place minimally. The bed level upstream in the Niederrhein erodes quicker than in the reference simulation but the difference only reaches approximately 1 cm. The effect of the backwater curve is counteracted by the reduced erosion on the Boven-Rijn since this leads to a smaller difference in equilibrium water levels between the reaches.

Upstream in the Pannerden Canal (PC) the reach experiences reduced erosion. The reduced erosion is the result of (1) a M1-backwater curve which arises upstream of a water addition and of (2) the reduced discharge upstream in the PC with respect to the reference simulation. The reduced erosion in the PC eventually reaches a value of 0.8 m while in the Boven-Rijn this is only 0.3 m. The bed level upstream in the PC responds more extreme since the relative water addition to the PC is much larger than the relative water extraction from the Boven-Rijn. This means that the M1-backwater curve is steeper upstream in the PC and the effect due to the reduced discharge is larger. Furthermore, the reduced erosion upstream in the PC is intensified by the enhanced coarsening with respect to the reference case, see Figure 7.5.

Downstream of the water addition in the PC there is enhanced erosion as an erosion pit forms. Just downstream of the water addition the bed level keeps decreasing with respect to the reference case throughout the simulation. This can be coupled to the mean grain size development since the mean grain size in the PC downstream of the water addition shows reduced coarsening throughout the simulation, see Figure 7.5. The erosion pit travels downstream. From Figure 7.2 and Figure 7.3 it is seen that the enhanced erosion downstream of the water addition in the PC also reaches the IJssel and Nederrijn-Lek (NR-Lek). In the NR-Lek this leads to a bed level lowering with respect to the reference case until the Driel weir. The IJssel experiences a lowering of the bed level with respect to the reference case up until approximately rkm 895.

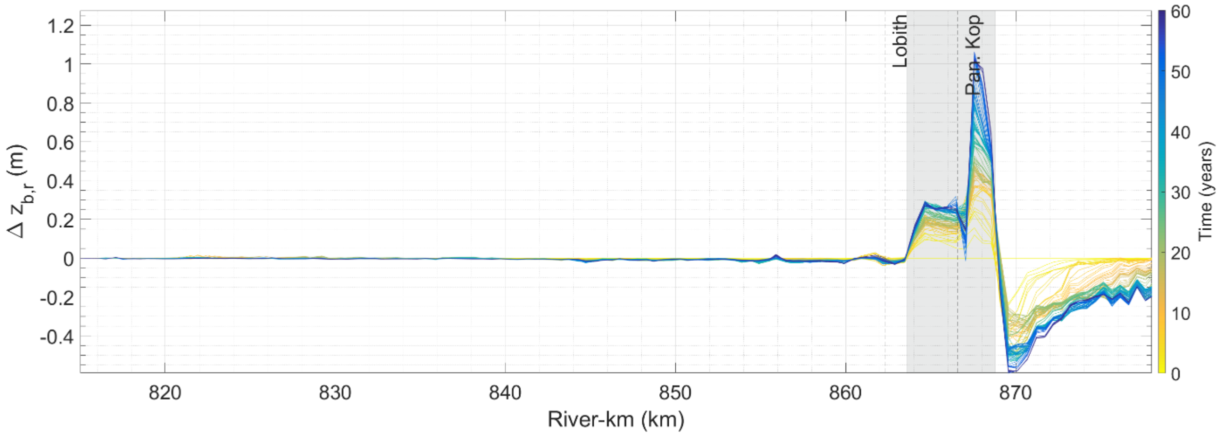

Figure 7.1: Difference in bed level of the Niederrhein, Boven-Rijn and Pannerden Canal between the simulation with the side channel (A) and the reference simulation. The grey area indicates the location of the side channel.

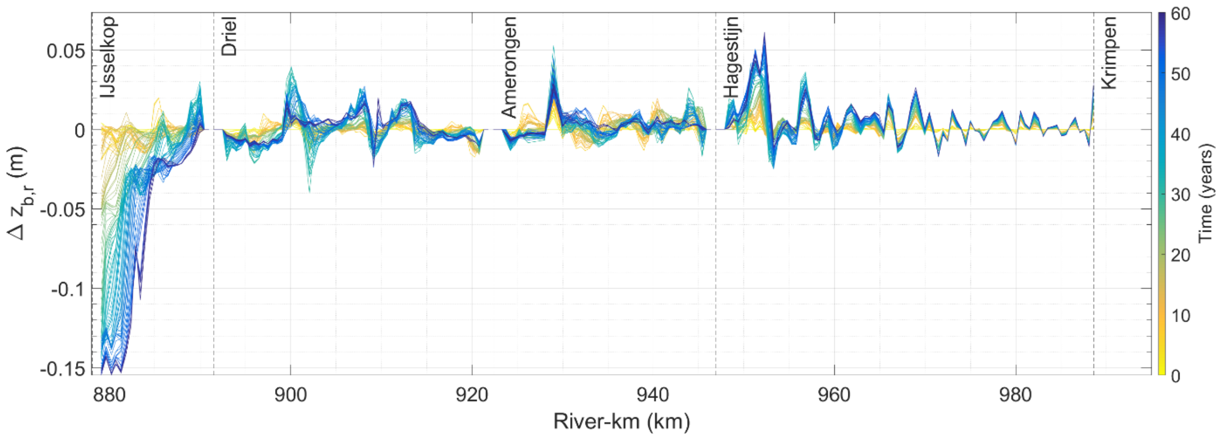

Figure 7.2: Difference in bed level of the Nederrijn-Lek between the simulation with the side channel (A) and the reference simulation.

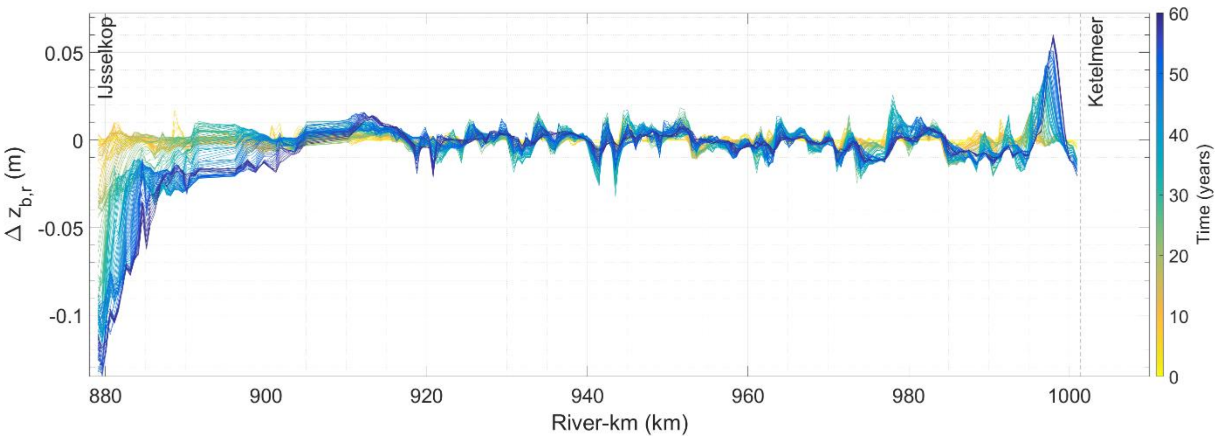

Figure 7.3: Difference in bed level of the IJssel between the simulation with the side channel (A) and the reference simulation.

In Figure 7.4 the bed level development with respect to the reference case is shown for the Boven-Rijn and Waal. The bed level in the Waal initially decreases and afterwards slowly increases with respect to the reference case throughout the simulation. The initial relative decrease in bed level and the relative increase afterwards both start upstream in the Waal and travel downstream with a propagation speed of approximately 0.5 km/year. The initial relative decrease in bed level with respect to the reference case is caused by the enhanced initial aggradation on the Boven-Rijn. There is less fine sediment available to deposit upstream in the Waal such that the initial aggradation in the Waal is decreased with respect to the reference case. The further development of the bed level of the Waal is understood from the development of the discharge partitioning. Over time the discharge towards the Waal decreases compared to the reference case. In Figure 7.8a it is observed that for both high and low flows the semiannually averaged decrease in discharge partitioning with respect to the reference case is 0.5% at the end of the simulation. This small decrease in discharge towards the Waal leads to a small relative bed level increase along the Waal which maximally reaches 0.1 m. The discharge partitioning is based on the discharge at Lobith. However when the discharge partitioning based on the Boven-Rijn discharge downstream of the water offtake is taken, then the Waal discharge fraction increases with respect to the reference case, see Appendix H. The sediment partitioning across the Pannerdense Kop is based on the discharge fractions of the Waal and PC relative to the Boven-Rijn discharge downstream of the water offtake. So there is less discharge in the Waal compared to the reference case and, for equal discharges, there is a larger sediment supply compared to the reference case. The increased sediment supply is another reason for the reduced erosion which occurs in the Waal.

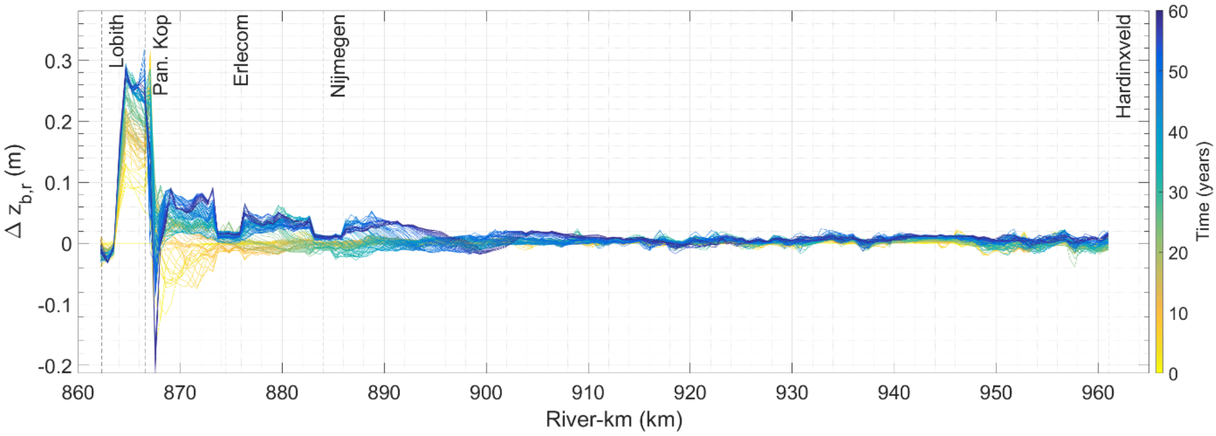

Figure 7.4: Difference in bed level of the Boven-Rijn and Waal between the simulation with the side channel (A) and the reference simulation.

Reach averaged bed level difference

Figure 7.6 shows the reach averaged bed level development of the different reaches with respect to the reference case. The negligible effect on the Niederrhein becomes visible in this figure. The bed is on average 1 cm lower than in the reference case. The bed level difference for the Midden Waal and Beneden-Waal are also approximately 1 cm. The reduced erosion from the Boven-Waal did not yet travel to these reaches during the 60 year simulation. From Figure 7.6 it is observed that the bed level development with respect to the reference case stabilizes for the Boven-Rijn and the Boven-Waal. This had not happened yet for both reaches in the Pannerden Canal. The PC is split in two reaches: One reach upstream of the water addition point and one reach downstream of it. This separation is made because the bed level development is different for these reaches.

The effect of the side channel on the bed level in the PC does not stabilize because of the mean grain size development. The development of the mean grain size with respect to the reference run is presented in Figure 7.5. The Boven-Rijn quickly becomes finer compared to the reference run as a result of the initial aggradation. Initially fine sediment is transported from the Rein. This fine sediment leads to the fining. The same holds for the upstream part of the PC. After the initial fining compared to the reference case this section coarsens. Throughout the simulation the supplied sediment from the Boven-Rijn coarsens a lot. The decreased erosion in the upstream reach means that less of the coarser sediment is transported downstream compared to the reference case. Downstream of the water addition point the side channel leads to a increased coarsening wave initially after which the bed sediment composition fines with respect to the reference case. The increased erosion along this section leads to less interaction with the coarse sediment supply from upstream, which is already reduced due to the aggradation upstream, and therefore to reduced coarsening. This development of the bed sediment composition enhances the bed level development as a result of the side channel intervention since the enhanced coarsening upstream in the PC leads to less sediment transport capacity and therefore to reduced erosion. The reduced coarsening leads to more sediment transport capacity and therefore to enhanced erosion.

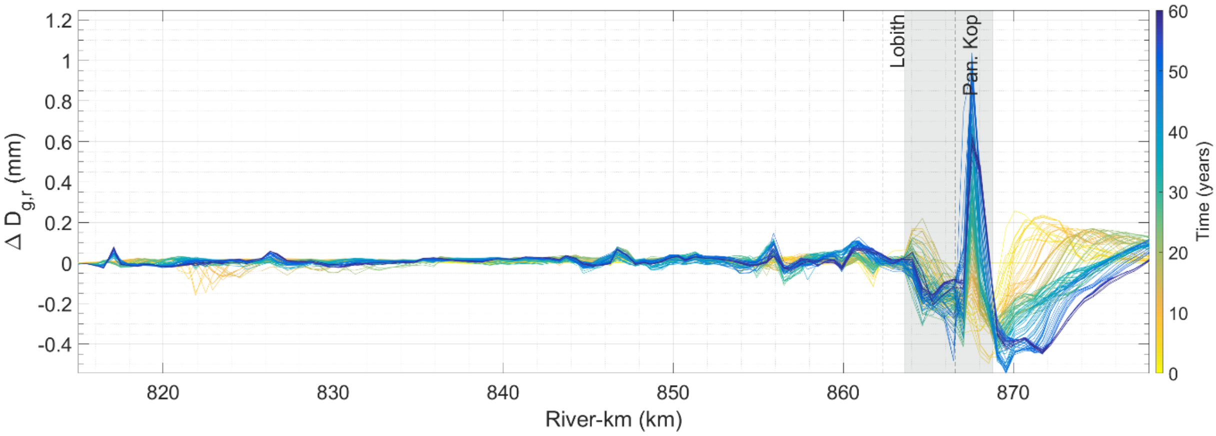

Figure 7.5: Difference in geometric mean grain size of the Niederrhein, Boven-Rijn and Pannerden Canal between the simulation with the side channel (A) and the reference simulation. The grey area indicates the location of the side channel.

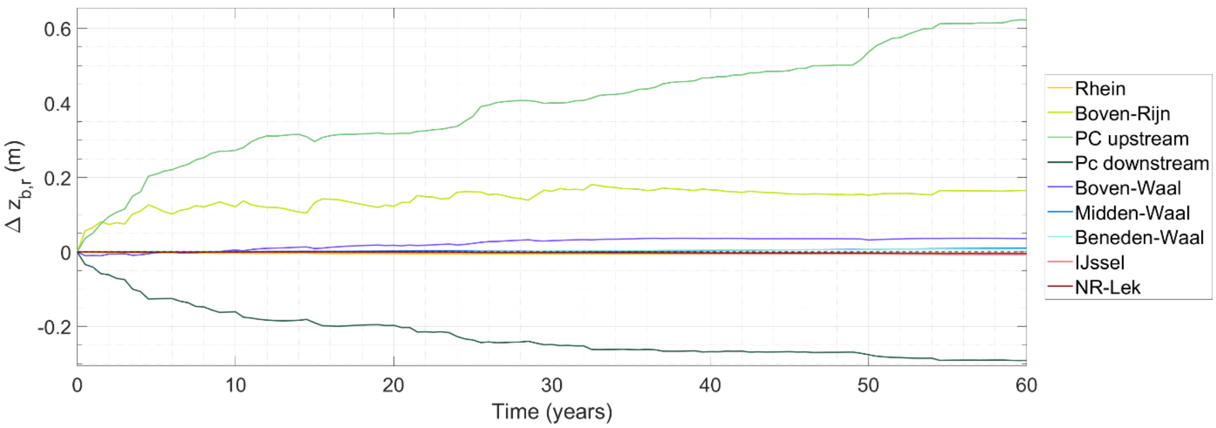

Figure 7.6: Reach averaged bed level difference between the simulation with the side channel (A) and the reference simulation.

Discharge partitioning

The difference in the Waal discharge fraction between the simulation with the side channel and the reference simulation is shown in Figure 7.7. Figure 7.8a shows the semiannually averaged relative difference in Waal discharge fraction for both low and high flows. From both figures it is observed that the influence of the side channel on the discharge partitioning at the Pannerdense Kop (PK) is limited. The relative decrease in the Waal discharge fraction at the end of the simulation is approximately 0.5%. Figure 7.8c and Figure 7.8d show the biyearly averaged Waal discharge fraction for both the reference and the side channel simulation for high and low flows. Here a biyearly average is chosen to obtain a clear picture since the variability of the absolute discharge fraction data is higher than of the data for the difference in discharge fraction. The figures show that the trend in discharge partitioning is not reversed throughout the simulation but only slightly reduced. The limited effectivity is attributed to the backwater curve which arises as a result of the water addition in the PC. This leads to an increased water level upstream in the PC which repels discharge from the PC. Apparently the water level increases upstream in the PC is capable of almost completely counteracting the discharge addition from the side channel. The discharge partitioning influence initially is higher for high flows than for low flows. This is as expected since the side channel includes a sill which prevents discharge from entering the side channel for low Boven-Rijn discharges. For the low flows the discharge partitioning at the PK is even negatively influenced initially. This is explained from the initial bed level development as follows. Initially the influence of the side channel remains upstream from the IJsselkop. The reduced erosion in the upstream part of the PC is dominant with respect to the enhanced erosion downstream in the PC. This leads to an increased water level in the PC and therefore to more discharge to the Waal. It is seen from Figure 7.1 that throughout the simulation the enhanced erosion downstream in the PC increases more rapidly and is more widespread than the reduced erosion upstream. Furthermore the reduced erosion also reaches the IJssel and NR-Lek leading to a lower water level at the IJsselkop. Together this development of the bed level leads to a relative decrease in the Waal discharge fraction throughout the simulation. This relative decrease is more evident for the low flows than for the high flows as the low flows are affected more by the bed level development of the summer bed. By executing the LSF analysis it is found the for the for the Lobith discharge of 1400 m^3/s the difference in Waal discharge ratio equals 0.18% initially and -0.45 % after 60 years. In absolute figures this would be a initial increase of 2.5 m^3/s to the Waal and a decrease of 6.3 m^3/s after 60 years.

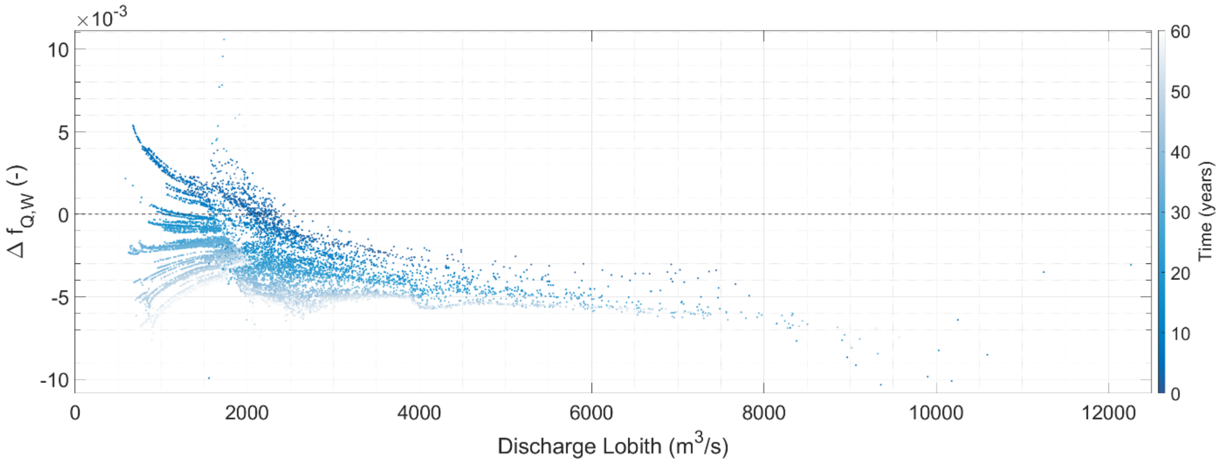

Figure 7.7: Difference in Waal discharge fraction between the simulation with the side channel (A) and the reference simulation.

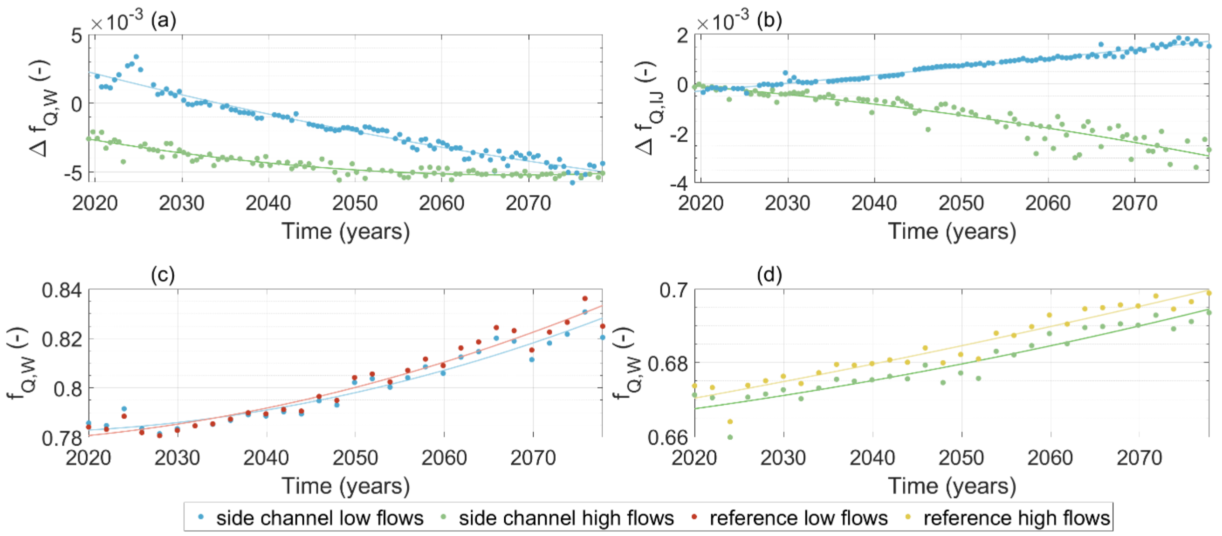

Figure 7.8: The semiannually averaged difference in discharge fraction between the simulation with the side channel (A) and the reference simulation for both low and high flows for a) the Waal and b) the IJssel. The discharge fraction of the IJssel is relative to the PC discharge. Development of the biyearly averaged Waal discharge fraction for both the reference simulation and the simulation with the side channel for c) low flows and d) high flows.

From Figure 7.8b it is seen that the discharge partitioning at the IJsselkop relative to the PC discharge is barely influenced by the side channel intervention. This is plausible since the bed levels of the IJssel and NR-Lek only show small changes compared to the reference case and the changes are similar. Figure 7.9a and Figure 7.9b show the semiannually averaged difference in respectively the IJssel and NR-Lek discharge fractions relative to the Lobith discharge for both low and high flows. For low flows more discharge enters the PC compared to the reference case and a larger part of this discharge is diverted towards the IJssel throughout the simulation. For the IJssel these processes both lead to added discharge compared to the reference case and for the NR-Lek these processes counteract each other leading to almost no change in discharge. For the high flows initially more discharge enters the PC compared to the reference case. This initially leads to more discharge on both the IJssel and the NR-Lek compared to the reference case. This increase stays relatively constant for the IJssel and increases slightly for the NR-Lek since both the PC discharge and the fraction of it diverted towards the NR-Lek increase slightly throughout the simulation with respect to the reference simulation.

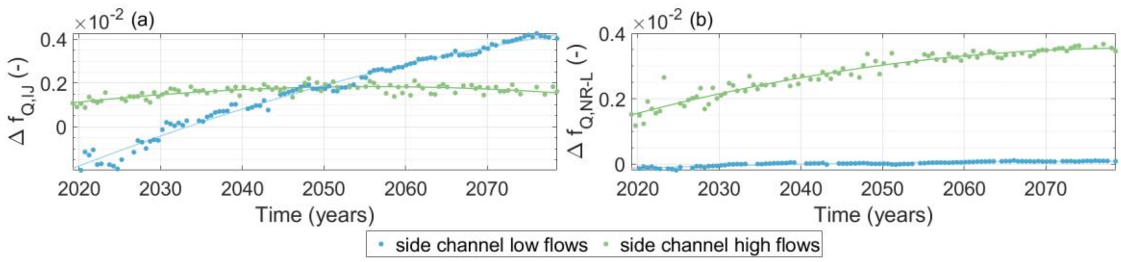

Figure 7.9: The semiannually averaged difference in discharge fraction between the simulation with the side channel (A) and the reference simulation for both low and high flows for a) the IJssel and b) the Nederrijn-Lek. The discharge fractions are fractions of the Lobith discharge.

7.2 Fully opening the weirs

For this intervention the weirs at Driel, Amerongen and Hardinxveld in the Nederrijn-Lek are completely opened. The bed level around the weirs stays fixed such that it is modeled as if the structures of the weirs are still present and the weirs are always fully opened.

Overview effects

- Upstream in the IJssel the erosion is reduced and at some locations even changes to aggradation and upstream in the NR-Lek the aggradation is reduced and at some locations even changes to erosion.
- The Boven-Waal and Midden-Waal show reduced erosion. The reduced erosion is larger for the Boven-Waal since it starts upstream.
- The PC shows enhanced erosion and enhanced coarsening.
- For low flows the Waal discharge fraction for open weirs remains below the initial Waal discharge fraction from the reference simulation. For high flows there is a small relative decrease in Waal discharge fraction throughout the simulation.
- For high flows the low flows opening the weirs also leads to significant changes in the discharge partitioning at the IJsselkop. The relative decrease in the IJssel discharge fraction relative to the PC discharge is approximately 44%.

Bed level difference

In Figure 7.10 and Figure 7.11 the bed level development with respect to the reference case is shown for the Nederrijn-Lek and the IJssel. Due to the opening of the weirs the discharge fraction towards the Pannerden Canal and the Nederrijn-Lek immediately increases. Since the weirs are located in the NR-Lek, significant bed level changes compared to the reference case occur on the NR-Lek and the IJssel. The bed level changes start upstream and travel downstream. In the IJssel the reach up to rkm 905 is influenced by the opening of the weirs. For the NR-Lek, the reduced aggradation as a result of the opening of the weirs is limited by the presence of the Driel weir. The weirs are open and the structures remain present. In the Nr-Lek there is no water level set-up at the weirs anymore for the low and intermediate flows. Together with the increased discharge this leads to the bed level lowering compared to the reference case. The bed level increase compared to the reference case on the IJssel is caused by the reduced discharge on the IJssel for low and intermediate flows. By comparing the area underneath the graphs for the upstream sections where the bed level influence by the opening of the weirs exceeds 10 cm, it is found that the relative bed level increase on the IJssel is larger than the relative bed level decrease on the NR-Lek and therefore for the high flows the water level at the IJsselkop will increase initially with respect to the reference case.

In Figure 7.11 the bed level development with respect to the reference case is shown for the PC and the Boven-Rijn. The bed level upstream in the PC decreases compared to the reference case. This decrease continues throughout the simulation and travels downstream. The bed level is expected to decrease due to the increased discharge on the PC and the absence of the water level set-up for the low and intermediate flows. What is interesting is that initially downstream in the PC the bed level increases compared to the reference case. This is attributed to the water level increase at the IJsselkop for high flows due to the dominant relative bed level increase in the IJssel. As a result of the water level increase at the IJsselkop a M1-backwater curve arises in the PC leading to aggradation which is largest downstream. This effect is counteracted by the relative bed level decrease which started upstream. After 25 years there is no relative bed level increase anymore in the PC. At the end of the simulation the relative bed level decrease downstream in the PC is larger than upstream. This is due to the development of the mean grain size. As a result of the enhanced erosion in the PC also enhanced coarsening is expected. The bed load initially is finer than the bed itself so increased erosion leads to more erosion of finer material from the bed which coarsens the bed with respect to the reference case. Upstream in the PC the enhanced coarsening is stronger than downstream, see Appendix H. The enhanced coarsening counteracts the relative bed level lowering and therefore the relative bed level lowering is larger downstream.

For the Boven-Rijn (BR) the relative bed level changes are in the order of 5 cm. Bed level changes occur due to changes in the backwater curve only because the discharge in the BR does not change due to the opening of the weirs. The backwater curve along the BR changes with respect to the reference case since the water level at the Pannerdense Kop changes. The water level changes are small compared to the water depth on the BR leading to the small relative bed level changes.

In Figure 7.12 the bed level development with respect to the reference case is shown for the Waal. The Waal shows a bed level increase with respect to the reference case. Again the relative bed level increase starts upstream and travels downstream. The relative bed level increase is attributed to the reduced discharge in the Waal. The bed level difference for the Waal maximally is in the order of 0.2 m. This is smaller than 0.5 m for the PC since the relative discharge difference is smaller for the Waal than for the PC.

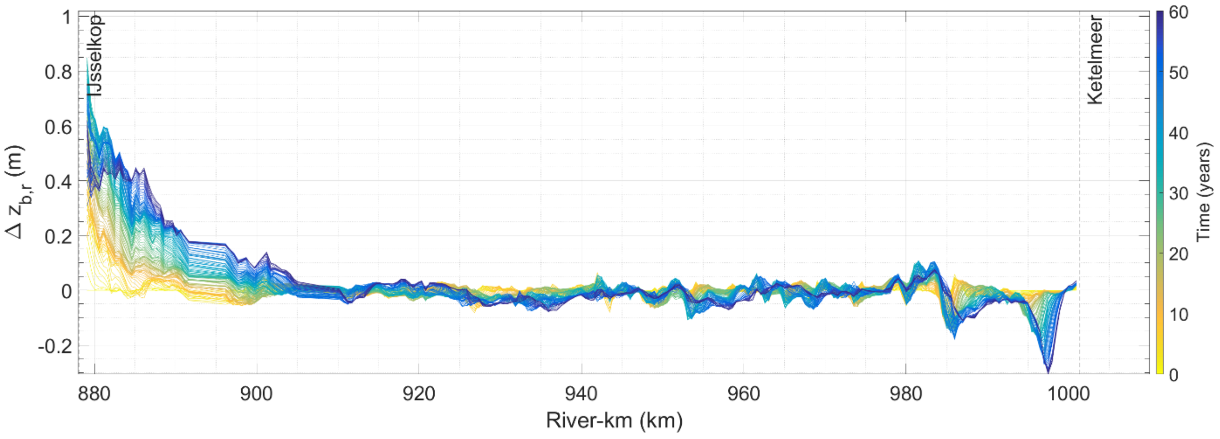

Figure 7.10: Difference in bed level of the IJssel between the simulation with the open weirs (B) and the reference simulation.

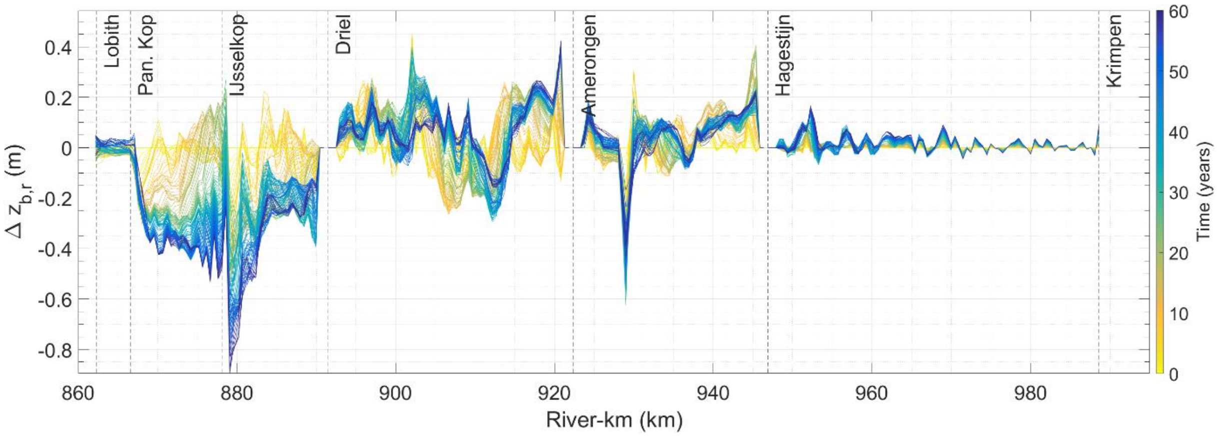

Figure 7.11: Difference in bed level of the Boven-Rijn, Pannerden Canal and Nederrijn-Lek between the simulation with the open weirs (B) and the reference simulation.

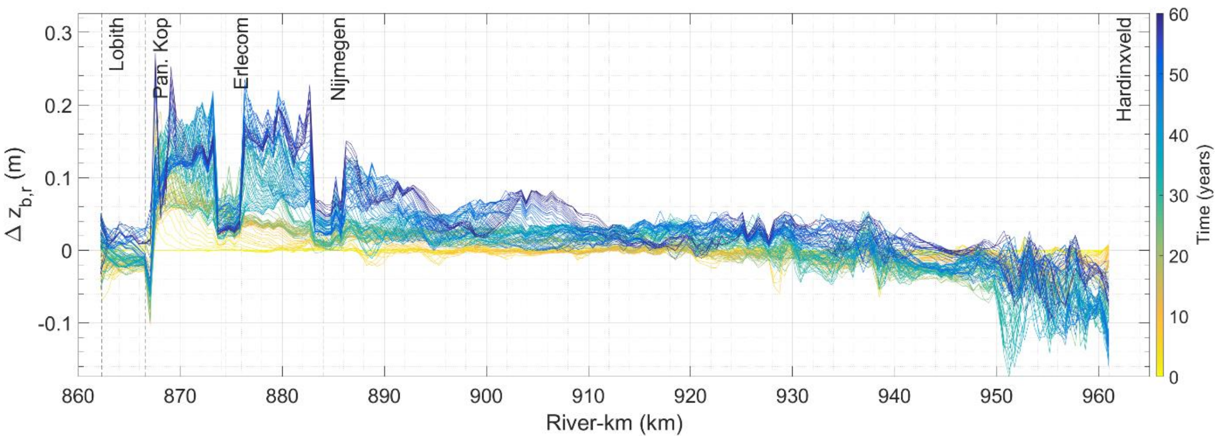

Figure 7.12: Difference in bed level of the Boven-Rijn and Waal between the simulation with the open weirs (B) and the reference simulation.

Reach averaged bed level difference

Figure 7.13 shows the reach averaged bed level development of the different reaches with respect to the reference case. It is found that the absolute reach averaged bed level difference with respect to the reference case remain within 5 cm for all reaches except the Boven-Waal,

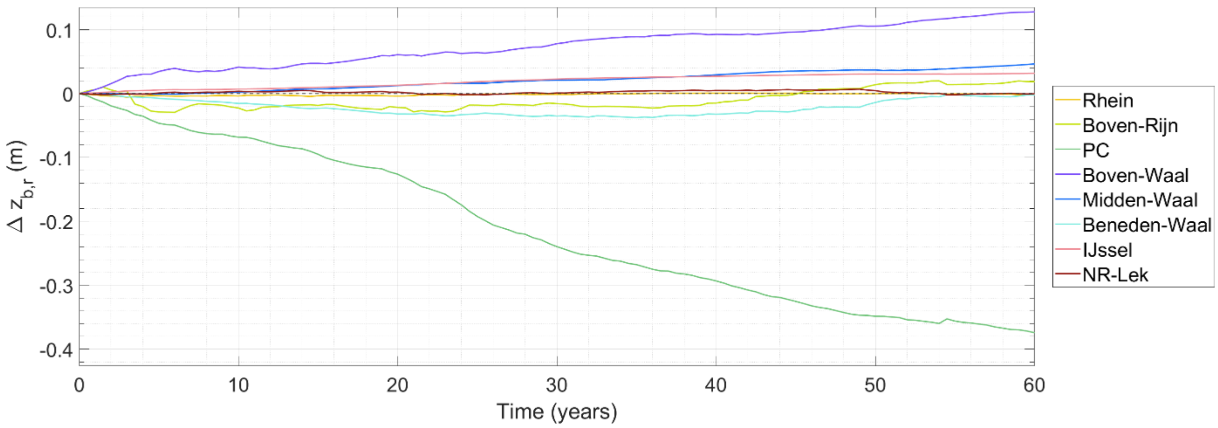

Figure 7.13: Reach averaged bed level difference between the simulation with the open weirs (B) and the reference simulation.

Midden-Waal and the PC. The relative bed level increase upstream in the Waal reaches the Midden-Waal and leads to a bed level increase here as well. Furthermore it is found that the bed level difference compared to the reference case does not stabilize during the simulation for the Waal and the Pannerden Canal. For the Waal and the PC respectively the relative bed level increase and the relative bed level decrease in the branches both still increase at the end of the simulation.

Discharge partitioning Waal

The difference in the Waal discharge fraction between the simulation with the side channel and the reference simulation is shown in Figure 7.14 and Figure 7.15a and Figure 7.15b show the semiannually averaged difference in Waal discharge fraction for respectively low and high flows. From the figures it is observed that the influence of the opening of the weirs on the discharge partitioning at the Pannerdense Kop is different for the low and the high flows. For the high flows the weirs were opened in the reference case as well so initially nothing changes. For the low flows the relative decrease in Waal discharge fraction is 7.8% at the start of the simulation. Throughout the simulation this reduces to 6.6%. For the high flows on the other hand, the difference in discharge fraction between the simulation with the open weirs and the reference simulation increases throughout the simulation. The final relative decrease is 1.1%.

The different trends in the difference in discharge fraction for the low and high flows is due to the bed level development of the NR-Lek, IJssel and the PC. As mentioned above the bed level increase compared to the reference case of the IJssel was larger than the bed level decrease compared to the reference case of the NR-Lek. For low flows, when the flow is restricted to the summer bed, this leads to a increase in the difference in the IJsselkop water level with respect to reference case throughout the simulation. The same holds for the Pannerdense Kop and therefore, for low flows, the discharge fraction towards the Waal increases with respect to the reference case.

For high flows this is different. For the high flows the winter bed receives parts of the flow. (Klijn et al., 2022) showed that for the Waal the width of the winter bed per m^3 discharge it receives, is approximately three quarters of the width of the PC, a quarter of the width of the IJssel and half of the width of the upstream part of the NR-Lek. This means that for the PC and the Waal and PC larger parts of the flow remains in the main channel and therefore the bed level development in the main channel of these reaches starts to dominate in the discharge partitioning. For both reaches the bed lowered throughout the simulation with respect to the reference case leading to a lower water level at the IJsselkop and Pannerdense Kop compared

to the reference case. Therefore, for high flows, the discharge fraction towards the Waal with respect to the reference case decreases throughout the simulation. Figure 7.15c shows that despite the relative increase in Waal discharge fraction throughout the simulation with open weirs, the Waal discharge fraction for low flows remains below the initial Waal discharge fraction of the reference simulation. Figure 7.15d shows that for high flows the increase in Waal discharge fraction throughout time is slowed down by opening the weirs.
By executing the LSF analysis it is found the for the for the Lobith discharge of 1400 m^3/s the difference in Waal discharge ratio equals -7.8 % initially and -6.9 % after 60 years. In absolute figures this would be a initial decrease of 109.6 m^3/s to the Waal and a decrease of 97.0 m^3/s after 60 years.

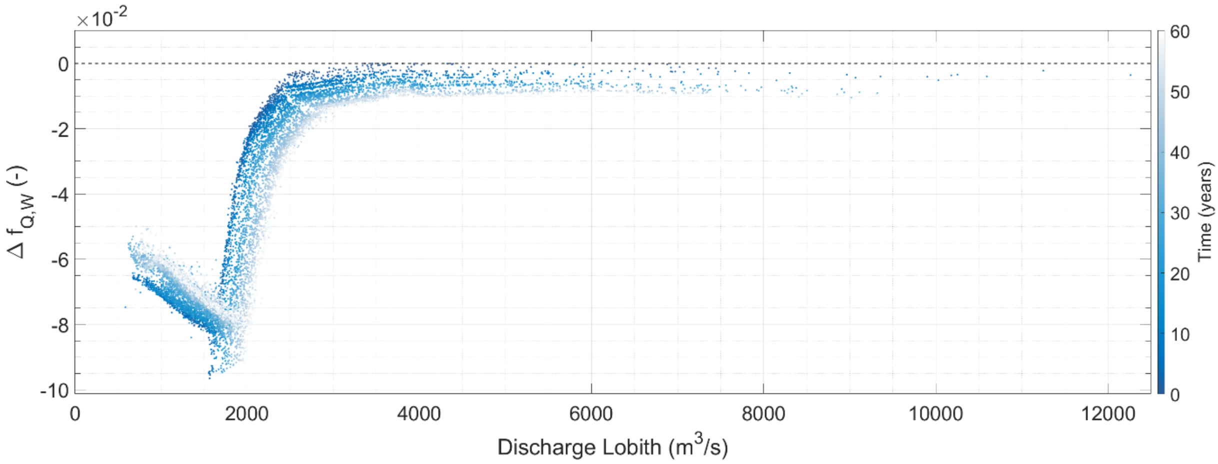

Figure 7.14: Difference in Waal discharge fraction between the simulation with the open weirs (B) and the reference simulation.

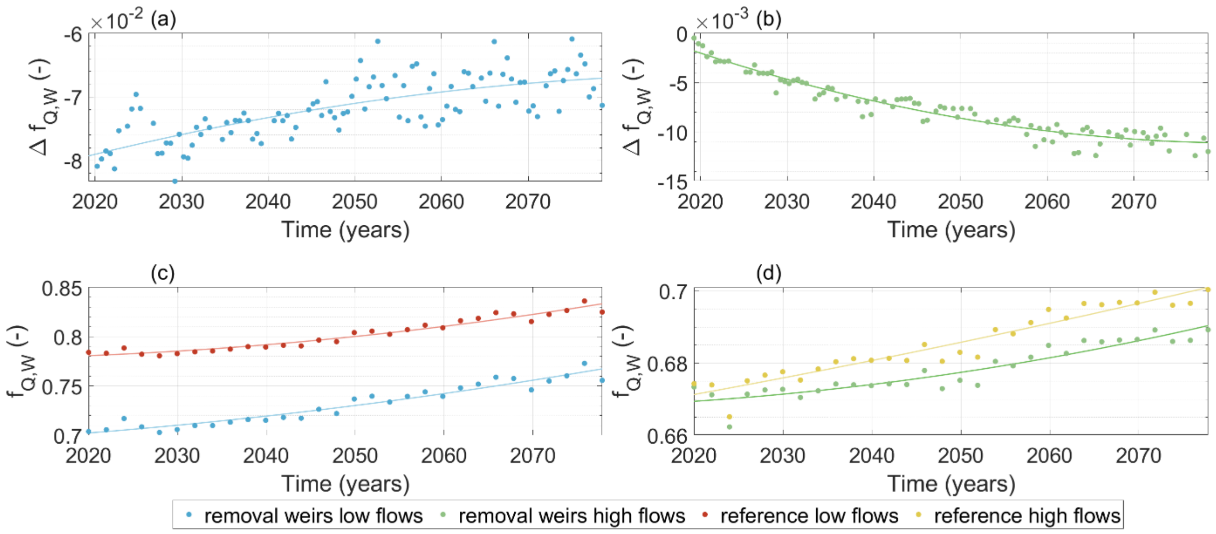

Figure 7.15: The semiannually averaged difference in Waal discharge fraction between the simulation with the open weirs (B) and the reference simulation for a) low flows and b) high flows. Development of the biyearly averaged Waal discharge fraction for both the reference simulation and the simulation with the side channel for c) low flows and d) high flows.

Discharge partitioning IJssel

The difference in the IJssel discharge fraction relative to the PC discharge between the simulation with the side channel and the reference simulation is shown in Figure 7.16c and Figure 7.16a and Figure 7.16b show the semiannually averaged difference in IJssel discharge fraction for respectively low and high flows. From the figures it is observed that the influence of the opening of the weirs on the discharge partitioning at the IJsselkop is different for the low and the high flows. For the high flows again initially nothing changes. For the low flows the relative decrease in IJssel discharge fraction is 44.1% at the start of the simulation. Throughout the simulation this reduces to 43.1%. For the high flows on the other hand, the difference in discharge fraction between the simulation with the open weirs and the reference simulation increases throughout the simulation. The final relative decrease is 3.6%.
The different trends in the difference in discharge fraction for the high flows are understood from the bed level development of the NR-Lek and the IJssel. The bed level of the IJssel rises with respect to the reference case and the bed level of the NR-Lek decreases. As a result, throughout the simulation with the open weirs more discharge is diverted towards the NR-Lek compared to the reference simulation for the high flows.

For all flows in the reference case the discharge fraction towards the IJssel increases throughout the simulation. Figure 7.16a and Figure 7.16b show that this increase is sped up for low flows and slowed down for high flows due to the opening of the weirs. Since the IJssel shows a relative bed level increase and the NR-Lek shows a relative bed level decrease it is expected that the relative IJssel discharge fraction decreases throughout the simulation for all flows. The opposite is true for the low flows. The reason for this is that the water level set-up due to the closed Driel weir causes relatively large changes in water level for small differences in discharge. So the water levels can match the bed level development in the IJssel and NR-Lek through small changes in the discharge partitioning at the IJsselkop. In the simulation with open weirs the water level set-up in the NR-Lek is absent which means a larger change in discharge is needed compared to the reference case to obtain a similar water level difference. Therefore, for low flows the difference in IJssel discharge fraction compared to the reference case increases throughout the simulation even though the bed level development for the simulation with open weirs suggests a decrease.

Figure 7.17a and Figure 7.17b show the semiannually averaged difference in respectively the IJssel and NR-Lek discharge fractions relative to the Lobith discharge for both low and high flows. For low flows more discharge enters the PC compared to the reference case and a smaller part of this discharge is diverted towards the IJssel. The change in the discharge partitioning at the IJsselkop dominates and therefore the discharge on the IJssel reduces significantly compared to the reference case and the NR-Lek discharge increases significantly compared to the reference case. At the end of the simulation, the relative decrease in IJssel discharge fraction is 4.3% and the relative increase in NR-Lek discharge fraction is 11.2% For high flows more discharge enters the PC compared to the reference case and a smaller part of this discharge is diverted towards the IJssel throughout the simulation.
For the IJssel these developments counteract leading to a relative decrease in IJssel discharge fraction of 0.5%. For the NR-Lek these developments enforce each other leading to an increase in relative discharge fraction of 1.7%.

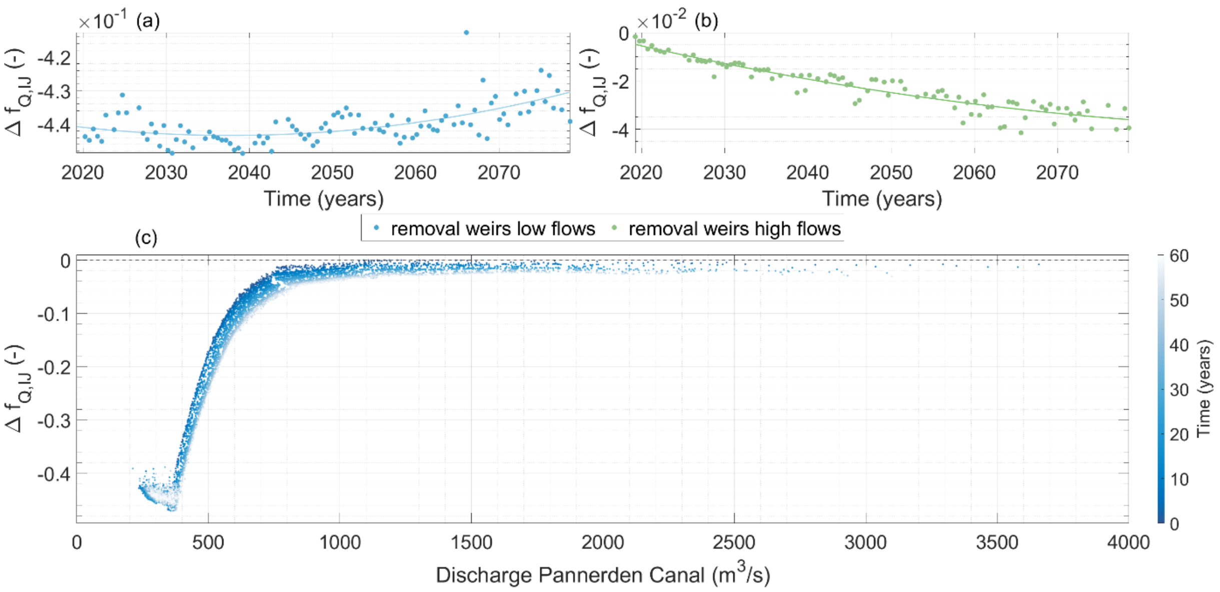

Figure 7.16: The semiannually averaged difference in IJssel discharge fraction relative to the PC discharge between the simulation with the open weirs (B) and the reference simulation for a) low flows and b) high flows. c) Difference in IJssel discharge fraction between the simulation with the side channel and the reference simulation.

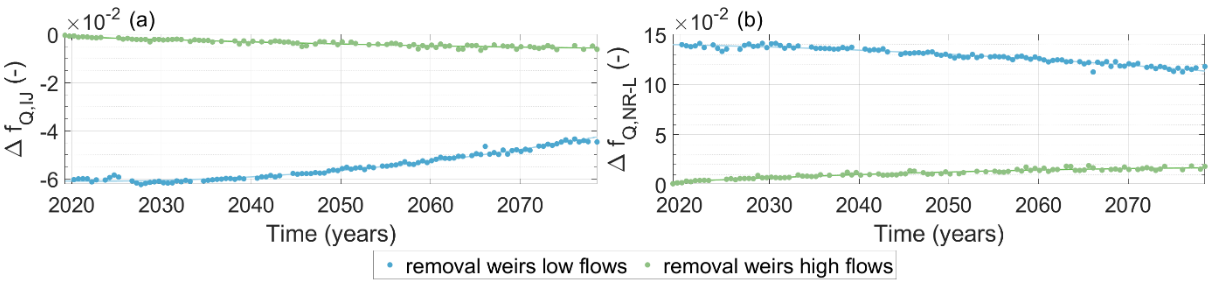

Figure 7.17: The semiannually averaged difference in discharge fraction between the simulation with opened weirs (B) and the reference simulation for both low and high flows for a) the IJssel and b) the Nederrijn-Lek. The discharge fractions are fractions of the Lobith discharge.

7.3 Widening of the IJssel

For this intervention a reach of the IJssel river is widened. The reach is located 3 km upstream of the IJsselkop bifurcation and has a length of 17 km. The additional width of the main channel is 30 m on both sides of the river.

Overview effects

- The IJssel shows enhanced erosion upstream of the widened section. Along the widened section aggradation occurs and up to 20 km downstream of the widened section degradation is observed. Upstream in the NR-Lek the aggradation is enhanced.
- Along the widened section there initially is a relative decrease in mean grain size. The difference reduces throughout the simulation. Up to 20 km downstream of the widened section initially there is a slight relative coarsening. Throughout the simulation this changes to a significant relative fining which almost completely prevents coarsening along this section.
- The Boven-Waal and Midden-Waal show reduced erosion. The reduced erosion is larger for the Boven-Waal since it starts upstream.
- The PC shows enhanced erosion.

- The effect on the Waal discharge fraction is larger for low flows than for high flows. The effectivity of widening on the IJssel reduces throughout the simulation for low flows.
- For all flows, the IJssel discharge fraction relative to the Lobith discharge increases with respect to the reference case. Especially for low flows, the NR-Lek discharge fraction relative to the Lobith discharge decreases with respect to the reference case.

Bed level difference

In Figure 7.18 the bed level development with respect to the reference case is shown for the IJssel. Along the widened section the bed level increases with respect to the reference case throughout the simulation. The bed level increases due to the M1-backwater curve and the aggradation hump which occur as a result of the widening. The aggradation hump forms at the upstream end of the widened reach. Downstream along the widened reach initially a bed level decrease with respect to the reference case occurs. Figure 6.10b shows that aggradation occurs along this section in the reference simulation. Due to the increased bed level upstream in the widened reach there is less sediment available to deposit initially downstream in the widened reach which leads to the initial bed level decrease compared to the reference case.

Downstream of the widened section an erosion pit forms as a result of the widening and a lower bed level compared to the reference case is observed. The erosion pit travels downstream throughout the simulation. The erosion also occurs due to the increased discharge on the IJssel, see Figure 7.24b. Just downstream of the widened section the bed level increases compared to the reference case during the last 20 years of the simulation. This is caused by the mean grain size change as a result of the widened section. The widened section significantly influences the mean grain size of the IJssel.

Figure 7.19a shows the difference in mean grain size between the simulation with the widening on the IJssel and the reference simulation. Figure 7.19b shows the development of the mean grain size for the simulation with the widening on the IJssel. During the first 10 years the widened section fines compared to the reference case. This limits the aggradation along the widened section. The fining is due to the deposition of fine sediment which is initially transported. As a consequence downstream of the widened section the bed initially coarsens compared to the reference case. After the first ten years the sediment supply coarsens and therefore the coarser sediment deposits along the widened section increasing the mean grain size compared to the reference case. Again this leads to the opposite effect downstream where coarse sediment is eroded which leads to a decrease in the mean grain size compared to the reference case. The maximum difference is 1.1 mm which significantly enhances the erosion pit. From Figure 7.19b it is observed that during the last 20 years of the simulation the bed starts to coarsen downstream of the widened section. This causes the increase in bed level compared to the reference case just downstream of the widened section.

Upstream of the widened section the bed level decreases rapidly with respect to the reference case. The decrease is due to the M2-backwater curve which arises as a result of the widening and the increased discharge on the IJssel. The effect of the M2-backwater curve is counteracted throughout the simulation by the bed level increase along the widened section. Therefore the bed level decrease compared to the reference case upstream of the widened section stabilizes quickly.

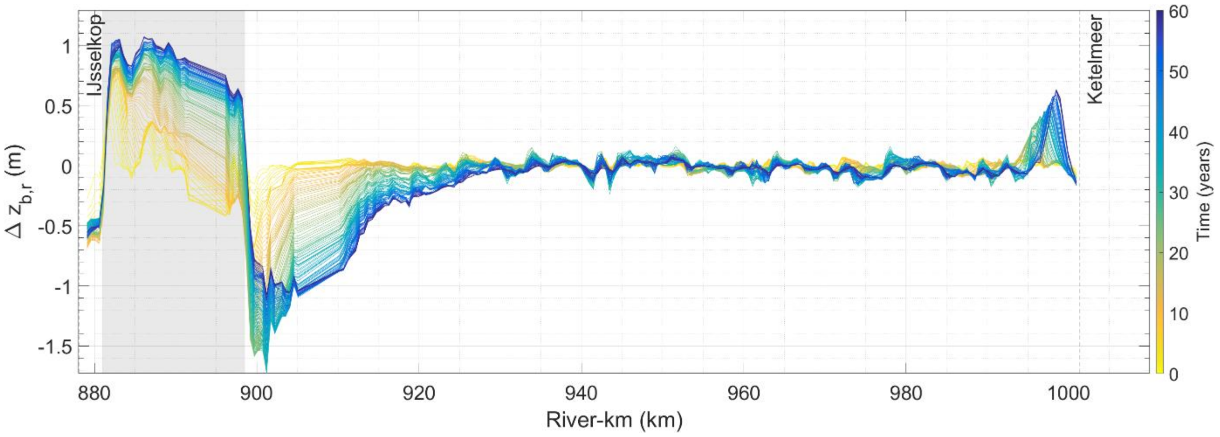

Figure 7.18: Difference in bed level of the IJssel between the simulation with the widening on the IJssel (C) and the reference simulation. The grey area indicates the widened section.

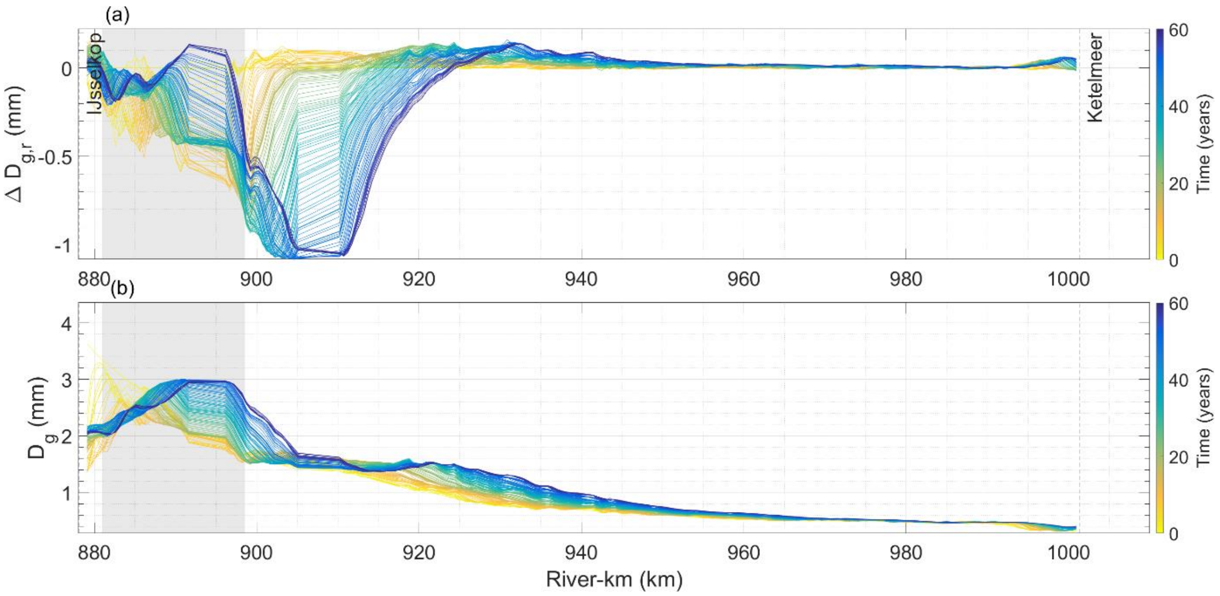

Figure 7.19: a) Difference in mean grain size of the IJssel between the simulation with the widening on the IJssel (C) and the reference simulation and b) absolute mean grain size of the IJssel for the simulation with the widening on the IJssel. The grey area indicates the widened section.

In Figure 7.20 the bed level development with respect to the reference case is shown for the Boven-Rijn, the Pannerden Canal and the Nederrijn-Lek. The bed level of the NR-Lek increases compared to the reference case. The bed level increase is due to the decreased discharge in the NR-Lek, see Figure 7.24b. The bed level increase compared to the reference case starts upstream and travels downstream until the Driel weir is reached. Downstream of the Driel weir only small changes in bed level are observed. The bed level of the PC decreases with respect to the reference case throughout the simulation. Due to the widening on the IJssel, the IJsselkop water level drops. This leads to steeper backwater curves compared to the reference case which explains the bed level decrease with respect to the reference case. Furthermore the discharge to the Pannerden Canal increases which also leads to a bed level decrease with respect to the reference case.

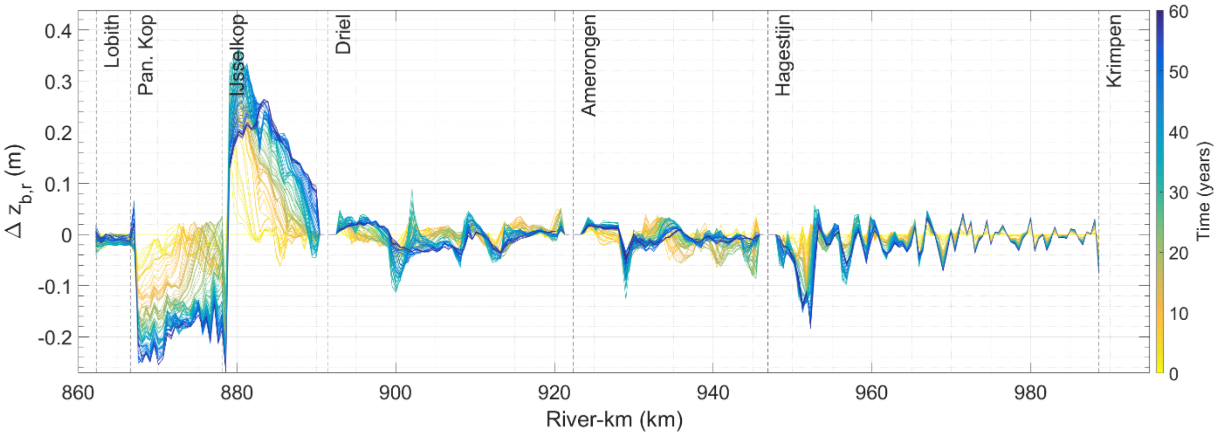

Figure 7.20: Difference in bed level of the Boven-Rijn, Pannerden Canal and Nederrijn-Lek between the simulation with the widening on the IJssel (C) and the reference simulation.

In Figure 7.21 the bed level development with respect to the reference case is shown for the Boven-Rijn and Waal. For the BR the relative bed level changes are maximally 3 cm. The bed level changes occur due to water level changes at the Pannerdense Kop since the Boven-Rijn discharge does not change compared to the reference case. The water level changes are small compared to the water depth on the Boven-Rijn leading to the small relative bed level changes. The Waal shows a bed level increase with respect to the reference case. Again the relative bed level increase starts upstream and travels downstream. The relative bed level increase is attributed to the reduced discharge in the Waal. The bed level difference for the Waal maximally is in the order of 0.1 m.

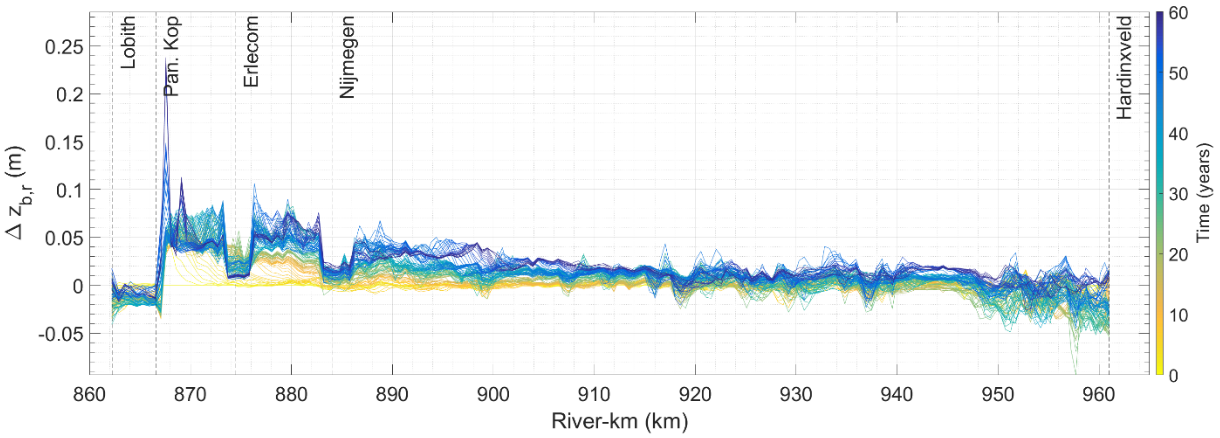

Figure 7.21: Difference in bed level of the Boven-Rijn and Waal between the simulation with the widening on the IJssel (C) and the reference simulation

Reach averaged bed level difference

Figure 7.22 shows the reach averaged bed level development of the different reaches with respect to the reference case. The IJssel is split in three reaches: A reach until the end of the widening (rkm 878-898), a reach for the erosion pit downstream of the widening (rkm 899-932) and a reach for the remaining part downstream (rkm 933-1001). This separation is made because the bed level development is different for these reaches.
It is found that the absolute reach averaged bed level difference with respect to the reference case remain within 5 cm for all reaches except the Boven-Waal, the PC and the two most upstream reaches of the IJssel. Furthermore it is found that the bed level difference compared to the reference case stabilizes during the last five years of the simulation for the most upstream

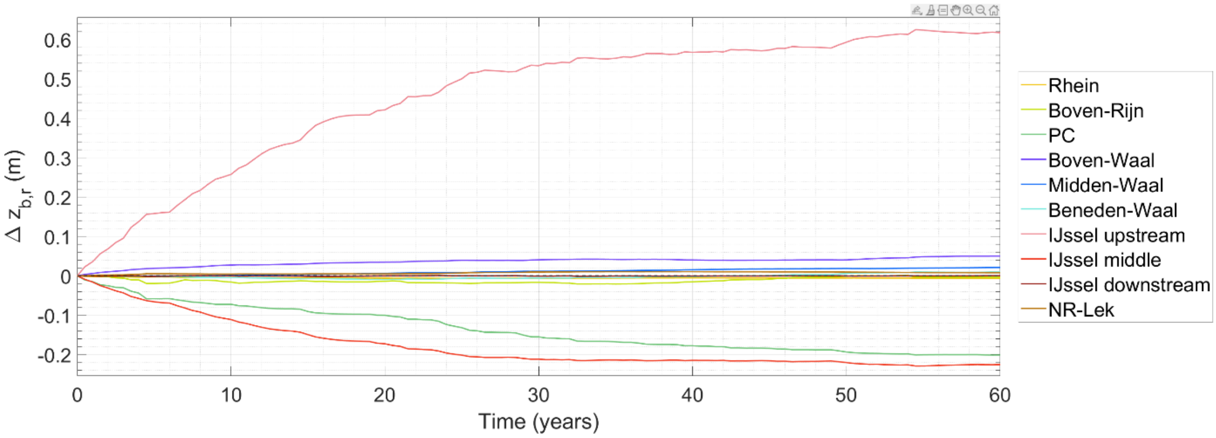

Figure 7.22: Reach averaged bed level difference between the simulation with widening on the IJssel (C) and the reference simulation.

IJssel reach, the Boven-Waal and the PC. The average bed level difference compared to the reference case for the middle IJssel reach already stabilizes after 35 years.

Discharge partitioning

The difference in the Waal discharge fraction between the simulation with the side channel and the reference simulation is shown in Figure 7.23 and Figure 7.24a shows the semiannually averaged difference in Waal discharge fraction for low and high flows. Figure 7.24c and Figure 7.24d show the biyearly averaged Waal discharge fraction for both the reference and the widening simulation for respectively low and high flows. From the figures it is observed that the influence of the widening on the IJssel on the discharge partitioning at the Pannerdense Kop (PK) is different for the low and the high flows initially and that the development of the Waal discharge partitioning is different for low and high flows. This is as expected since for the higher flows the floodplains are inundated and the relative effect of the widening on the water level reduction is limited. For the low flows the relative decrease in Waal discharge fraction is 2.4% at the start of the simulation. Throughout the simulation this reduces to 1.3%. For the high flows on the other hand, the difference in discharge fraction between the simulation with the open weirs and the reference simulation increases throughout the simulation. The initial relative decrease is 0.6% and the final decrease is 0.8%.

For the low flows the effectivity of the widening on the IJssel reduces throughout the simulation. A lot of aggradation occurs along the widened section due to the extreme dimension of the widening. This counteracts the water level lowering induced by the widening. Furthermore the bed level increase with respect to the reference case in the upstream part of the NR-Lek also increases the water level on the IJsselkop with respect to the reference case. Together these bed level developments lead to the reduced effectivity of the widening intervention throughout the simulation.

For the high flows the opposite effect is observed since the effectivity of the widening intervention increases throughout the simulation for high flows. As mentioned in section 6.2.2, the bed level development of the PC and the Waal dominate over the bed level development of the NR-Lek and the IJssel in the discharge partitioning for the high flows. For the widening simulation the Waal shows reduced erosion and in the PC the erosion is enhanced both leading to reduced discharge towards the Waal compared to the reference simulation. Since the reduced erosion in the Waal and the enhanced erosion in the PC stabilize throughout the simulation, the difference in discharge fraction compared to the reference case also stabilizes throughout the simulation. During the last 15 years even a slight increase is observed. This is related to the reduced effectivity of the widening on the IJssel. From Figure 7.22 it is observed that the erosion pit downstream of the widening section stabilizes with respect to the reference case while the bed level of the widened section keeps increasing.

By executing the LSF analysis it is found the for the for the Lobith discharge of 1400 m^3/s the difference in Waal discharge ratio equals -2.2% initially and -1.4% after 60 years. In absolute figures this would be a initial decrease of 30.8 m^3/s to the Waal and a decrease of 19.6 m^3/s after 60 years.

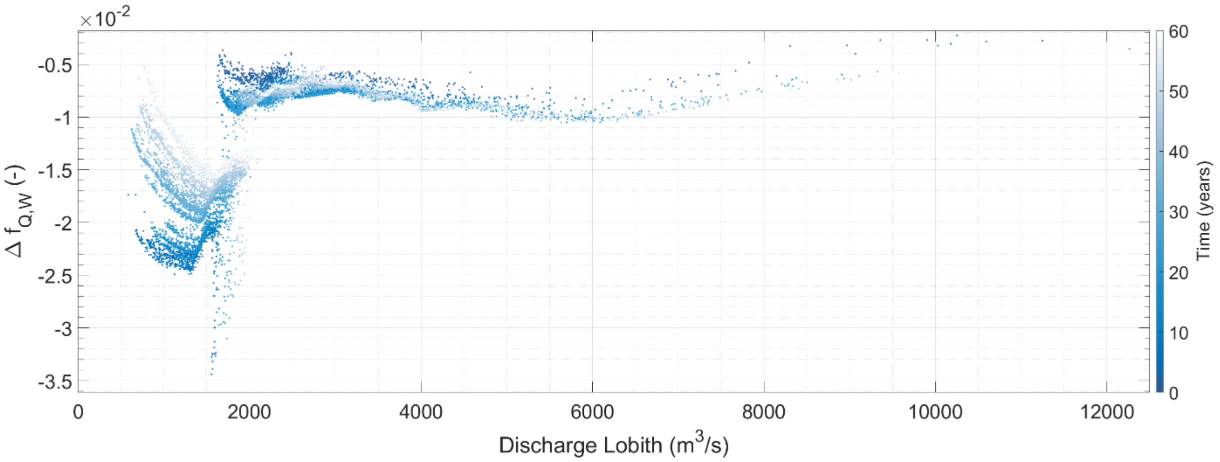

Figure 7.23: Difference in Waal discharge fraction between the simulation with the widening on the IJssel (C) and the reference simulation.

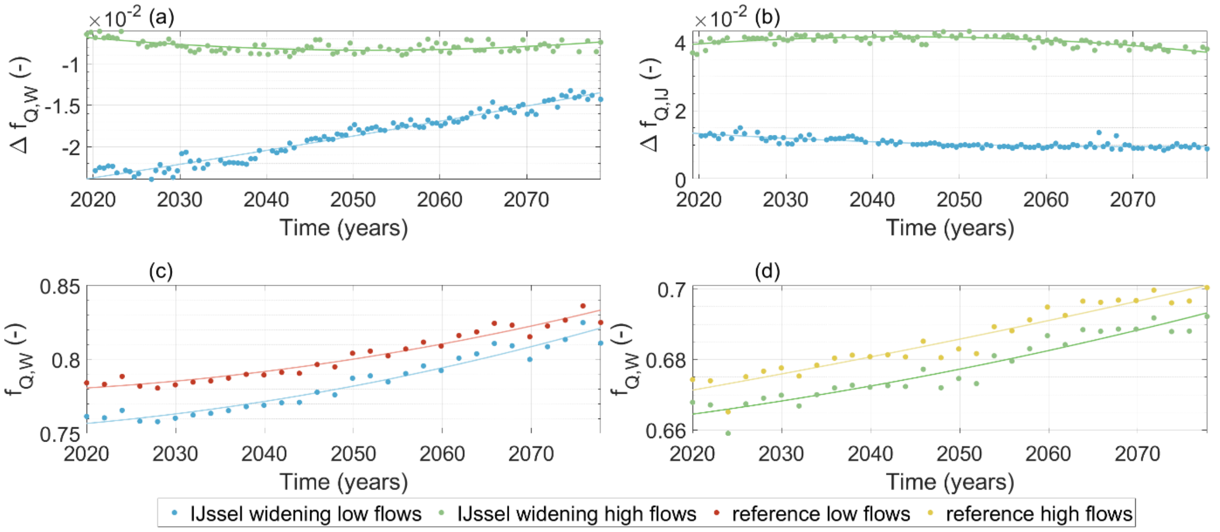

Figure 7.24: The semiannually averaged difference in discharge fraction between the simulation with the widening on the IJssel (C) and the reference simulation for both low and high flows for a) the Waal and b) the IJssel. The discharge fraction of the IJssel is relative to the PC discharge. Development of the biyearly averaged Waal discharge fraction for both the reference simulation and the simulation with the widening on the IJssel for c) low flows and d) high flows.

Figure 7.24b shows the semiannually averaged difference in IJssel discharge fraction relative to the Pannerden Canal discharge for low and high flows. In both cases the IJssel discharge fraction is increases compared to the reference case. For the low flows the relative increase in IJssel discharge fraction is 1.4% at the start of the simulation. Throughout the simulation this reduces to 0.9%. For the high flows the initial relative increase is 3.9% and this is 3.7% at the end of the simulation. The relative difference in the IJssel discharge fraction is larger for high flows than for low flows. As explained in section 6.2.2, in case the Driel weir is closed only small changes in discharge are needed to accomplish a change in water level. Therefore the relative difference in the IJssel discharge fraction is larger for high flows than for low flows even though the influence of the widening on the IJsselkop water level is smaller for high flows than for low flows.

Figure 7.25a and Figure 7.25b show the semiannually averaged difference in respectively the IJssel and NR-Lek discharge fractions relative to the Lobith discharge for both low and high flows. For low flows initially more discharge enters the PC compared to the reference case and a larger part of this discharge is diverted towards the IJssel. For the IJssel this leads to an increased discharge fraction compared to the reference case and for the NR-Lek this leads to a decreased discharge fraction throughout the reference case. The differences in discharge fraction become smaller throughout the simulation since the difference in Waal discharge fraction compared to the reference case also becomes smaller throughout the simulation.
For the high flows initially more discharge enters the PC compared to the reference case and a larger share of the PC discharge is diverted towards the IJssel. The change in the discharge partitioning at the IJsselkop dominates and therefore the discharge on the IJssel increases compared to the reference case and the NR-Lek discharge decreases compared to the reference case.

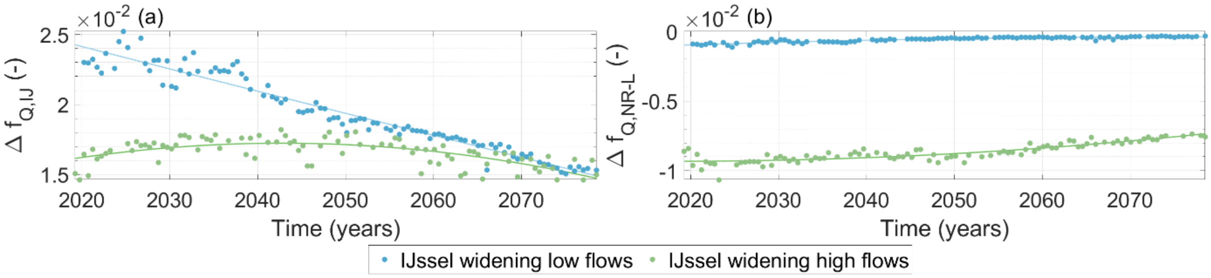

Figure 7.25: The semiannually averaged difference in discharge fraction between the simulation with the widening on the IJssel (C) and the reference simulation for both low and high flows for a) the IJssel and b) the Nederrijn-Lek. The discharge fractions are fractions of the Lobith discharge.

7.4 Directly steering the sediment partitioning at the PK

This intervention groups the interventions in the Boven-Rijn which are aimed at changing the sediment partitioning at the PK. These interventions change the sediment partitioning through two dimensional processes which can not be modeled in 1D. Therefore this group of measures is modeled by changing the nodal point relation.

Overview effects

- The Boven-Waal shows reduced erosion throughout the first 35 years. Afterwards the reduced erosion decreases slightly. The Midden-Waal show reduced erosion throughout the whole simulation. The reduced erosion is larger for the Boven-Waal since it starts upstream.
- The PC shows enhanced erosion. After 35 years the enhanced erosion reduces upstream in the PC.
- The Waal shows a relative increase in bed slope and the PC shows a relative decrease in bed slope.

- Upstream in the IJssel the erosion is enhanced and upstream in the NR-Lek the aggradation is reduced and at some locations even changes to erosion.
- The development of the Waal discharge fraction is not influenced initially. The effect is similar for all flows. The positive trend in the Waal discharge fraction is still present but it is reduced with respect to the reference case. The maximum reduction is reached after 35 years after which the relative decrease in the Waal discharge fraction reduces.

Bed level difference

In Figure 7.26 the bed level development with respect to the reference case is shown for the Boven-Rijn and Waal. A bed level increase with respect to the reference case is observed which starts upstream and travels downstream. After 35 years the bed level increase compared to the reference case halts at the upstream end of the Waal and the bed level even starts decreasing with respect to the reference case. This relative decrease also travels downstream and reaches up until rkm 890.

The bed level development of the Waal is understood from the development of the bed load sediment transport in the Waal. In Figure 7.27 the 5-yearly averaged bed load sediment transport difference with respect to the reference case is shown for the Boven-Rijn and Waal. During the first 35 years of the simulation the relative bed level increase is such that the slope of the Waal increases with respect to the reference case to match the increased incoming sediment supply. In Figure 7.27 the adaptation to the higher incoming sediment supply is seen for the first 35 years. The difference in sediment supply with respect to the reference case is maintained further downstream throughout the simulation. After 35 years the sediment supply towards the Waal has reduced significantly, see Figure 6.4c. Therefore also the difference in sediment supply compared to the reference case drops. Due to the increased bed slope of the Waal the difference in sediment transport capacity is now larger than the difference in sediment supply meaning that the slope should reduce again to adapt to the incoming supply. This is observed in Figure 7.27 as the low difference in sediment supply with respect to the reference case is maintained further downstream throughout the simulation. Next to the difference in incoming sediment supply the bed level development of the Waal is also influenced by the incoming discharge. Figure 7.32 shows that the discharge towards the Waal with respect to the reference case decreases throughout the simulation. This reduces the sediment transport capacity and therefore also leads to reduced erosion.

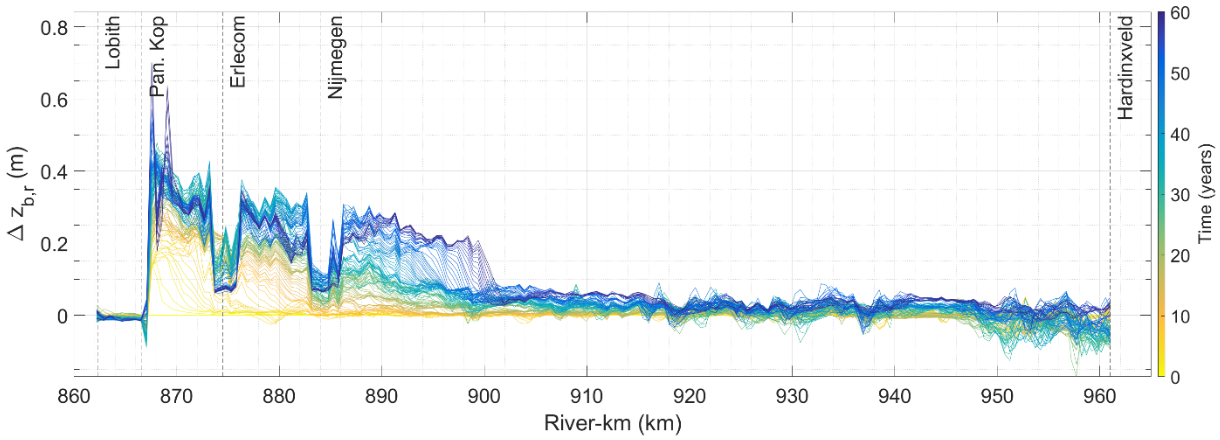

Figure 7.26: Difference in bed level of the Boven-Rijn and Waal between the simulation with the changed nodal point relation (D) and the reference simulation.

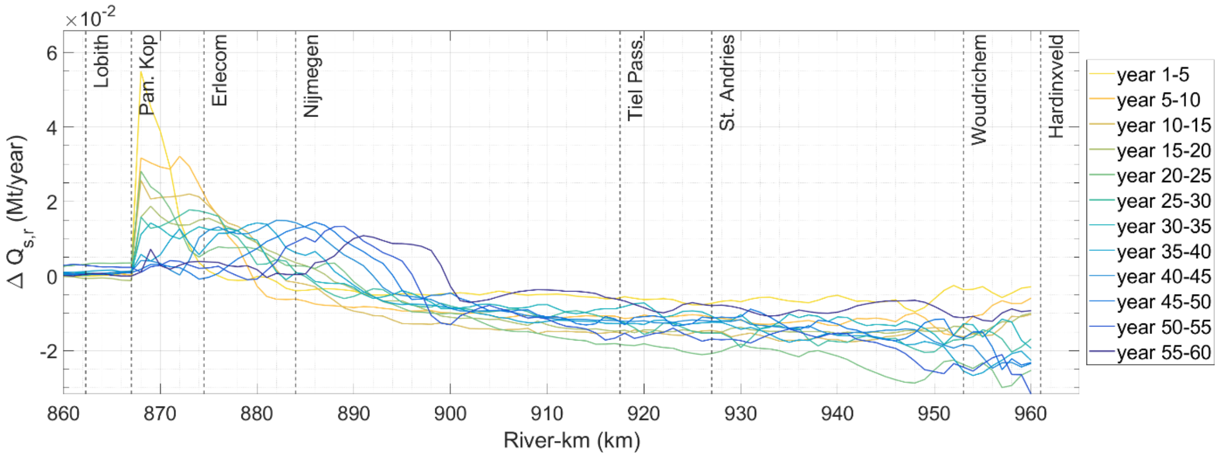

Figure 7.27: Difference in 5-yearly averaged bed load sediment transport of the Boven-Rijn and Waal between the simulation with the changed nodal point relation (D) and the reference simulation.

For the Boven-Rijn the relative bed level changes are maximally 3 cm. Again, the bed level changes occur due to water level changes at the Pannerdense Kop since the BR discharge does not change compared to the reference case. Since the water level changes are small compared to the water depth on the BR, the bed level changes compared to the reference case are also small.

In Figure 7.28 the bed level development with respect to the reference case is shown for the Boven-Rijn, Pannerden Canal and the Nederrijn-Lek. For the PC, the bed level decreases with respect to the reference case throughout the simulation. The relative bed level decrease starts upstream and travels downstream. After 35 years the bed level decrease with respect to the reference case halts upstream in the PC and the bed level even starts increasing compared to the reference case. This relative increase travels upstream and reaches rkm 872 at the end of the simulation. The magnitude of the difference in bed level compared to the reference case for the PC is approximately three times as large as for the Waal. Since the sediment supply to the Waal is larger than the supply to the PC, the relative influence on the sediment supply is larger for the PC than for the Waal. Therefore the effect on the bed level of directly steering the sediment partitioning at the Pannerdense Kop is larger for the PC than for the Waal.

The bed level development of the PC can be understood from the development of the bed load sediment transport in the PC. In Figure 7.29 the 5-yearly averaged bed load sediment transport difference with respect to the reference case is shown for the Boven-Rijn and PC. During the first 35 years of the simulation the bed level decrease is such that the slope of the PC decreases with respect to the reference case to match the decreased incoming sediment supply. From this figure the adaptation to the higher incoming sediment supply is observed for the first 35 years. The difference in sediment supply with respect to the reference case is maintained further downstream throughout the simulation. After 35 years the sediment supply towards the PC has reduced significantly. Therefore also the absolute difference in sediment supply compared to the reference case drops. Due to the relative decrease in bed slope of the PC the sediment transport capacity compared to the reference case is now lower than the relative difference in sediment supply meaning that the slope should increase again relative to the reference case to adapt to the incoming supply. This happens as the bed level upstream in the PC increases compared to the reference case in the last 25 years of the simulation. Next to the difference in incoming sediment supply the bed level development of the PC is also influenced by the incoming discharge. Figure 7.32 shows that the discharge towards the PC with respect to the reference case increases throughout the simulation. This increases the sediment transport capacity and therefore also leads to enhanced erosion.

The bed level development of the PC is also influence by the mean grain size development since it shows significant changes with respect to the reference case. In Figure 7.30 the development of the mean grain size compared to the reference case is shown. A relative coarsening wave starts at the upstream end of the PC and travels downstream. The relative coarsening wave starts due to the reduced aggradation of fine sediment initially. The coarsening wave limits degradation as it runs through the PC. The relative increase in mean grain size decreases the sediment transport capacity which means a smaller change in slope is required to match the relative decrease in sediment supply. Eventually the relative increase in mean grain size goes down again and upstream in the PC there is even a relative decrease in mean grain size in the last 10 years of the simulation. At this point in time the supply has coarsened. Due to the relative decrease in coarse sediment supply more coarse sediment erodes than in the reference case leading to the reduced coarsening. The coarsening wave also travels into the downstream branches. For the NR-Lek this is visible in Figure 7.30. The magnitude of the enhanced coarsening is smaller here. The coarsening also reduces the bed level decrease with respect to the reference case here.

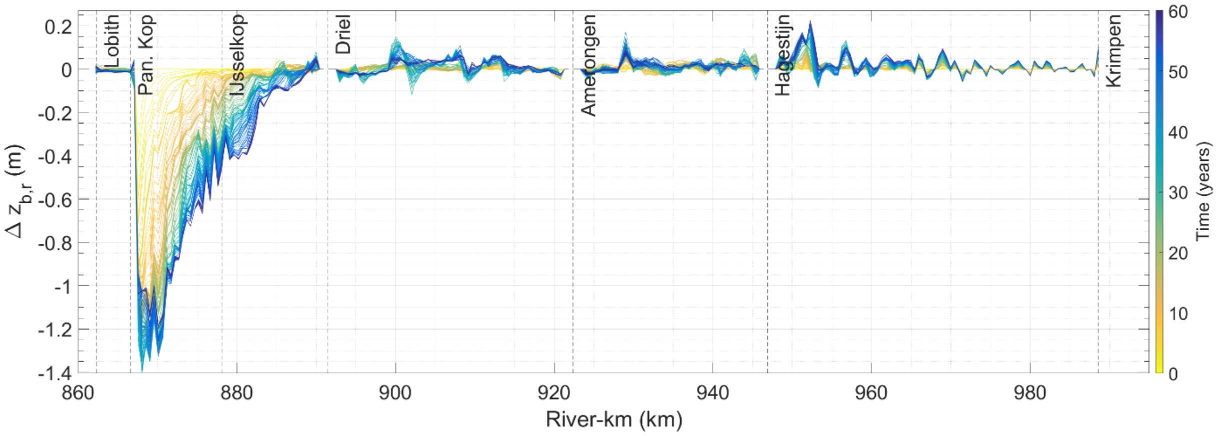

Figure 7.28: Difference in bed level of the Boven-Rijn and Pannerden Canal and Nederrijn-Lek between the simulation with the changed nodal point relation (D) and the reference simulation.

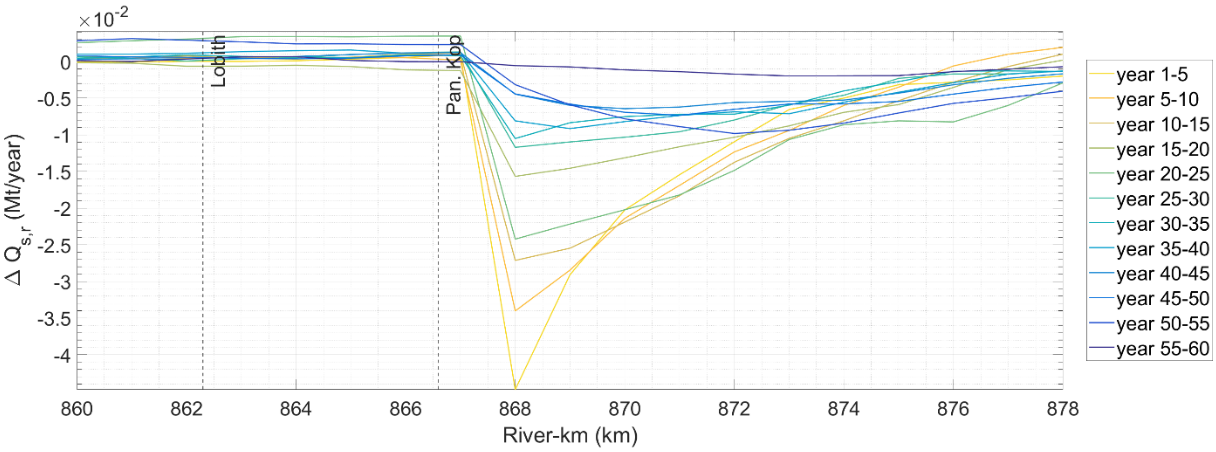

Figure 7.29: Difference in 5-yearly averaged bed load sediment transport of the Boven-Rijn and Pannerden Canal between the simulation with the changed nodal point relation (D) and the reference simulation.

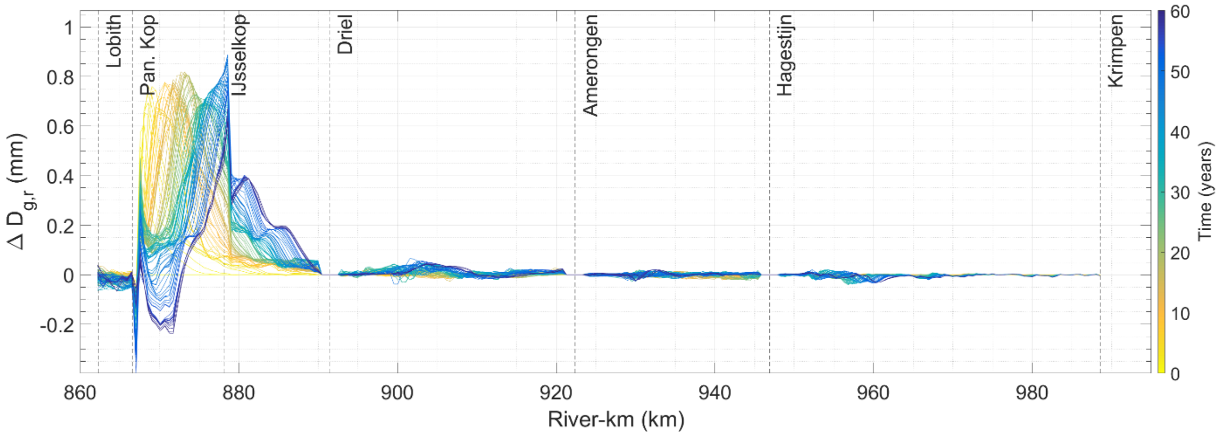

Figure 7.30: Difference in geometric mean grain size of the Boven-Rijn and Pannerden Canal and Nederrijn-Lek between the simulation with the changed nodal point relation (D) and the reference simulation.

Figure 7.31 shows the bed level development with respect to the reference case for the IJssel. The enhanced erosion on the Pannerden Canal travels downstream into the IJssel and the NR-Lek. Upstream in both reaches the bed level decreases with respect to the reference case. In the Nederrijn-Lek the bed level decrease with respect to the reference case reaches the Driel weir. The IJssel experiences a lowering of the bed level with respect to the reference case up until approximately rkm 900. The magnitude of the relative bed level decrease is higher for the NR-Lek where the maximum bed level decrease reaches 0.4 m. For the IJssel this is just over 0.3 m.

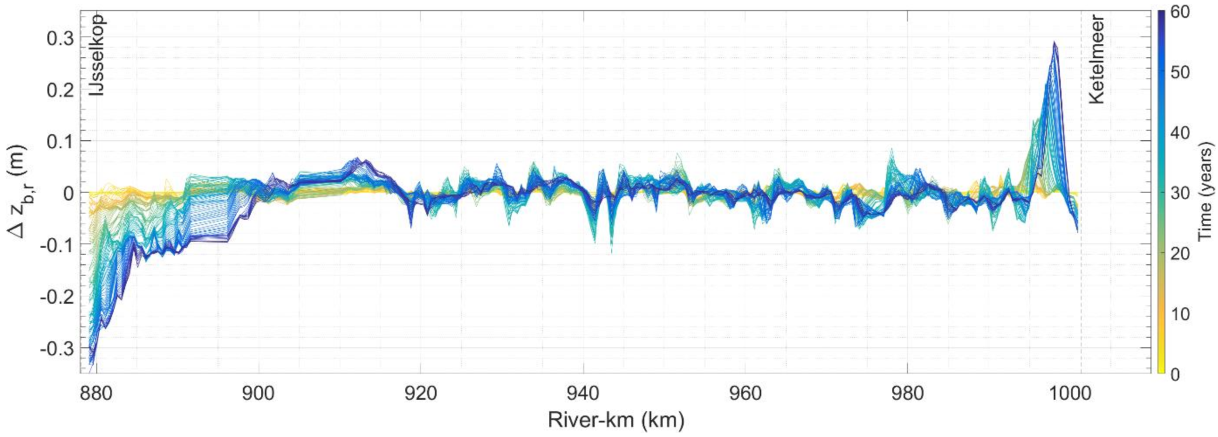

Figure 7.31: Difference in bed level of the IJssel between the simulation with the changed nodal point relation (D) and the reference simulation.

Discharge partitioning

The difference in the Waal discharge fraction between the simulation with the changed nodal point relation and the reference simulation is shown in Figure 7.32. Figure 7.33a shows the semiannually averaged difference in Waal discharge fraction for both low and high flows. It is seen that the influence of the changed sediment partitioning at the Pannerdense Kop on the discharge partitioning at the PK is similar for low and high flows. For low flows the semiannually averaged change in Waal discharge fraction compared to the reference case is slightly larger. For both the low and high flows the semiannually averaged results show that initially there is no relative difference in the Waal discharge fraction. Throughout the simulation the relative decrease becomes 1.8% for the low flows and 1.7% for the high flows.

For the low flows the semiannually averaged data also shows larger variability. This is due to the different effects on the discharge partitioning within the low flows. From Figure 7.32 it is seen that the lower the Lobith discharge, the higher the relative difference in Waal discharge fraction. The water level does not change initially and therefore the changed discharge partitioning is purely a result of the changed bed levels. For the intermediate flows it also holds that lower Lobith discharges lead to a larger relative difference in the Waal discharge fraction. This is due to a difference in weir operation compared to the reference case. Throughout the simulation the weirs start closing at slightly lower Lobith discharges leading to less water level set up and a lower Waal discharge fraction compared to the reference case.

Figure 7.33c and Figure 7.33d show the biyearly averaged Waal discharge fraction for both the reference and the side channel simulation for high and low flows. Initially the positive trend in Waal discharge fraction is reversed by steering the sediment partitioning at the PK but after 15 years the Waal discharge fraction starts to increase. Between year 30 and year 40 of the simulation the speed of the Waal discharge fraction increase starts to exceed the speed of the Waal discharge fraction increase for the reference simulation. This is due to the bed level development in the branches downstream of the PK. After 35 years upstream in the PC the bed level starts to increase with respect to the reference case and upstream in the Waal the bed level starts to decrease with respect to the reference case.

By executing the LSF analysis it is found the for the for the Lobith discharge of 1400 m^3/s the difference in Waal discharge ratio equals -0.4% initially and -2.0% after 60 years. In absolute figures this would be a initial decrease of 6.1 m^3/s to the Waal and a decrease of 28.1 m^3/s after 60 years.

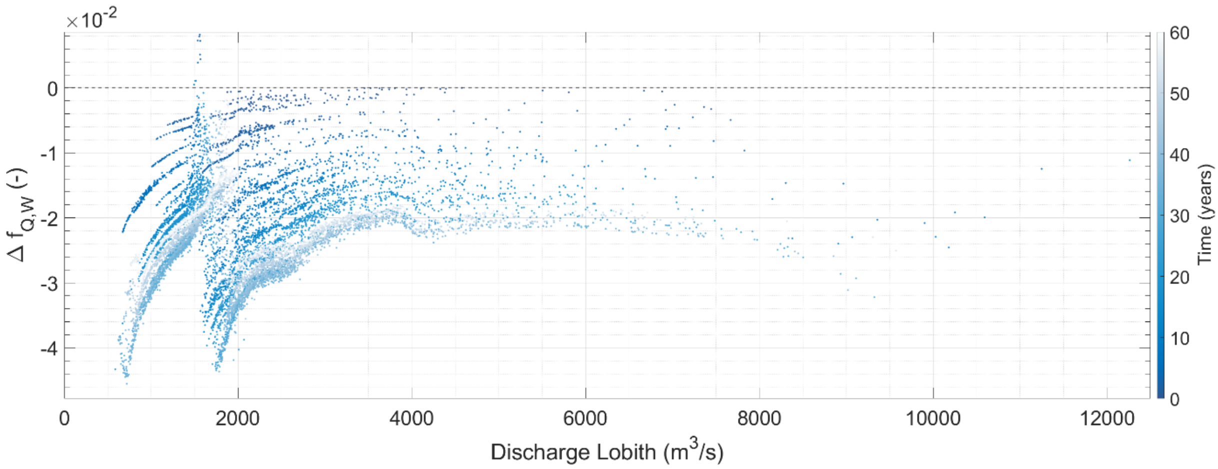

Figure 7.32: Difference in Waal discharge fraction between the simulation with the changed nodal point relation (D) and the reference simulation.

Figure 7.33b shows the semiannually averaged difference in IJssel discharge fraction relative to the Pannerden Canal discharge for low and high flows. In both cases initially the IJssel discharge fraction is the same as in the reference case. For the low flows the relative difference in IJssel discharge fraction is 0.4% at the end of the simulation and for the high flows this is -0.8%. Figure 7.34a and Figure 7.34b show the semiannually averaged difference in respectively the IJssel and NR-Lek discharge fractions relative to the Lobith discharge for both low and high flows. The change in discharge partitioning compared to the reference case is larger for the PK than for the IJsselkop. For all flows more discharge enters the PC throughout the simulation compared to the reference case so therefore for all flows the discharge fractions of the IJssel and NR-Lek relative to the Lobith discharge increase with respect to the reference case. On the IJssel the relative difference in discharge fraction is higher for low flows and on the NR-Lek this is the other way around. This is due to the opposite development of the difference in IJssel discharge fraction relative to the PC discharge.

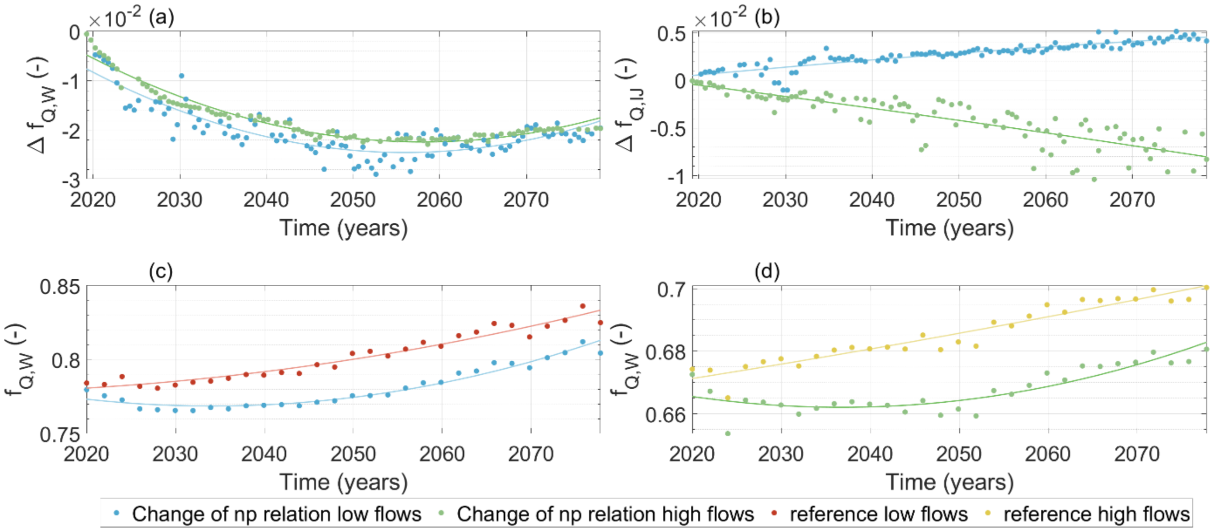

Figure 7.33: The semiannually averaged difference in discharge fraction between the simulation with changed nodal point relation (D) and the reference simulation for both low and high flows for a) the Waal and b) the IJssel. The discharge fraction of the IJssel is relative to the PC discharge. Development of the biyearly averaged Waal discharge fraction for both the reference simulation and the simulation with the widening on the IJssel for c) low flows and d) high flows.

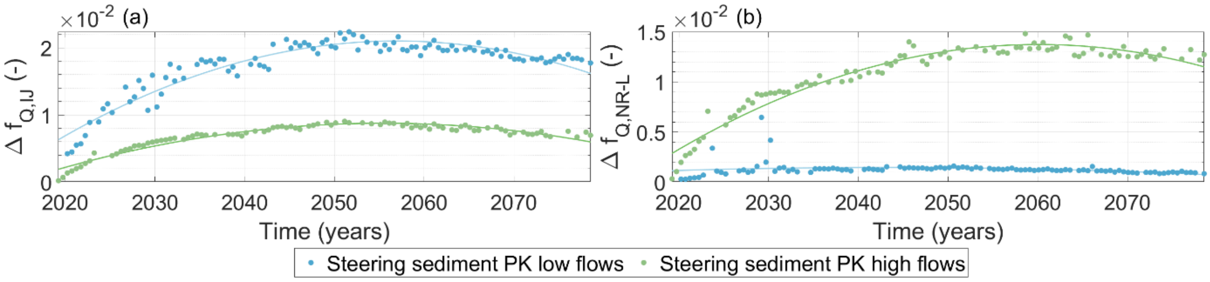

Figure 7.34: The semiannually averaged difference in discharge fraction between the simulation with the changed nodal point relation (D) and the reference simulation for both low and high flows for a) the IJssel and b) the Nederrijn-Lek. The discharge fractions are fractions of the Lobith discharge.

7.5 Dredging in the Pannerden Canal and dumping in the Waal

For this intervention, every 2.5 years dredging takes place in the main channel of the Pannerden Canal along rkms 871-876. The sediment obtained by the dredging activities is immediately dumped in the main channel of the Waal along rkms 867.5-870.

Overview effects

- The Boven-Waal and the Midden-Waal show reduced erosion throughout the whole simulation. The reduced erosion is larger for the Boven-Waal since the nourishments are placed upstream in the Boven-Waal.
- The PC shows enhanced erosion. The enhanced erosion starts at the dredged section. Throughout the simulation enhanced erosion also starts upstream and downstream of the dredged section.

- The relative bed level decrease only slowly propagates along the IJssel and NR-Lek. Upstream in the IJssel the erosion is enhanced and upstream in the NR-Lek the aggradation is reduced and at some locations even changes to erosion.
- The coarsening of the Boven-Waal and Midden-Waal is enhanced. The PC coarsens but the coarsening is reduced compared to the reference case.
- The development of the Waal discharge fraction is not influenced initially. The effect is similar for all flows. The positive trend in the Waal discharge fraction is still present but it is reduced with respect to the reference case. The relative difference in Waal discharge fraction keeps growing throughout the simulation.

Bed level difference

In order to show the propagation of the dredging along the Pannerden Canal and its downstream branches and the propagation of the nourishments along the Waal, Figure 7.35, Figure 7.36 and Figure 7.37 are shown. In Figure 7.35 the bed level development with respect to the reference case is shown for six points in time for the Boven-Rijn and Waal.

In the Waal a bed level increase with respect to the reference case is observed which starts upstream and travels downstream. The bed level increase is highest for the reach where the nourishments take place. Here the maximum bed level increase is 0.94 m. Due to the water depth increase downstream of a nourishment a hump arises. Furthermore nourishments increase the sediment transport downstream of the nourishment which leads to aggradation since the sediment transport capacity downstream is not immediately changed. The processes both cause the nourishments to travel downstream which leads to a relative bed level increase downstream of the nourishments. After 10 years the nourishments have reached rkm 890. After 30 years this is rkm 915. After 40 years the nourishments cause a bed level increase up until rkm 930 and after 50 years this is rkm 945. In the years after this the nourishments do not seem to travel any further. This is due to the bed level effect as a result of the decreased Waal discharge fraction relative to the reference case. From Figure 7.12 it is observed that a relative decrease in Waal discharge fraction leads to a bed level lowering relative to the reference case downstream of rkm 945. This counteracts the effect of the nourishment along this reach. Upstream of rkm 945 a relative decrease in Waal discharge fraction leads to reduced erosion. Figure 7.39 shows that the relative decrease in Waal discharge fraction increases through time. Therefore the bed level in the Waal upstream of rkm 945 also increases throughout the simulation compared to the reference case as a result of the relative difference in Waal discharge fraction. This is also visible from the bed level difference at the nourishment location. In the first 40 years the maximum height increases with approximately 0.1 m every 10 years after which the increase becomes 0.2 m every 10 years.

In Figure 7.36 the bed level development with respect to the reference case is shown for six points in time for the Boven-Rijn, Pannerden Canal and Nederrijn-Lek and in Figure 7.37 this is shown for the IJssel. In the PC a bed level decrease with respect to the reference case is observed. The relative decrease starts at the section where the dredging occurs. The maximum relative decrease is 1.4 m. The relative decrease travels downstream slowly. After 10 years it has reached rkm 882 in the NR-Lek and the IJssel. After 30 years this is rkm 885 for the NR-Lek and rkm 890 for the IJssel. At the end of the simulation the dredging caused a relative bed level decrease until rkm 887 on the NR-Lek and rkm 900 on the IJssel. The relative bed level decrease exceeds 5 cm on the IJssel until rkm 890. The downstream propagation of the dredging hole is due to the sudden water depth decrease at its downstream end which causes a sudden increase in sediment transport and therefore an erosion pit with respect to the reference case. Upstream of the dredging hole enhanced erosion takes place as well. The enhanced erosion is

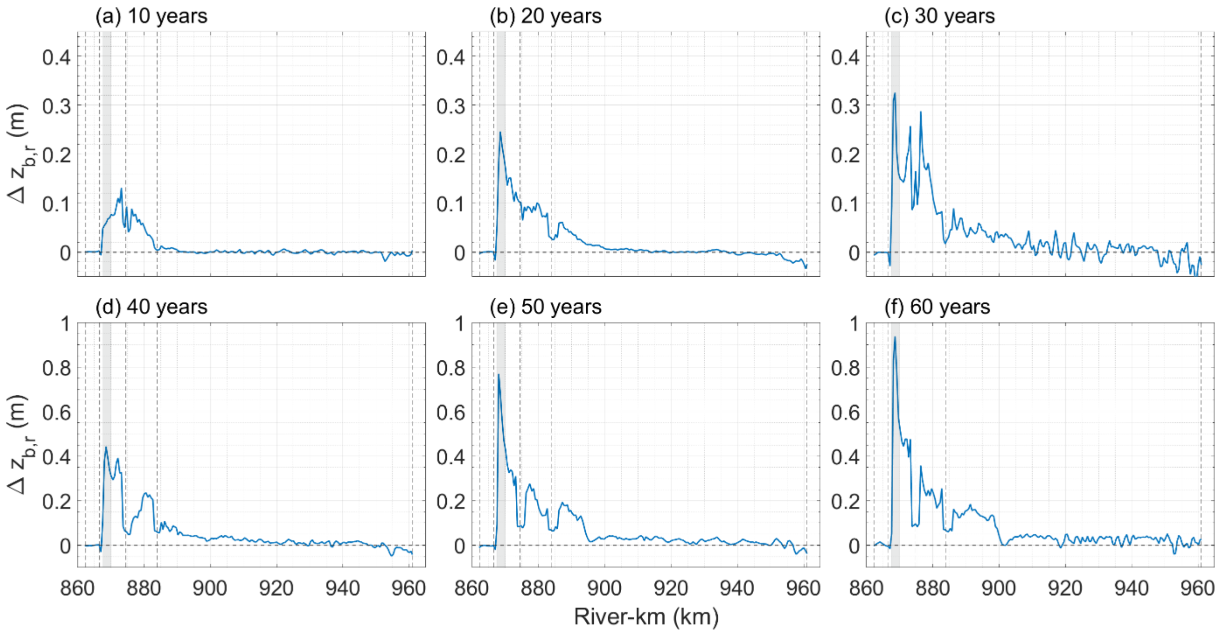

Figure 7.35: Difference in bed level of the Boven-Rijn and Waal between the dredge and dump simulation (E) and the reference simulation. The grey areas indicate the location of the nourishments. Note the difference in the y-axes between subplots a-c and subplots d-f.

the result of the M2-backwater curve which arises upstream of the dredging hole. The relative bed level decrease is also a result of the increase in the PC discharge fraction throughout the simulation relative to the reference case, see Figure 7.39.

The magnitude of the relative bed level difference is much larger for the PC than for the Waal even though the nourishment and dredging lengths are approximately scaled with the width of the main channels. This is because (1) the relative difference in discharge compared to the original discharge is much larger for the PC than for the Waal. Therefore the relative bed level difference is also larger for the PC than for the Waal. (2) The relative bed level decrease on the PC is also larger than the relative bed level increase on the Waal because the nourishments on the Waal propagate downstream faster than the dredging hole on the PC. (3) Furthermore, the mean grain size development enhances the relative bed level difference more on the PC than on the Waal.

In Figure 7.38 the reach averaged mean grain size development is shown for the PC, the Boven-Waal and the Midden-Waal are shown. It is found that the reach averaged mean grain size relative to the reference case on the PC drops. The dredging repeatedly removes a part of the active layer and this is replenished by the substrate layers. The substrate layers have the same composition as the initial active layer composition. Since the Pannerden Canal coarsens over time this means that the replenishment of the active layer by the substrate layers leads to a reduced coarsening. The reach averaged mean grain size relative to the reference case increases for the Waal. The bed of the PC consists of coarser sediment than the bed of the Waal. Therefore the nourishments with coarser sediment lead to a relative increase in mean grain size on the Boven-Waal and the Midden-Waal. The relative mean grain size difference on the PC is larger than the relative mean grain size difference on the Waal Therefore the influence of the relative coarsening of the Waal on the relative bed level increase is smaller than the influence of the relative fining of the PC on the relative bed level decrease.

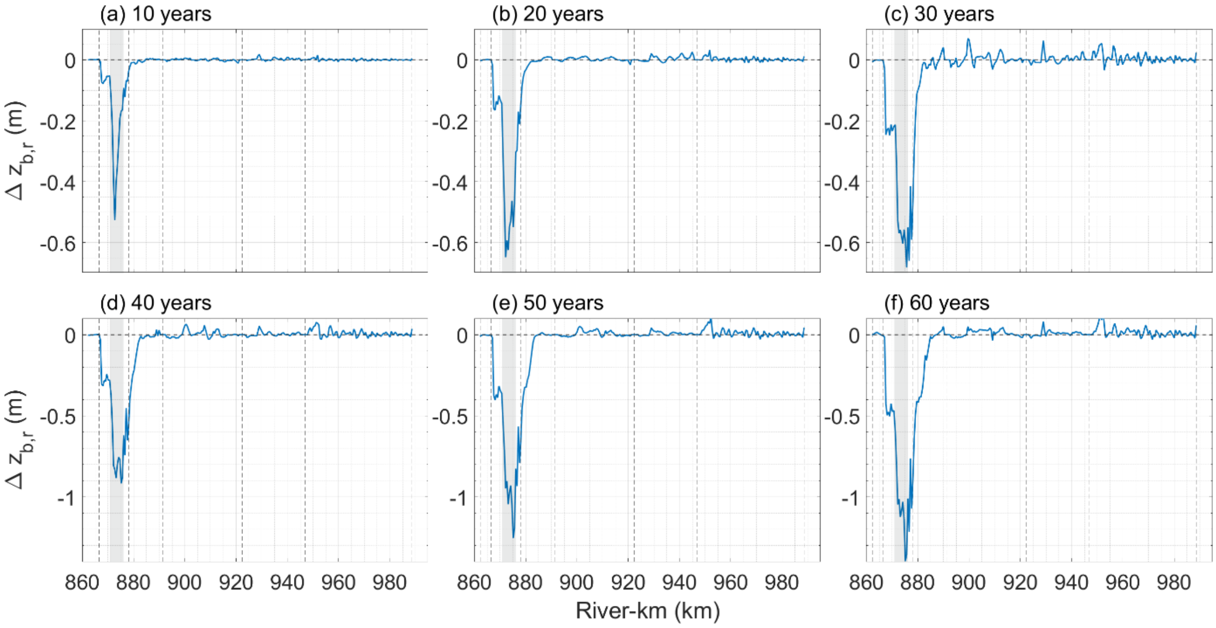

Figure 7.36: Difference in bed level of the Boven-Rijn, Pannerden Canal and the Nederrijn-Lek between the dredge and dump simulation (E) and the reference simulation. The grey areas indicate the location of the dredging activities. Note the difference in the y-axes between subplots a-c and subplots d-f.

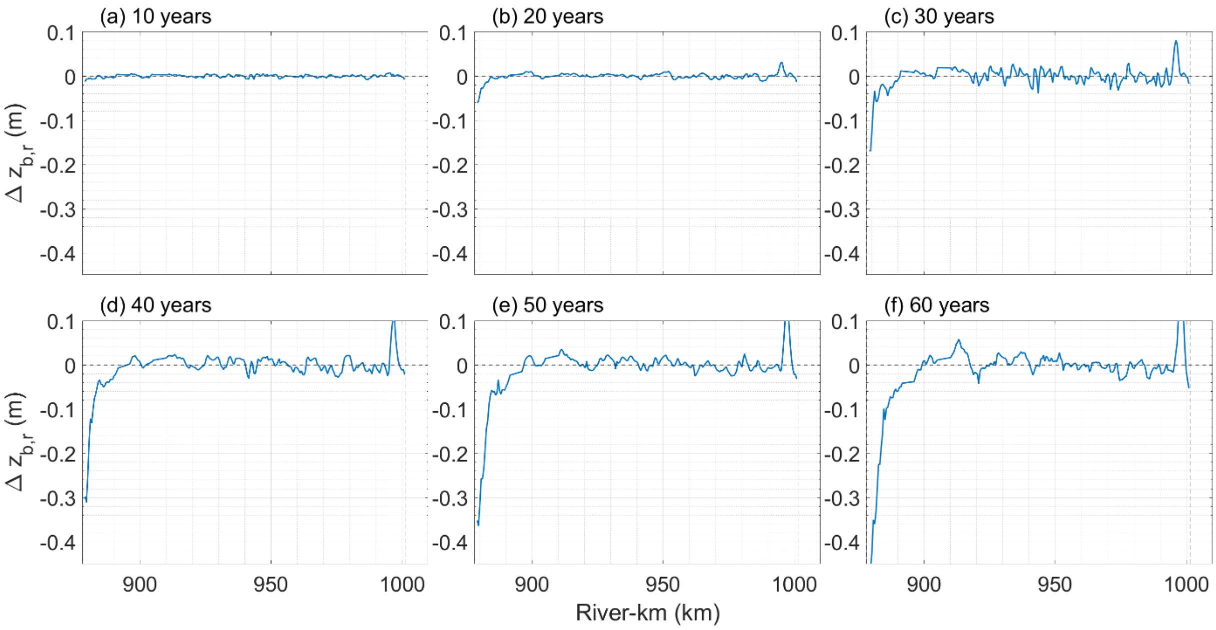

Figure 7.37: Difference in bed level of the IJssel between the dredge and dump simulation and the reference simulation.

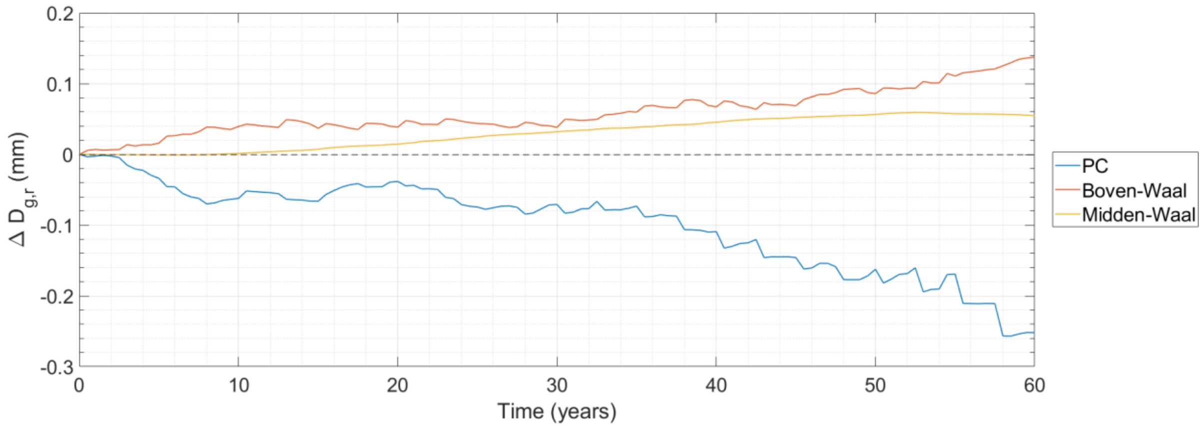

Figure 7.38: Reach averaged difference in geometric mean grain size compared to the reference case for the Pannerden Canal, Boven-Waal and Midden-Waal.

Discharge partitioning

The difference in the Waal discharge fraction between the simulation with the changed nodal point relation and the reference simulation is shown in Figure 7.39. Figure 7.40a shows the semiannually averaged difference in Waal discharge fraction for both low and high flows. It is seen that the influence of the dredging and dumping on the discharge partitioning at the PK is slightly larger for low than for high flows. For both the low and high flows the semiannually averaged results show that initially there is no relative difference in the Waal discharge fraction. Throughout the simulation the relative decrease in Waal discharge fraction is 2.4% for the low flows and 2.2% for the high flows. For both the low and the high flows the relative difference in Waal discharge fraction decreases steadily throughout the whole simulation. This is the because of the repeated dredging and nourishments since this causes the relative bed level decrease in the PC and the relative bed level increase in the Waal to also increase steadily throughout the simulation.

For the low flows the semiannually averaged data in Figure 7.40a shows larger variability just as for the simulation with the changed nodal point relation. This is due to the different effects on the discharge partitioning within the low flows. From Figure 7.39 it is seen that the lower the Lobith discharge, the higher the relative difference in Waal discharge fraction. Similar to the simulation with the changed nodal point relation, the dredge and dump simulation also leads to closing of the weirs for slightly lower Lobith discharges. Therefore, for the intermediate flows it also holds that lower Lobith discharges lead to a larger relative difference in the Waal discharge fraction.

Figure 7.40c and Figure 7.40d show the biyearly averaged Waal discharge fraction for both the reference and the side channel simulation for high and low flows. During the first thirty years the relative decrease in the Waal discharge fraction is enough to keep the Waal discharge fraction constant for low and high flows for the dredge and dump simulation. After the first 30 years the Waal discharge fraction also starts increasing for the dredge and dump simulation.

By executing the LSF analysis it is found the for the for the Lobith discharge of 1400 m^3/s the difference in Waal discharge ratio equals -0.1% initially and -2.4% after 60 years. In absolute figures this would be a initial decrease of 1.8 m^3/s to the Waal and a decrease of 33.0 m^3/s after 60 years.

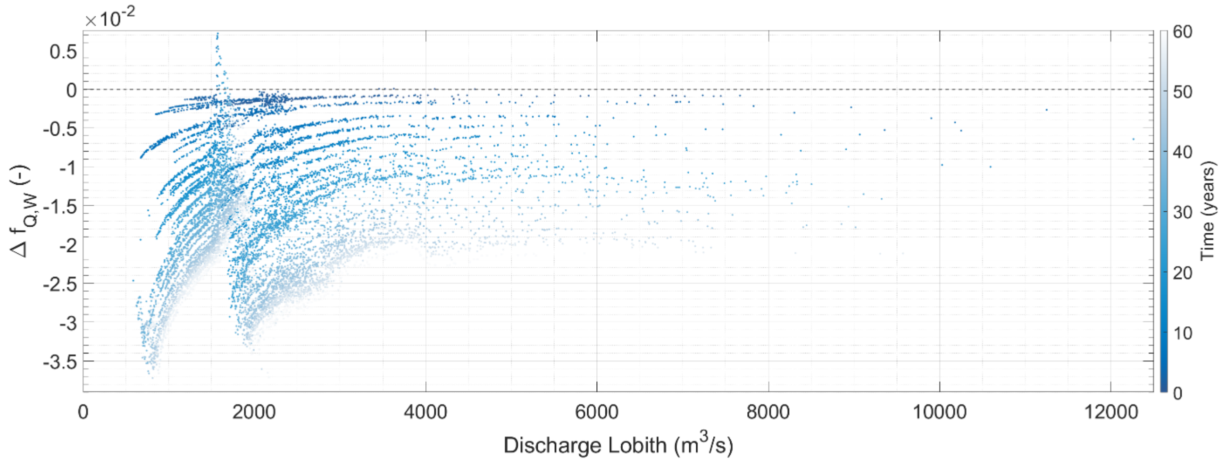

Figure 7.39: Difference in Waal discharge fraction between the dredge and dump simulation (E) and the reference simulation.

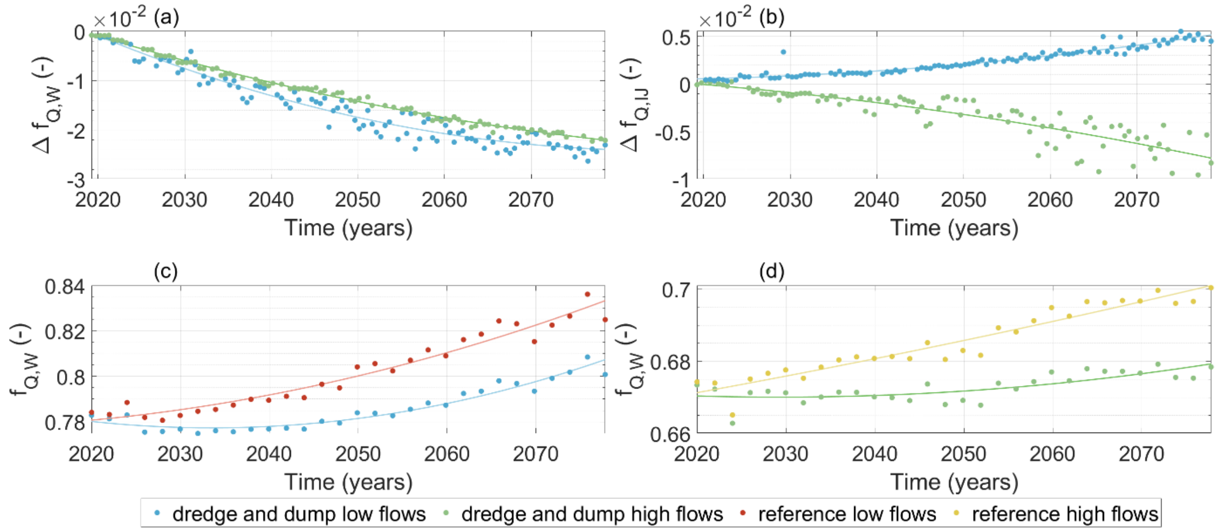

Figure 7.40: The semiannually averaged difference in discharge fraction between the dredge and dump simulation (E) and the reference simulation for both low and high flows for a) the Waal and b) the IJssel. The discharge fraction of the IJssel is relative to the PC discharge. Development of the biyearly averaged Waal discharge fraction for both the reference simulation and the simulation with the widening on the IJssel for c) low flows and d) high flows.

Figure 7.40b shows the semiannually averaged difference in IJssel discharge fraction relative to the Pannerden Canal discharge for low and high flows. In both cases initially the IJssel discharge fraction is the same as in the reference case. For the low flows the relative difference in IJssel discharge fraction is 0.5% at the end of the simulation and for the high flows this is -0.8%. Figure 7.41a and Figure 7.41b show the semiannually averaged difference in respectively the IJssel and NR-Lek discharge fractions relative to the Lobith discharge for both low and high flows. Due to the large relative increase in PC discharge fraction, the discharge fractions of the IJssel and NR-Lek all increase throughout the simulation compared to the reference case. On the IJssel the relative difference in discharge fraction is higher for low flows and on the NR-Lek this is the other way around. This is due to the opposite development of the difference in IJssel discharge fraction relative to the PC discharge for the low and high flows.

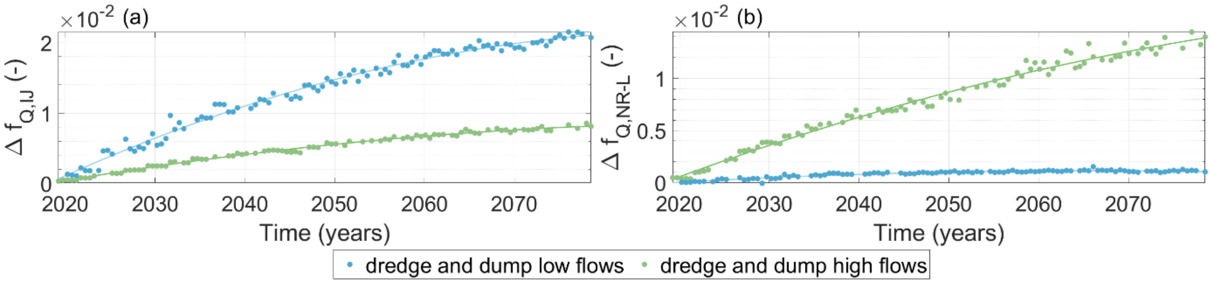

Figure 7.41: The semiannually averaged difference in discharge fraction between the dredge and dump simulation (E) and the reference simulation for both low and high flows for a) the IJssel and b) the Nederrijn-Lek. The discharge fractions are fractions of the Lobith discharge.

7.6 Morphological effects of interventions

The sub question that is answered by this chapter is “What are the effects of the selected interventions on the discharge partitioning over the Pannerdense Kop and on the morphology downstream of the bifurcation?”.

In the previous sections the effects on the bed level development and the effect on the discharge partitioning at the Pannerdense Kop and the IJsselkop of the different interventions was analyzed. Also the effect on the effects on the mean grain size development and the sediment transport were analyzed when this was required to understand the bed level development. Table 7.1 contains an overview of the morphological effects of the interventions and the effects of the intervention on the discharge partitioning at the Pannerdense Kop and the IJsselkop are shown in Table 7.2.

Table 7.1: Long-term reach averaged effects of the interventions on the bed level developments in the Dutch Rhine branches downstream of the Pannerdense Kop. For the reach averaged relative bed level difference two values are presented. The first value represents the average over the entire simulation and the second value represents the value at the end of the simulation.

	Boven-Waal	Midden-Waal	Beneden-Waal	PC	IJssel	NR-Lek
Intervention	$\Delta z_{b,r}$ (cm)	$\Delta z_{b,r}$ (cm)	$\Delta z_{b,r}$ (cm)	$\Delta z_{b,r}$ (cm)	$\Delta z_{b,r}$ (cm)	$\Delta z_{b,r}$ (cm)
Side channel	2.3/3.6	0.3/1.0	0.3/0.8	-11.6/-13..2	-0.3/-0.2	-0.2/-0.4
Opening of weirs	7.4/12.8	2.1/4.6	-2.1/-0.2	-21.2/-37.4	2.0/3.2	0.2/0.0
Widening IJssel	3.6/5	1.0/2.1	-0.2/1.0	-13.6/-20.1	-1.3/-1.3	0.7/0.8
Change of np relation	20.4/24.2	4.3/9.9	0.2/2.6	-70.0/-78.3	-0.7/-1.7	0.1/-0.2
Dredge and dump	18.6/38.1	2.7/7.4	-0.4/1.9	-42.7/-79.5	-0.4/-1.6	1.3/0.7

Table 7.2: The effects of the interventions on the discharge partitioning at the Pannerdense Kop and the IJsselkop relative to the reference simulation. For all variable two values are presented: The first value indicates the relative difference in discharge fraction at the start of the simulation and the second value indicates the difference in discharge fraction at the end of the simulation. The include variables are: the relative change in $f_{QW,1400}$, and the average relative changes in the Waal, Pannerden Canal and Nederrijn-Lek discharge fractions relative to the Lobith discharge for both high and low flows.

	PK			IJK			
Intervention	$\Delta f_{QW,1400}$ (%)	$\Delta \frac{Q_W}{Q_L}$ low (cm)	$\Delta \frac{Q_W}{Q_L}$ high (cm)	$\Delta \frac{Q_{IJ}}{Q_L}$ low (cm)	$\Delta \frac{Q_{IJ}}{Q_L}$ high (cm)	$\Delta \frac{Q_{NR-L}}{Q_L}$ low (cm)	$\Delta \frac{Q_{NR-L}}{Q_L}$ high (cm)
Side channel	0.18/-0.45	0.22/-0.47	-0.26/-0.51	-0.19/0.42	0.11/0.16	-0.01/0.01	0.15/0.36
Opening of weirs	-7.83/-6.93	-7.93/-6.71	0.00/-1.11	-6.09/-4.26	0.00/-0.56	13.99/11.35	0.00/1.67
Widening IJssel	-2.17/-1.38	-2.39/-1.35	-0.68/-0.74	2.43/1.49	1.61/1.47	-0.10/-0.04	-0.93/-0.73
Change of np relation	-0.44/-2.01	0.00/-1.82	0.00/-1.75	0.00/1.62	0.00/0.60	0.00/0.08	0.00/1.15
Dredge and dump	-0.13/-2.36	0.00/-2.39	0.00/-2.20	0.00/2.11	0.00/0.81	0.00/0.11	0.00/1.39

8 Discussion

This chapter provides a discussion on the results of this study. In section 8.1 the model features and choices are discussed. Section 8.2 provides a discussion on the design of the interventions. Finally, in section 8.3 the potential of the interventions related to the IRM programme are discussed. This section also provides a coupling between the results of this study and the goals set in the IRM programme.

8.1 Model features and choices

8.1.1 Sediment transport

The active layer concept of Hirano (1972) is used in the 1D Rhine branches model. In this concept the active layer is fully mixed. This limits the formation of a armouring layer (Chavarrías & Ottevanger, 2021). A severe coarsening on the Niederrhein and Boven-Rijn is observed in all simulations. In reality an armouring layer could form which shields the underlying fine sediment from the flow and thereby reducing the sediment transport capacity. This is not modelled and therefore the sediment transport supply to the Dutch Rhine branches downstream of the Pannerdense Kop may be overestimated. Furthermore, the sediment from the Pannerden Canal which is nourished in the Waal is coarser than the Waal river bed. The difference in mean grain size was relatively small but still the nourishments may form a protective layer for the finer sediment in the Waal river bed. As a result the sediment transport at the nourishment location and therefore the reduced erosion downstream may be overestimated in the model results.

The effect described above is also influenced by the hiding and exposure relations which are used in the 1D Rhine branches model. For sand, the sediment transport relation of Engelund and Hansen (1967) is used. For gravel, the sediment transport relation of Meyer-Peter and Müller (1948) is used. In the gravel transport formula hiding-exposure effects are included through the hiding-exposure relation by Ashida and Michiue (1971) which adjusts the critical bed shear stress. No hiding-exposure effects are included for the sand transport since the Engelund and Hansen load relation does not contain a critical bed shear stress. Therefore the mobility of the sand is not influenced by the gravel in the bed while the mobility of the gravel is influenced by the sand particles. In reality the presence of gravel in the bed reduces the mobility of the sand fractions which may lead to an overestimation of the sand transport in the model.

Since a 1D model is used, 2D and 3D effects that are observed in reality are not captured in the model. For the sediment transport influential processes which are not captured in the model are spiral flow in bends and the resulting sediment sorting. These processes lead to a different development of the inner and outer bend of a river while in the model only main channel morphology is included. The upstream part of the Waal contains multiple consecutive bends. In the simulation where the sediment partitioning at the Pannerdense Kop is steered, large relative bed level increases are observed upstream in the Waal and for the dredge and dump simulation the nourishments are located in the Waal just downstream of the PK. The bend effects are especially important for these simulations.

Furthermore, a nodal point relation has to be applied since a 1D model is used, see equation B.10. The nodal point relation is a highly simplified representation of reality. In reality the sediment division over the bifurcates is a three-dimensional process which is among others dependent on the transverse slope, the bifurcation angle and the approach condition of the bifurcation. These effects all have to be captured in the calibration coefficient of the nodal point relation. Using a physics-based nodal point relation, like the one from Kleinhans et al., (2008) which explicitly incorporates the effects of a meander bend just upstream of the bifurcation and a transverse bed slope, is expected to lead to a better match between the modelled and measured sediment loads in the bifurcates. The results of the calibration of the nodal point relation are limited due to the high uncertainty and the large variability of the sediment loads estimated by Frings et al. (2019). Accurate measurements of the sediment load in the upstream branches and bifurcates of the bifurcations are necessary for correctly calibrating the nodal point relation.

8.1.2 Spin-up time

The morphological changes in the model are disabled for the first 7 days as this is the time it takes for the model to fill with water. It may be advantageous to adjust the spin-up time to multiple years. The model results for the Boven-Rijn show aggradation of 22 cm in the first 2 years. This seems to be unrealistic since erosion is expected and the aggradation speed is much higher than the current aggradation and erosion speeds of a few cm per year. This strong initial response of the bed level may be the result of the mismatch between the initial bed sediment composition and the initial bathymetry and also the mismatch in the initial bathymetries from different years for the Niederrhein (2012) and Boven-Rijn (2019). Therefore the model can be spun up by only allowing for development of the mean grain size for the first 5 years to let the bed sediment composition adjust to the initial bathymetry. This was tried but the 1D Rhine branches model does not contain an option to switch the development of the mean grain size on and off throughout the simulation. Therefore the model had to be restarted with the results from the spin-up period. This functionality however also does not work yet and therefore the spin-up time is limited to 7 days.

8.1.3 Boundary conditions

The sediment flux into the model domain is determined by a ghost cell. The sediment influx is such that the bed level and the bed sediment composition of the ghost cell remain unchanged. This way the sediment influx is only dependent on the flow conditions at the upstream boundary and not on the development of the German Rhine. Coarse nourishments and bed degradation both influence the sediment supply towards the model domain. It is recommended to do a sensitivity analysis in order to get insight into the effects of changes to the sediment influx.

Initially it was planned to run the simulations for 100 years. The simulations have been run for 60 years due to time constraints. The hydrograph used for these simulations is the discharge hydrograph from 1916-2016. By taking the hydrograph from the past century the effects of climate change on the discharge at the upstream end of the model domain are ignored. This hydrograph allows for a prediction of the morphological development of the Dutch Rhine branches without the influence of climate change. The variability of the hydrograph complicated the comparison of the influence of the interventions on the discharge partitioning at the Pannerdense Kop. Another possibility is to use a hydrograph consisting of several constant discharges based on the averaged yearly Rhine hydrograph as used by Ottevanger et al. (2015). This approach simplifies the comparison of the influence of the interventions on the discharge partitioning at the PK.

At the downstream boundaries Qh-relations are imposed. This way a water level is defined for a certain discharge. The Qh-relations stay constant throughout the simulation. The bed level does change. Downstream in the Waal aggradation occurs. At the start and at the end of the simulation the water level downstream in the Waal is the same for equal discharges. However, due to the increased bed level, the water depth reduces which leads to larger flow velocities throughout the simulation. Higher flow velocities lead to a higher sediment transport capacity and therefore the aggradation near the downstream boundary in the Waal may be underestimated.

8.1.4 Sediment composition

The model results for the reference scenario showed a significant coarsening on the Niederrhein and Boven-Rijn. The other Dutch Rhine branches also coarsen but less fiercely. The severe coarsening of the Boven-Rijn only minimally reaches the PC and the Boven-Waal at the end of the simulation. The question arises whether the reduction in sediment transport and the magnitude and timescales of the coarsening and erosion of the Niederrhein, Boven-Rijn, Pannerden Canal and Boven-Waal branches are realistic. This behavior is largely determined by the initial bed sediment composition and the implemented sediment transport formulas and the calibration thereof. The initial bed sediment composition is taken from Sloff (2006) which used measurements from 1995 for which it is known that the measurements contain large uncertainty, especially the measurements for the coarse fractions around the Pannerdense Kop bifurcation. In 2020 the bed sediment composition of the Rhine branches is fully measured again. This data was not available yet at the time of calibration so it is not used yet in the model from Chavarrías et al. (2020). From these measurements, it is known that the bed has coarsened since 1995, see Figure 8.1. Therefore also a coarsening in the model is expected. However it is unknown whether the timescale of the coarsening is realistic. The measurements also show that the mean grain size around the Pannerdense Kop changes gradually. This is also found by Ylla Arbós et al. (2023), who mention that the gravel-sand transition (GST) has shifted downstream. The shift in the GST is not in the model results. This might be related to the nodal point relation at the Pannerdense Kop. It is recommended to further investigate whether this behavior is realistic. This is also one of the recommendations of Paarlberg and Van Lente (2021).

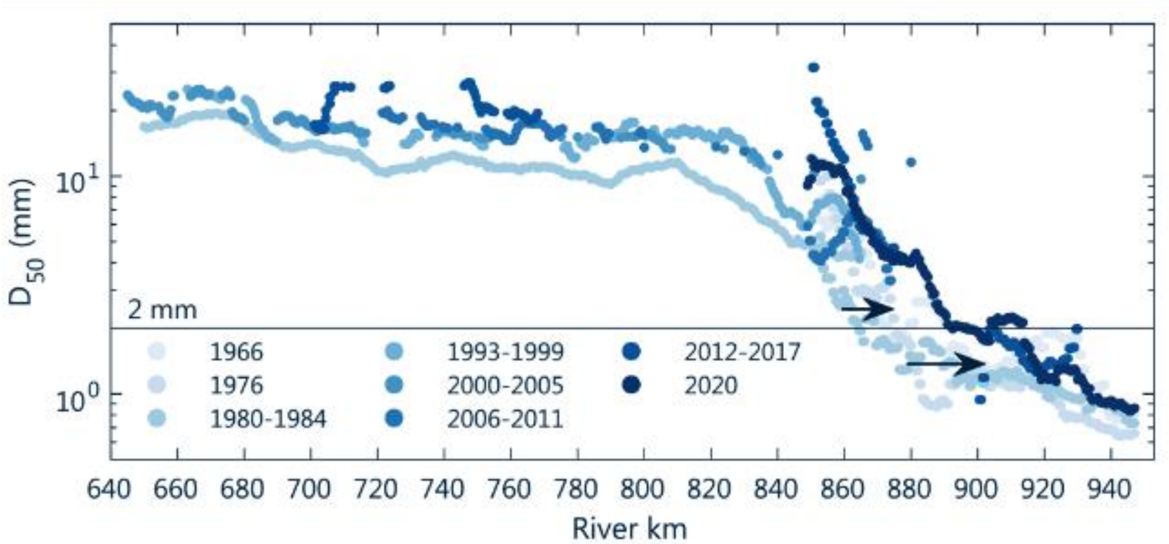

Figure 8.1: Median bed surface grain size D_{50}, moving average with window size 10 km for the Niederrhein, Boven-Rijn and Waal reaches. Adapted from Ylla Arbós et al. (2021)

The initial bathymetry is from 2019 and therefore the initial sediment composition is too fine for the bed level. The sediment composition of the bed is inherently connected to the bed level development since the sediment composition of the bed influences the sediment transport capacity. Because of the large uncertainty of the 1995 measurement data and the mismatch in time between the initial bed sediment composition and the initial bathymetry, it is recommended to update the initial bed sediment composition with the measurements from 2020. Furthermore it is recommended to perform a sensitivity analysis for the initial sediment composition and the sediment transport formulas to get more insight into the possible effect of using the outdated sediment composition on the bed level development.

8.1.5 Calibration and verification

In chapter 3 it is discussed that due to the variability of the measured discharges it is not possible to assess whether the model correctly models the discharge distribution. However, it is known that the main focus in the calibration of the friction values was on correctly modeling the flow velocities and not on discharges. In the hydrodynamic step, for four different Lobith discharges only one manning coefficient is calibrated for all Rhine branches. Chavarrías et al. (2020) note that with the 1D Rhine branches model errors in water level in the order of a centimeter and up to a decimeter are obtained compared to the WAQUA model. It should be noted that the WAQUA model is a 2D-model which means the error also incorporates the shortcomings of 1D-model compared to a 2D-model. The water level errors affects the reliability of the discharge partitioning results. Therefore the exact values of the results with respect to the discharge partitioning should not be directly copied from this study. The results are useful for the orders of magnitude and the trends in the discharge partitioning and the relative differences in discharge fractions at the PK and the IJsselkop as a result of the interventions.

There are several ways in which the accuracy and the reliability of the results can be increased. An option is to include the floodplain friction in the hydrodynamic calibration step such that there are more possibilities in the calibration step to match the main channel velocities and the discharge partitioning to the WAQUA results. Since the 1D Rhine branches model includes morphological development it is not possible to calibrate the manning coefficient of the Rhine branches separately. Another possibility to obtain more reliable results on the discharge partitioning is to implement the resulting bed levels of the Dutch Rhine branches in another 1D FLOW FM model which is calibrated with the purpose of getting the water levels and discharges right. This way the results from this study can also be verified.

In the calibration and verification runs performed by Chavarrías et al. (2020) for the bed levels of the Waal and the Pannerden Canal a mismatch was observed downstream. The Engelund and Hansen and Meyer-Peter and Müller sediment transport relations are calibrated for the different Rhine branches. Optionally the model can be recalibrated to provide a better match for the Waal and Pannerden Canal bed level developments by separating the Waal and PC in several reaches which are separately calibrated.

Paarlberg and Van Lente (2021) mention it is still unknown whether the long term model results are realistic and reliable. As mentioned in the previous section the magnitude and the timescales of the coarsening in the model should first be further investigated. If through further investigation it is found that the model results are unreliable then it is recommended to implement the 2020 measurements of the bed sediment composition in the model. This does not necessarily lead to recalibration (Paarlberg and Van Lente (2021). However, ideally the model is then recalibrated with the changes to the hydrodynamic and morphodynamic steps as described above when using the model to study long term effects of river interventions on the morphology of the branches downstream of the PK and the effect on the discharge partitioning at the PK.

8.2 Design choices and assumptions of the interventions

Side channel from the BR to the PC

The length of the side channel is set to 5 km as often there is no space to implement side channels with a longer length. Implementing a longer side channel would also lead to a longer section of the PC with reduced discharge which is unwanted. In the design of the side channel the slope is assumed to be the same as for the Boven-Rijn. The slope will be much lower in reality due to the connectivity with the PC. As a result the discharge through the side channel calculated with the water extraction tool is overestimated. Therefore the water extraction and insertion values belong to a wider side channel and the effects of a side channel of 50 m wide is overestimated. No sediment is assumed to enter the side channel such that it works the same throughout the whole simulation period. This assumption partly holds due to the presence of the inlet step. The assumption can also be viewed as dredging the deposited sediment in the side channel and dumping it back in the main channel which can be realized.

Fully opening the weirs

The weirs are completely opened in the simulation. Always fully opening the weirs is not realistic and the results should therefore be regarded as the full potential of changing the weir settings with respect to the effect on the bed level development in the Dutch Rhine branches and the and discharge division between them. In this study it is found that opening the weirs significantly reduces the discharge towards the Waal for low flows. The discharge partitioning at the IJsselkop changes even more for low flows which is unwanted related to the freshwater supply of the IJsselmeer. Therefore it may be of interest to see how the discharge partitioning of both the IJsselkop and Pannerdense Kop is affected if the weir setting are changed such that the weirs are open more often instead of all the time.

Widening on the IJssel

For the widening on the IJssel the design parameters are the length of the widened section, the location of the widening and the additional main channel width. With the schematization tools it was found that in order to completely reverse the positive trend of the Waal discharge fraction, a unrealistically long and wide widened section was required. This unrealistically large widening has been applied such that the model results show the full potential of the widening on the IJssel. The results show strong aggradation along the widened section. This leads to a reduced influence on the discharge distribution at the PK during the simulation. Dredging the widened section can be implemented such that the effectivity of the intervention is retained throughout its lifetime. Furthermore the discharge on the Nederrijn-Lek is reduced with respect to the reference case for. It is interesting to see whether these negative consequences of the widening interventions can be reduced without affecting the positive influence on the discharge partitioning at the PK too much.

Directly steering the sediment partitioning at the PK

The nodal point coefficients are changed for the interventions which aim to influence the sediment partitioning at the PK. Consequently the results do not directly reflect the effect of placing a sill in front of the PC or changing the transverse slope upstream of the PK. Therefore the results provide insight into the general effects of interventions aimed at steering the

sediment partitioning at the PK. A 2D-model should be used in order to obtain insight into the specific effects of placing a sill in front of the PC or changing the transverse slope upstream of the PK.
The nodal point is changed such that 20% extra sand and gravel are diverted towards the Waal. It is unknown whether this percentage is realistic through the placement of a sill upstream in the PC or changing the transverse slope upstream of the PK. This should be investigated.

Dredging and dumping

In the design of the dredging and dumping values variables have to be chosen for many variables. The variables are the locations of the dredging and dumping, the lengths, the volume that is dredged and the periodicity of the dredging and dumping activities. This means that there are many different possibilities to optimize the intervention. This is especially the case for the dredging volume and location since limiting the length of the dredging activities to 2.5 km and placing it immediately downstream of the PK would lead to a larger effect on the discharge partitioning. In this study the dredging location and length were chosen to limit the added erosion on the Pannerden Canal to 1.5 m. It would be interesting to add dredging locations to increase the nourishment volume on the Waal without further decreasing the Pannerden Canal bed level. A possible dredging location is the Beneden-Waal which is dredged in reality to provide sufficient depth for navigation. Another possibility is to dredge the floodplains. This way the conveyance capacity of the floodplains is increased leading to less flow in the main channel during floods. This leads to reduced erosion which is beneficial for the discharge partitioning if it is applied along the Waal. However, dredging the floodplains can not be implemented through the dredge and dump module.

In the dredging and dumping module it is assumed that the dredged material is directly disposed on the river bed. In reality the sediment has to travel down through the water column. During this process some sediment will be transported downstream by the flow. As a result the aggradation at the nourishment location may be overestimated.

8.3 Potential of the interventions related to IRM

In the IRM program it is mentioned that the bed level degradation of all Dutch Rhine branches should be stopped and if necessary and feasible the bed level should even be increased. One of the goals for the IRM program with respect to the bed level of the Rhine branches is to obtain a sufficiently stable and maintainable bed level which contributes to a proper water distribution across the Netherlands during low discharges (Ministerie van Infrastructuur en Waterstaat, 2023). It is not mentioned what the proper water distribution should be but by preventing further erosion of the Rhine branches the discharge partitioning at the bifurcation remains approximately equal to its current state. For high flows, the goal of IRM is to have sufficient capacity to deal with the more frequent high flows in the future (Ministerie van Infrastructuur en Waterstaat, 2023). To retain sufficient range of control with the regulating structures in the future it is therefore also important that the discharge partitioning towards the Waal does not increase anymore.

Except for the implementation of the side channel, all interventions positively influence the discharge partitioning at the PK since more water is diverted towards the PC. Steering the sediment partitioning at the PK and the dredging and dumping also positively influence the discharge partitioning at the IJsselkop since the discharge fractions of the IJssel and NR-Lek increase with respect to the reference case. Fully opening the weirs leads to significant relative decrease in the IJssel discharge fraction for low flows which is unwanted with respect to the goals of IRM. Widening on the leads to a relative decrease in the NR-Lek discharge fraction for high flows. However the NR-Lek discharge fraction for high flows still increases throughout the simulation.

With respect to the bed level development, it is found that all studied interventions lead to a relative bed level increase on the Waal and a relative bed level decrease on the PC. The relative bed level increase on the Waal is not large enough to counter the ongoing bed level lowering. The relative bed level decrease on the PC is unwanted since the goal of IRM is to stop the degradation of the Dutch Rhine branches. For the dredge and dump simulation the relative bed level decrease of the PC can be reduced by selecting different dredging locations. As mentioned in section 7.2, the Beneden-Waal or the floodplains could serve as dredging locations.

Conclusion

The interventions which show potential for reaching the goals of IRM are the widening on the IJssel and the dredge and dump intervention. Widening on the IJssel leads to a relative bed level decrease in the PC and downstream in the IJssel. However widening on the IJssel shows potential for IRM despite the negative bed level effects since these are small. The dredge and dump intervention shows negative effects on the PC bed level. This can partly be resolved by regarding different sediment sources.

The other studied interventions do not show potential regarding the goals of IRM. The reasons are listed below.

- Fully opening the weirs negatively affects the NR-Lek discharge fraction. This effect is larger than the positive effect on the PK discharge partitioning.
- The side channel does not positively influence the bed level development or the discharge partitioning.
- Directly steering the sediment partitioning at the PK has a larger negative impact on the PC bed level than the positive impact on the bed level of the Waal which is inherent to the intervention.

9 Conclusion and Recommendations

Section 9.1 provides an answer to the main question posed in this study. In section 9.2, recommendations for further research towards mitigating the trend in discharge partitioning at the Pannerdense Kop are given.

9.1 Conclusions

The objective of the research is to get insight into which interventions can mitigate the gradual change in discharge partitioning over the Pannerdense Kop (PK) to obtain a stable situation in the long term. Also, the aim is to get insight into the behavior of the river bed in the Dutch Rhine branches in response to the interventions. Using the results from this study the following main research question can be answered:

To what extent can interventions be used to mitigate the change in discharge partitioning of the Pannerdense Kop and what is their effect on the bed level of the Dutch Rhine branches?

Implementing a side channel (A) with a length of 5 km which runs from the Boven-Rijn to the Pannerden Canal (PC) hardly affects the discharge partitioning at the PK since the backwater effects from the water addition counteract the increased discharge towards the PC. Averaged over the low Lobith flows the side channel initially even leads to a relative increase in Waal discharge fraction. At the end of the simulation the Waal discharge fraction decreased with respect to the reference case by 0.5% for both low and high flows. This is mainly due to the relative bed level decrease in the PC downstream of the side channel and the small relative bed level increase in the Waal.

Fully opening the weirs (B) in the Nederrijn-Lek (NR-Lek) leads to significant changes in the discharge partitioning at the Pannerdense Kop with respect to the reference case for low flows. For low flows the Waal discharge fraction remains below the initial value from the reference simulation. Opening of the weirs also leads to a significant relative decrease in the IJssel discharge for low flows of 6.0% initially and 4.5% at the end of the simulation. The weirs initially don’t alter the discharge partitioning at the PK for high flows. Due to additional erosion on the PC and reduced erosion on the Waal the relative decrease in Waal discharge fraction is 1.1% at the end of the simulation. Fully opening the weirs also leads to a relative decrease in the IJssel discharge fraction of 4.3-6.0%.

Widening on the IJssel (C) causes an immediate relative decrease in the Waal discharge fraction of 2.4%. Due to high aggradation rates along the widened section in the IJssel the effectivity of the widening reduces to 1.4%. Widening is less effective for high flows since for high flows a smaller fraction of the flow is in the main channel. Therefore, for high flows the reduced effectivity is less evident. The reduced effectivity of the widening is counteracted by the relative bed level decrease of the PC and the small relative bed level increase of the Waal such that the relative decrease in Waal discharge fraction stays approximately constant throughout the simulation for high flows at a value of 0.7%. Widening on the IJssel also leads to a relative decrease in the NR-Lek discharge fraction of 0.7-0.9% for high flows.

Directly steering the sediment partitioning (D) does not alter the water level initially and therefore initially the discharge partitioning is not affected. Throughout the simulation the slope of the Waal adjusts to the increased sediment supply and the slope of the PC adjusts to the decreased sediment supply. The effect on the bed level in the PC is larger since the difference in sediment supply relative to the original supply is also larger for the PC than for the Waal. At the end of the simulation the PC has additionally eroded 78 cm. As a result of the reduction in sediment supply throughout the simulation, the relative decrease in Waal discharge fraction reaches a maximum throughout the simulation after approximately 35 years for both high and low flows. For both flows the final relative decrease in Waal discharge fraction is 1.8%.

Dredging and dumping (E) also does not lead to changes in the water level and the discharge partitioning initially. Due to the repeated dredging and dumping the Boven-Waal and Midden-Waal show a relative bed level increase throughout the simulation and the PC shows a relative bed level decrease throughout the simulation. The final reach-averaged bed level decrease of the PC is 80 cm which is approximately twice as large as the relative increase on the Boven-Waal. The additional erosion on the PC only affects the upstream parts of the NR-Lek and the IJssel where a relative bed level decrease is observed. The bed level developments of the Waal and PC lead to a relative decrease in Waal discharge fraction which becomes larger throughout the simulation and eventually reaches 2.4% for low flows and 2.2% for high flows.

9.2 Recommendations

The goals of the IRM programme are to at least fixate the current bed levels of the Dutch Rhine branches and to prevent further skewing of the discharge distribution. It is concluded that none of the interventions studied is capable of solving both problems at once. Multiple river interventions will have to be combined to be able to reach the ambitions of IRM. However, there are still knowledge gaps related to the combined effects of river interventions. Therefore it is recommended to do research into the combined effects of river interventions on the bed level development of the Dutch Rhine branches and the discharge partitioning at the Pannerdense Kop and the IJsselkop.

As a result of climate change summers are getting dryer and winters are getting wetter. Also the sea level rises. This influences the bed level development of the Dutch Rhine branches and consequently the discharge partitioning. As a result of climate change also the sediment influx at the upstream boundary may change. The effects of climate change can be implemented in the model through the boundary conditions. Ylla Arbós et al. (2023) studied the effect of climate change on engineered rivers. It is recommended to take their approach as a starting point.

Lastly, the model results are based on a 1D model which is a simplification of reality. To get a more realistic view on the effects of the interventions on the bed level development of the Dutch Rhine branches and the discharge division over the branches it is recommended to model the interventions in a 2D model when a design phase is started.

References

Arkesteijn, L., Blom, A., Czapiga, M. J., Chavarrías, V., & Labeur, R. J. (2019). The quasi-equilibrium longitudinal profile in backwater reaches of the engineered alluvial river: A space-marching method. *Journal of Geophysical Research: Earth Surface, 124*(11), pp. 2542-2560. doi:10.1029/2019jf005195

Ashida, K., & Michiue, M. (1972). Study on hydraulic resistance and bed-load transport rate in alluvial streams. *Proc. Jpn. Soc. Civ. Eng., 206*, pp. 59-69. doi:10.2208/jscej1969.1972.206_59

Asselman, N., Mens, M., Maarse, M., Maas, B., de Grave, P., & Van der Deijl, E. (2022). *Effectbepaling nulalternatief IRM.* Deltares, Netherlands.

Barneveld, H., Reneerkens, M., van Vuren, S., Blom, A., & Paarlberg, A. (2022). Hoe stoppen we bodemerosie op de Rijn? *Bodem*, pp. 28-30.

Barneveld, H., van Hove, A., Paarlberg, A., Daggenvoorde, R., Spruyt, A., Fujisaki, A., . . . Schielen, R. (2019). *Ruimte voor levende rivieren; Effect grootschalige rivierverruiming op bodemerosie Waal.* . Rapport PR3633.20 (HKV) & 11202191-003 (Deltares), Lelystad: HKV Lijn in Water, Deltares, Wereld Natuur Fonds en Rijkswaterstaat.

Becker, A. (2021). *Slim suppleren Boven-Waal.* Delft: Deltares, Netherlands.

Berkhof, A., Kabout, J., Loeve, R., van de Paverd, M., & Verhoeven, D. (2018). *MIRT Onderzoek Duurzame Bodemligging Rijntakken; Eindrapportage, "De Rivierbodem is de basis van alle belangen". Eindrapport MIRT onderzoek inclusief kostenramingen, Bijlage 1.* Arcadis, IenW and Rijkswaterstaat Oost-Nederland.

Blom, A. (2021). *Lecture materials of the coarse 'River Dynamics II'.* Delft: TU Delft.

Blom, A., Arkesteijn, L., Chavarrias Borras, V., & Viparelli, E. (2017). The equilibrium alluvial river under variable flow and its channel-forming discharge. *Journal of Geophysical research: Earth Surface, 122*(10), 1924-1948. doi:https://doi.org/10.1002/2017JF004213

Blom, A., Chavarrias Borras, V., Ferguson, R. I., & Viparelli, E. (2017). Advance, Retreat, and Halt of Abrupt Gravel-Sand Transitions in Alluvial Rivers. *Geophysical Research Letters, 44*(19), 9751-9760. doi:10.1002/2017GL074231

Blom, A., Viparelli, E., & Chavarrías, V. (2016). The graded alluvial river: Profile concavityand downstream fining. *Geophysical Reasearch Letters, 43*, pp. 6285-6293. doi:10.1002/2016GL068898

Bolla Pittaluga, M. B., Coco, G., & Kleinhans, M. G. (2015). A unified framework for stability of channel bifurcations in gravel and sand fluvial systems. *Geophysical Research Letters, 42*(18), pp. 7521-7536. doi:10.1002/2015gl065175

Bolla Pittaluga, M., Repetto, R., & Tubino, M. (2003). Channel bifurcation in braided rivers: Equilibrium configurations and stability. *Water Resources Research, 39*(3). doi:10.1029/2001wr001112

Chavarrías, V., & Ottevanger, W. (2021). *Modelling morphodynamics in the presence of immobile sediment - Model testing and sensitivity analysis.* Tech. rep. Deltares, Rijkswaterstaat.

Chavarrías, V., Busnelli, M., & Sloff, K. (2020). *Morphological models for IRM.* Deltares.

Chowdhury, M. K., Blom, A., Ylla Arbós, C., Verbeek, M. C., Schropp, M. H., & Schielen, R. M. (2022). Bed elevation, bed surface grain size (D50), and water discharge- Waal, Pannerden Channel, Nederrijn, and IJssel, 1928-2020. *4TU.ResearchData*. doi:10.4121/19650873

Chowdhury, M. K., Blom, A., Ylla Arbós, C., Verbeek, M. C., Schropp, M. H., & Schielen, R. M. (2023). Bifurcation response to peak flow events in an engineered river. *Water Resources Research.*

Czapiga, M. J., Blom, A., & Viparelli, E. (2022, June). Sediment Nourishments to Mitigate ChannelBed Incision in Engineered Rivers. *Journal of Hydraulic Engineering, 148*(6). doi:10.1061/(ASCE)HY.1943-7900.0001977

De Lange, B. M. (2022). *Sediment Nourishments in the River Waal to Mitigate Bed Degradation.* University of Twente and Sweco.

De Ruijsscher, T. V. (2020). *Alligned with the flow - Morphodynamics in a river trained by longitudinal dams.* Wageningen, The Netherlands: Wageningen University. doi:10.18174/503236

De Vriend, H. J. (2015). The long-term response of rivers to engineering works and climate change. *Proceedings of the Institution of Civil Engineers - Civil Engineering, 168*(3), pp. 139-144. doi:10.1680/cien.14.00068

De Vries, M. (1975). A morphological time scale for rivers. *Proceedings of International Association for Hydraulic Research 16th Congress. 2*, pp. 17-23. Sao Paulo, Brazil: Delft Hydraul. Lab.

Engelund, F., & Hansen, E. (1967). *A monograph on sediment transport in alluvial streams.* Copenhagen: Teknisk Vorlag.

Frings, R. M., Berbee, B. M., Erkens, G., Kleinhans, M. G., & Gouw, M. J. (2009). Human-induced changes in bed shear stress and bed grain size in the River Waal (The Netherlands) during the past 900 years. *Earth Surface Processes and Landforms, 34*(4), pp. 503-514. doi:10.1002/esp.1746

Frings, R., Hillebrand, G., Gehres, N., Banhold, K., Schriever, S., & Hoffmann, T. (2019). From source to mouth: Basin-scale morphodynamics of the Rhine River. *Earth Sci. Rev., 196*. doi:10.1016/j.earscirev.2019.04.002

Gensen, M. R. (2021). *Discharge and water level uncertainty in bifurcating rivers.* Twente: University of Twente.

Gruijters, S., Maljers, D., & Veldkamp, J. (2005, January 28). 3D interpolation of grain size distributions in the upper 5 m of the channel bed of three lower Rhine distributaries. *Physics and Chemistry of the Earth, 30*, pp. 303-316.

Havinga, H. (2020). Towards sustainable river management of the Dutch Rhine. *Water, 12*(6), p. 1827. doi:10.3390/w12061827

Hirano, M. (1971). River bed degradation with armoring. *Proc. Jpn. Soc. Civ. Eng., 195*, pp. 55-65. doi:10.2208/jscej1969.1971.195_55

Huthoff, F., & Vieira da Silva, J. (2019). *Rivierkundige ondersteuning RWS-ON; Modelanalyse vaste laag Nijmegen.* Lelystad: HKV Lijn in Water.

Ikeda, S., Asce, M., Yamasaka, M., & Chiyoda. (1987). BED TOPOGRAPHY AND SORTING IN BENDS. *J. Hydraul. Eng., 113*(2), pp. 190-204.

IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Kleinhans, M. G., Ferguson, R. I., Lane, S. N., & Hardy, R. J. (2013). Splitting rivers at their seams: bifurcations and avulsion. *Earth Surface Processes and Landforms, 38*(1), pp. 47-61. doi:10.1002/esp.3268

Kleinhans, M. G., Jagers, H. R., Mosselman, E., & Sloff, C. J. (2008, August 30). Bifurcation dynamics and avulsion duration in meandering rivers by one-dimensional and three-dimensional models. *Water Resources Research, 44*. doi:10.1029/2007WR005912, 2008

Klijn, F., Leushuis, H., Treurniet, M., Van Heusden, W., & Van Vuren, S. (2022). *Systeembeschouwing Rijn en Maas ten behoeve van ontwerp en besluitvorming.* Programma Integraal Riviermanagement, Ministerie van Infrastructuur en Water, Den Haag.

KNMI. (2015). *KNMI '14 Climate Scenarios for the Netherlands.* Royal Netherlands Meteorological Institute, the Netherlands.

Kondolf, G. M. (1997). Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management, 21*, 533-551.

Mackin, J. H. (1948, May). Concept Of The Graded River. *Bulletin of the geological society of America, 59*, pp. 463-512.

Majoor, R. (1995). *BodemSchermen Een Nieuw Ontwerp Voor Rivierbochten.* Delft: TU Delft.

Meyer-Peter, E., & Müller, R. (1948). Formulas for bed-load transport. *Proc. 2nd IAHR World Congress*, (pp. 39-64). Stockholm, Sweden.

Ministerie van Infrastructuur en Waterstaat. (2023). *Ontwerp Programma IRM: Naar een toekomstbestendig rivierengebied.* Retrieved from https://www.bouwplaatsirm.nl/documenten

Ottevanger, W., Giri, Sanjay, & Sloff, K. (2015). *Sustainable Fairway Rhinedelta II: Effects of yearly bed stabilisation nourishments, Delta Program measures and training walls.* Tech. rep. Deltares.

Paarlberg, A., & Van Lente, J. (2021). *Testen 1D morfologisch model Rijntakken.* HKV.

Paarlberg, A., Omer, A., & Yossef, M. (2021). *Eindevaluatie pilot Langsdammen in de Waal.* Delft: HKV Lijn in Water & Deltares.

Parker, G., & Andrews, E. D. (1985, September). Sorting of Bed Load Sediment by Flow in Meander Bend. *Water Resources Research, 21*(9), pp. 1361-1373.

Parker, G., Hassan, M., & Wilcock, P. (2007). Adjustment of the bed surface size distribution of gravel-bed rivers in response to cycled hydrographs. *Gravel-Bed Rivers VI: From Process Understanding to River Restoration, 11*, pp. 241-285. doi:10.1016/S0928-2025(07)11127-5

Programma Integraal Riviermanagement. (2021). *Informatiebladen Rijn Integraal Riviermanagement.* Tech. rep. Rijkswaterstaat.

Quick, I., König, F., Baulig, Y., Schriever, S., & Vollmer, S. (2020). Evaluation of depth erosion as a major issue along regulated rivers using the classification tool Valmorph for the case study of the Lower Rhine. *International Journal of River Basin Management, 18*(2), pp. 191-206. doi:10.1080/15715124.2019.1672699

Rahman, A., Rahman, M., Shampa, S., Haque, A., Dustegir, M., Nishat, N. J., . . . Hossain, M. (2020). Performance evaluation of bandal-like structures for sediment management in braided Jamuna river. *IAHR-APD Congress.* Sapporo, Japan.

Rozier, W., & Asselman, M. (2019). *Hydraulische systeemwerking in het rivierengebied.* BOA Rivieren; Ministerie van Infrastructuur en Waterstaat.

Schielen, R. M., & Blom, A. (2018). A reduced complexity model of a gravel-sand river bifurcation: Equilibrium states and their stability. *Advances in Water Resources, 121*, pp. 9-21. doi:10.1016/j.advwatres.2018.07.010

Sloff, C. J. (2006). *Uitbreiding SOBEK-RT model naar niet-uniform sediment.* Delft, Netherlands: Delft Hydraulics Laboratory.

Sloff, K., & Mosselman, E. (2012, July 11). Bifurcation modelling in a meandering gravel–sand bed river. *Earth Surface Processes and Landforms, 37*, pp. 1556-1566. doi: 10.1002/esp.3305

Sloff, K., Paarlberg, A., van Denderen, P., Barneveld, H., & Mosselman, E. (2023). *Onderbouwing beleidskeuze bodemligging IRM.* Delft: HKV Lijn in Water & Deltares.

Sperna Weiland, F., Hegnauer, M., Bouaziz, L., & Beersma, J. (2015). *Implications of the KNMI'14 climate scenarios for the discharge of the Rhine and Meuse.* Delft, the Netherlands: Deltares.

Teraguchi, H., Nakagawa, H., Kawaike, K., Baba, Y., & Zhang, H. (2011). ALTERNATIVE METHOD FOR RIVER TRAINING WORKS: BANDAL-LIKE STRUCTURES. *Jounal of Japan Society of Civil Engineers, 67*(4), pp. 151-156.

Twijnstra, J. J. (2020). *Water balance in the Dutch river Rhine and uncertainty of rating curves.* Twente: University of Twente.

Van Til, K. (1979). *De Rijntakken van de bovenrivieren sedert 1600.* Arnhem: Ministerie van Verkeer en Waterstaat, Rijkswaterstaat, Directie Bovenrivieren.

van Vuren, S., Paarlberg, A., & Havinga, H. (2015). The aftermath of ”Room for the River” and restoration works: Coping with excessive maintenance dredging. *Journal of HydroEnvironment Research, 9*(2), pp. 172-186. doi:10.1016/j.jher.2015.02.001

Visser, P. J. (2000). *Bodemontwikkeling Rijnsysteem: een verkenning van omvang, oorzaken, toekomstige ontwikkelingen en mogelijke maatregelen.* TU Delft, Department Hydraulic Engineering. Retrieved from tinyurl.com/2tss34rb

Wang, B., & Jun Xu, Y. (2016, December). Long-term geomorphic response to flow regulation in a 10-km reach downstream of the Mississippi–Atchafalaya River diversion. *Journal of Hydrology: Regional Studies, 8*, pp. 10-25.

Wang, Z. B., De Vries, M., Fokkink, R. J., & & Langerak, A. (1995). Stability of river bifurcations in 1D morphodynamic models. *Journal of Hydraulic Research, 33*(6), pp. 739-750. doi:10.1080/00221689509498549

Ylla Arbos, C., Blom, A., Acevedo Goldaracena, F., van Vuren, S., & Schielen, R. (2020). Bed level change in the Upper Rhine Delta and Niederrhein. *River Flow 2020: Proceedings of the 10th Conference onFluvial Hydraulics* (pp. 680-684). CRC Press / Balkema - Taylor & Francis Group.

Ylla Arbós, C., Blom, A., Sloff, C. J., & Schielen, R. M. (2023). Centennial Channel Response to Climate Change and Human Intervention in an Engineered River. *Geophysical Research Letters*.

Ylla Arbós, C., Blom, A., Viparelli, E., Reneerkens, M., Frings, R. M., & Schielen, R. M. (2021). River Response to Anthropogenic Modification: Channel Steepening and Gravel Front Fading in an Incising River. *Geophysical Research Letters, 48*(4), 1-10. doi:10.1029/2020GL091338

A River response

A.1 Initial response

First of all the change to the specific discharge, q, as a result of the measures is considered.

$$q = \frac{Q}{B}\left(\frac{m^2}{s}\right) \tag{A.1}$$

Where, Q = discharge (m^3/s)
B = width (m)

The change in specific discharge is related to the change in equilibrium depth, d_e, through equation A.2. The flow depth is determined by drawing backwater curves starting from the downstream flow depth.

$$d_e = \left(\frac{c_f}{i_b}\frac{q^2}{g}\right)^{\frac{1}{3}}\ (m) \tag{A.2}$$

Where, i_b = bed slope (-)
c_f = nondimensional friction coefficient (-)
g = gravitational constant (m/s^2)

The equilibrium flow velocity, u_e, is computed by dividing the specific discharge by the equilibrium flow depth. The flow velocity is computed by dividing the specific discharge by the flow depth.

$$u_e = \frac{q}{d_e} = \left(\frac{i_b}{c_f}qg\right)^{\frac{1}{3}}\left(\frac{m}{s}\right) \tag{A.3}$$

The sediment transport capacity, s, is obtained from the flow velocity. This is done through the Engelund-Hansen equation which is seen in equation 2.6.
The Exner equation relates the change of the bed level, z_b, in time to the change of the sediment transport capacity in space.

$$\frac{dz_b}{dt} = -\frac{1}{c_b}\frac{ds}{dx} \tag{A.5}$$

Where, c_b = sediment concentration in the bed

In order to derive the initial response of a river reach to a measure all these steps should be taken. An example is given for the initial response of a river reach to a widening measure on the Waal.

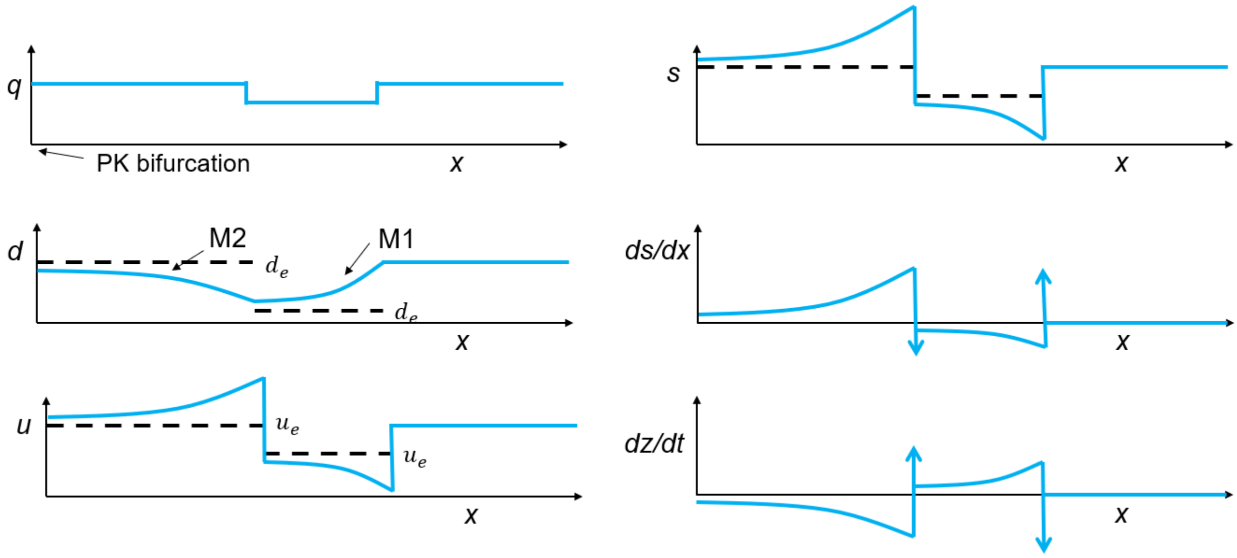

Figure A.1: Initial response to widening a part of the Waal river

A.2 Long term response

In a steady state all gradients with respect to time are 0. This leads to the following simplified conservation equations:

Conservation of sediment mass (Exner)

$$\frac{dS}{dx} = 0 \rightarrow S = Bmu^n = constant \rightarrow u = constant \tag{A.6}$$

Where, S = sediment transport capacity (m^3/s)

Conservation of water mass

$$\frac{dQ}{dx} = 0 \rightarrow Q = Bud = constant \rightarrow d = constant \tag{A.7}$$

Conservation of streamwise momentum

$$d = \left(\frac{c_f}{i_b}\frac{q^2}{g}\right)^{\frac{1}{3}} \tag{A.8}$$

The conservation equation of sediment mass is rewritten to an equation for the equilibrium flow velocity.

$$u_e = \left(\frac{S}{Bm}\right)^{\frac{1}{n}} \tag{A.9}$$

Combining equation A.9 with the conservation of water mass gives an equation for the equilibrium flow depth.

$$d_e = \frac{Q}{B^{1-\frac{1}{n}}}\left(\frac{m}{S}\right)^{\frac{1}{n}} \tag{A.10}$$

Rewriting equation A.8 gives an equation for the equilibrium bed slope.

$$i_{be} = \frac{c_f B^{1-\frac{3}{n}}}{gQ}\left(\frac{S}{m}\right)^{\frac{3}{n}} \tag{A.11}$$

These equations are valid for unisize sediment and a constant discharge. For variable flow the equilibrium equations which are valid for the quasi-normal flow segment change slightly (Blom et al., 2017a). The equilibrium equation for variable flow is seen in equations A.12-A.14.

$$u_e(t) = \left(\frac{Q(t)}{Q_{dom}}\right)^{\frac{1}{3}}\left(\frac{\bar{S}}{Bm}\right)^{\frac{1}{n}} \tag{A.12}$$

$$d_e(t) = \frac{Q(t)^{\frac{2}{3}} Q_{dom}^{\frac{1}{3}}}{B^{1-\frac{1}{n}}}\left(\frac{m}{\bar{S}}\right)^{\frac{1}{n}} \tag{A.13}$$

$$i_{be} = \frac{c_f B^{1-\frac{3}{n}}}{gQ_{dom}}\left(\frac{\bar{S}}{m}\right)^{\frac{3}{n}} \tag{A.14}$$

Where,

$$Q_{dom} = \left[\alpha Q_{base}^{\frac{n}{3}} + (1-\alpha) Q_{peak}^{\frac{n}{3}}\right]^{\frac{3}{n}} = \left[\int_0^{\infty} Q^{\frac{n}{3}} p(Q)\,dQ\right]^{\frac{3}{n}} \tag{A.15}$$

Where, α = the fraction of the year that baseflow occurs

B Model definition and input

B.1 Model equations

1D Shallow water equations

The flow is computed by solving the continuity equation as can be seen in Equation B.1 and the momentum equation as can be seen in Equation B.2

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial d + z_b}{\partial x} = -g\frac{u|u|}{C^2 d} \tag{B.1}$$

Where, C = the Chézy coefficient ($m^{1/2}/s$)

$$\frac{\partial d}{\partial t} + \frac{\partial (ud)}{\partial x} = 0 \tag{B.2}$$

Sediment transport formulae

The equations for the sediment transport are taken from Chavarrías et al. (2020). The sediment transport for the sand fractions is modelled by using the Engelund-Hanssen transport relation, see Equation B.3 (Engelund and Hanssen, 1967).

$$q_{bk}^{*} = \alpha\frac{0.05}{C_f}(\theta_k)^{\frac{5}{2}} \tag{B.3}$$

Where, α = a calibration parameter (-)
q_{bk}^{*} = the non-dimensional sediment transport rate (-), as defined in Equation B.4

$$q_{bk}^{*} = \frac{q_{bk}}{F_{ak}\sqrt{g d_k^3}} \tag{B.4}$$

Where, q_{bk}= the sediment transport rate (m^2/s)
F_{ak} = the volume of sediment size fraction k in the active layer (-)
d_k = the characteristic grain size of fraction k

The non-dimensional friction coefficient is defined in Equation B.5.

$$C_f = \frac{n^2 g}{R_h^{\frac{1}{3}}} \tag{B.5}$$

Where n = the Manning friction coefficient ($s/m^{1/3}$)
R_h = the hydraulic radius (m)

The Shields stress on size fraction k is defined in Equation B.6.

$$\theta_k = \frac{\tau_b}{\rho g \Delta \mathrm{d_k}} \tag{B.6}$$

Where, τ_b = the bed shear stress (N/m^2), as defined in Equation B.7

$$\tau_b = \rho g R_h S_f \tag{B.7}$$

The sediment transport for the gravel fractions is modelled using the Meyer-Peter and Müller relation (1948), see equation B.8.

$$q_{bk}^* = \alpha A(\theta_k - \xi_k \theta_c)^B \tag{B.8}$$

Where, α = a calibration parameter (-)
A = is an equation specific parameter (-)
θ_c = 0.025 (-) is the critical bed shear stress
B = is an equation specific parameter (-)
ξ_k = the hiding-exposure relation from Ashida and Michiue (1972), see equation B.9.

$$\xi_k = \begin{cases} 0.843\left(\frac{d_k}{D_m}\right)^{-1} & for\ \frac{d_k}{D_m} \leq 0.4 \\ \left(\frac{\log_{10}(19)}{\log_{10}\left(19\frac{d_k}{D_m}\right)}\right)^2 & for\ \frac{d_k}{D_m} > 0.4 \end{cases} \tag{B.9}$$

Where, D_m = the arithmetic mean grain size (m)
In table B.1 the calibration parameters for both sediment size fractions for the different branches can be seen.

Branch	α sand fractions (-)	α gravel fractions (-)
Rhein – Boven-Rijn	0.47	0.60
Waal	0.18	0.32
Pannerden Canal	0.22	0.12
Nederrijn – Lek	0.10	0.10
IJssel	0.10	0.10

Table B.1: Calibration parameters of the sediment transport relations for the Rhine branches.

Nodal point relation

In the 1D Rijntakken model the nodal point relation from Sloff (2006) is used. The nodal point relation is the same for both sediment size classes, see equation B.10.

$$\frac{Q_{sk1}}{Q_{sk2}} = \beta_k \frac{Q_1}{Q_2} \tag{B.10}$$

Where, Q_{skj} = the sediment transport rate of size fraction k on the outgoing branch j (m^3/s)
β_k = a calibration parameter (-)

In table B.2 the calibration parameters for the bifurcations in the model domain for both sediment size fractions can be seen.

Bifurcation	β sand fractions (-)	β gravel fractions (-)
Pannerdense Kop	1.79	1.79
IJsselkop	1.35	0.99

Table B.2: Calibration parameters of the nodal point relation for the bifurcations in the model domain.

B.2 Boundary conditions

Upstream discharge time series

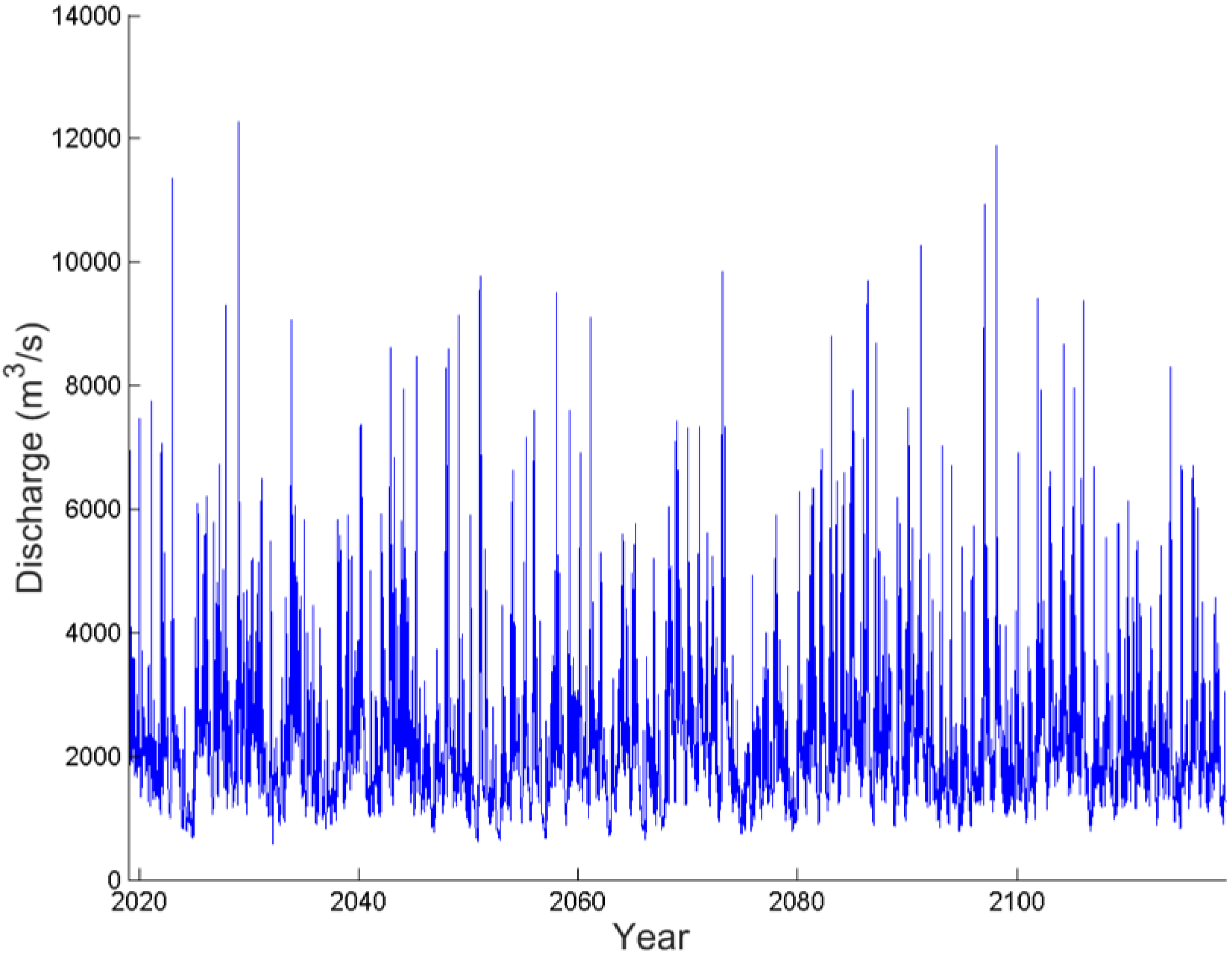

Figure B.1: Discharge time series from 1916 until 2016 for Lobith.

Downstream Q-h relations

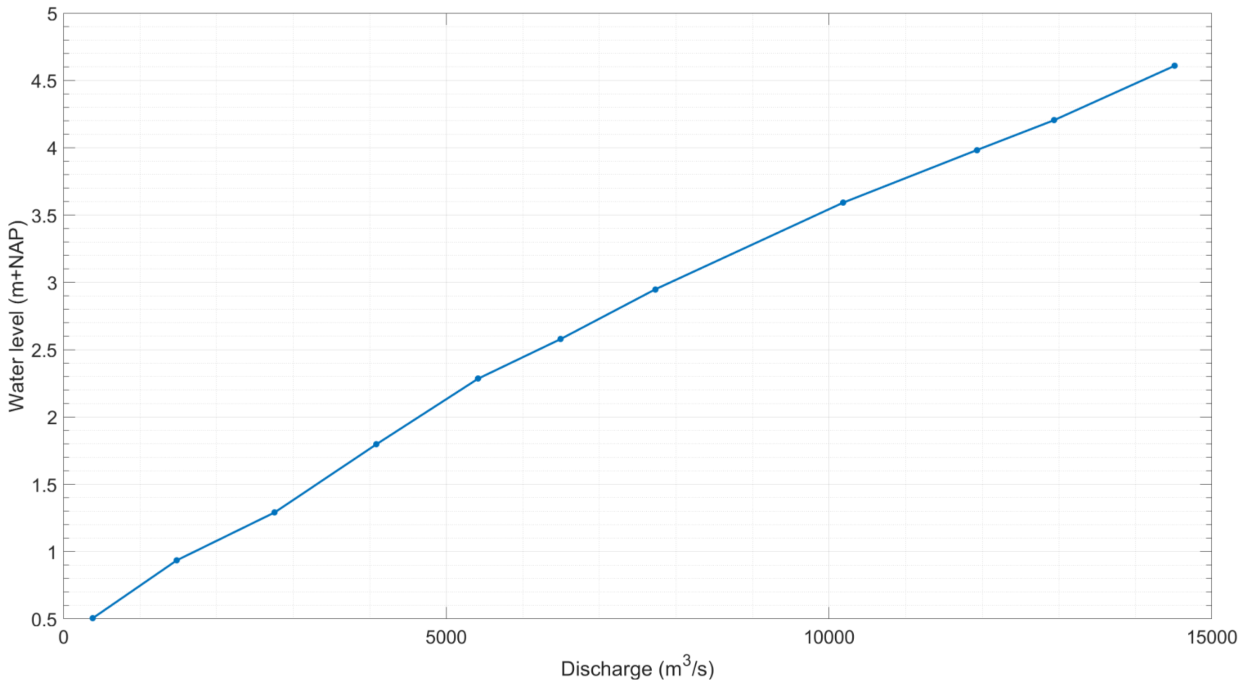

Figure B.2: Q-h relation for the downstream boundary at Hardinxveld. Adapted from de Lange (2022).

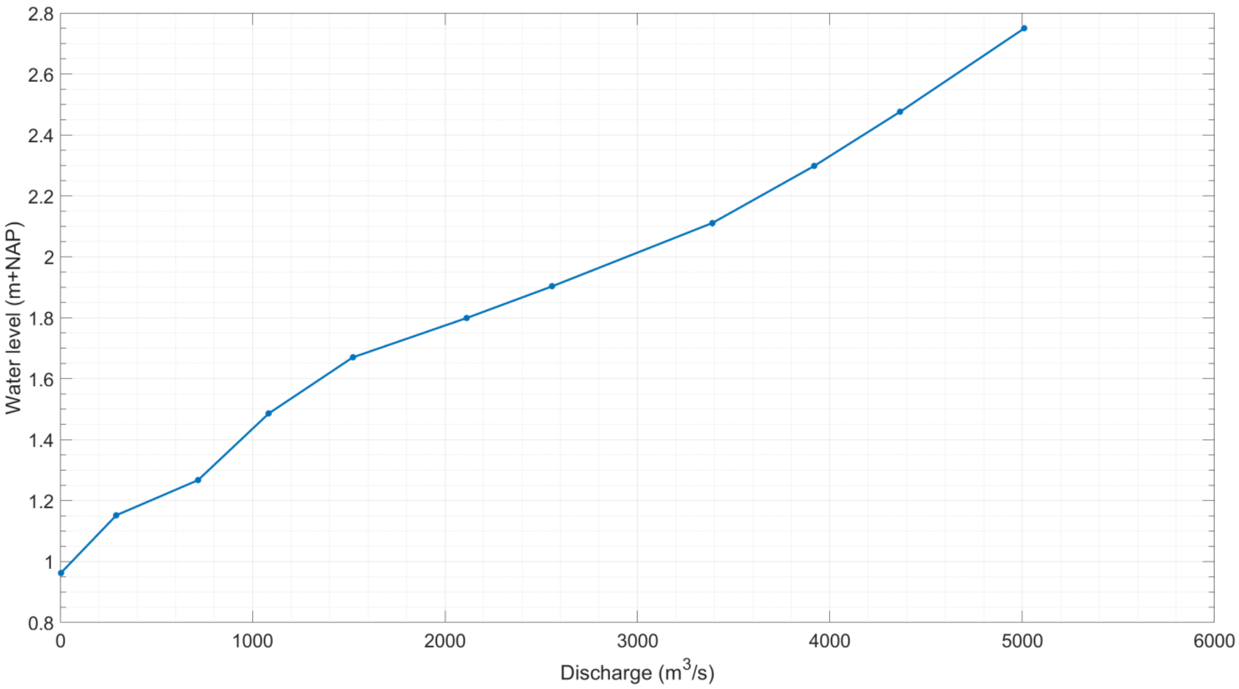

Figure B.3: Q-h relation for the downstream boundary at Krimpen. Adapted from de Lange (2022).

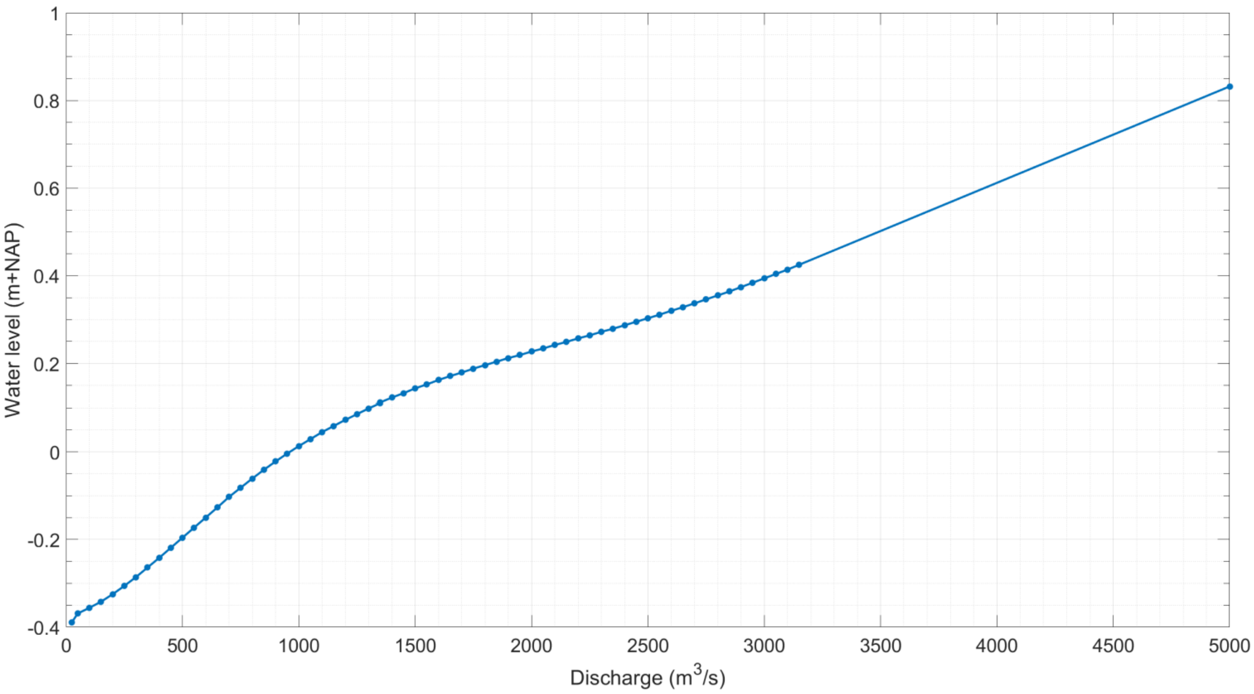

Figure B.4: Q-h relation for the downstream boundary at Kattendiep and Keteldiep. Adapted from De Lange (2022).

B.3 Locations of interventions

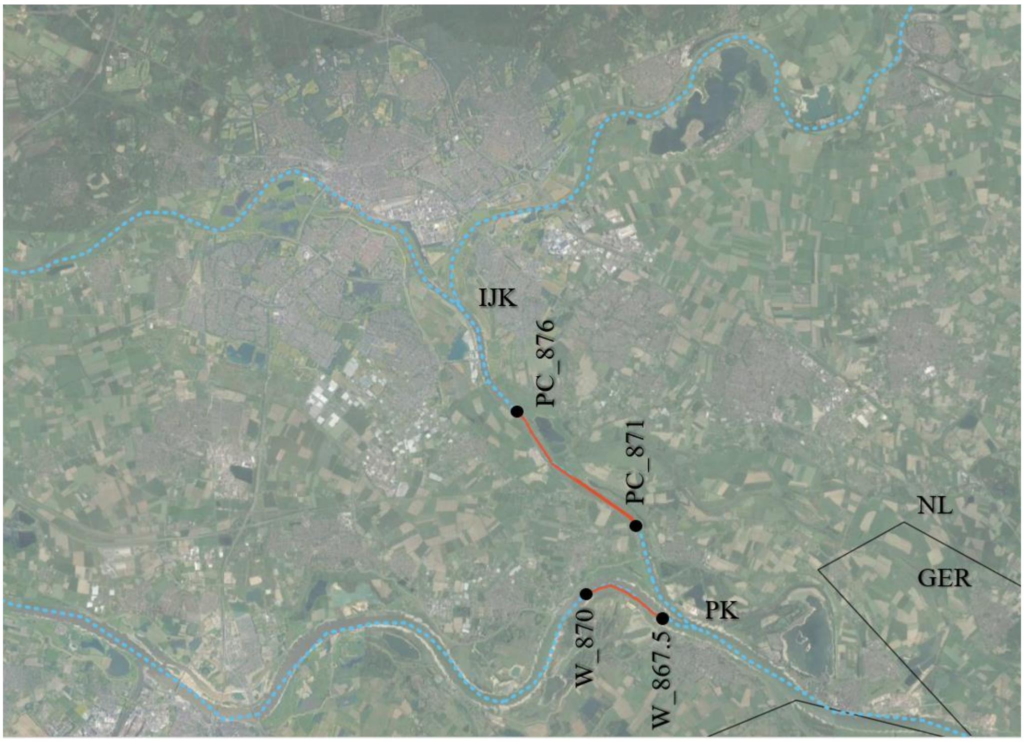

Figure B.5: Location for the dredging activities in the PC and the nourishments in the Waal. The labels indicate the river branch and the river kilometers according to the format 'riverbranch_rkm'.

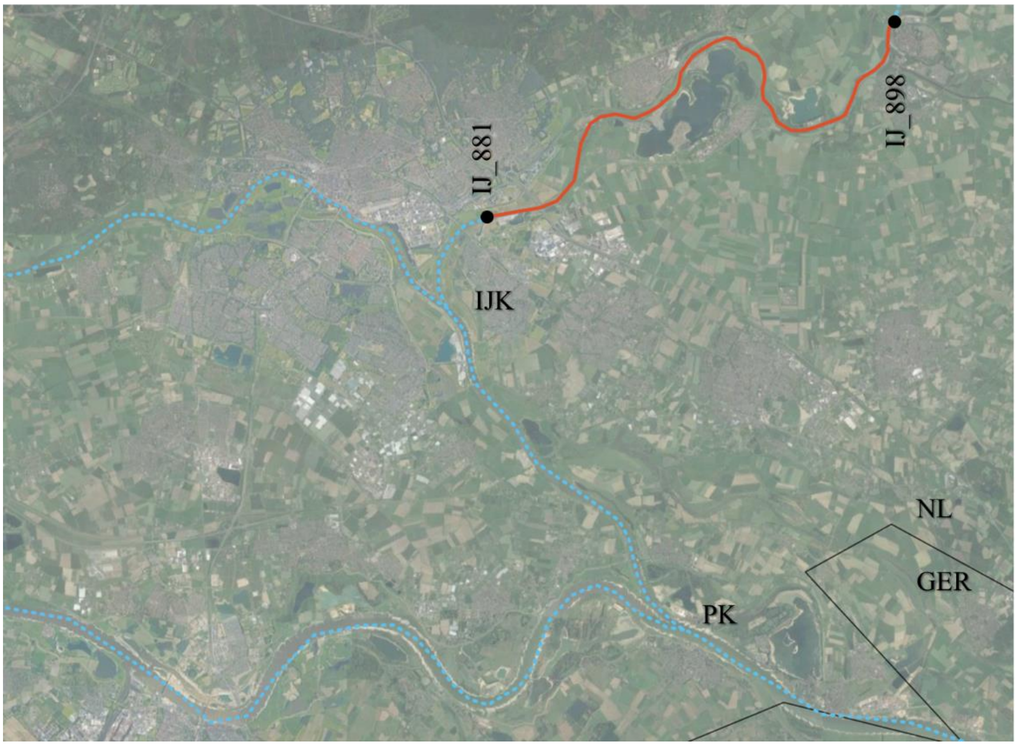

Figure B.6: Location for the widening on the IJssel. The labels indicate the river branch and the river kilometers according to the format 'riverbranch_rkm'.

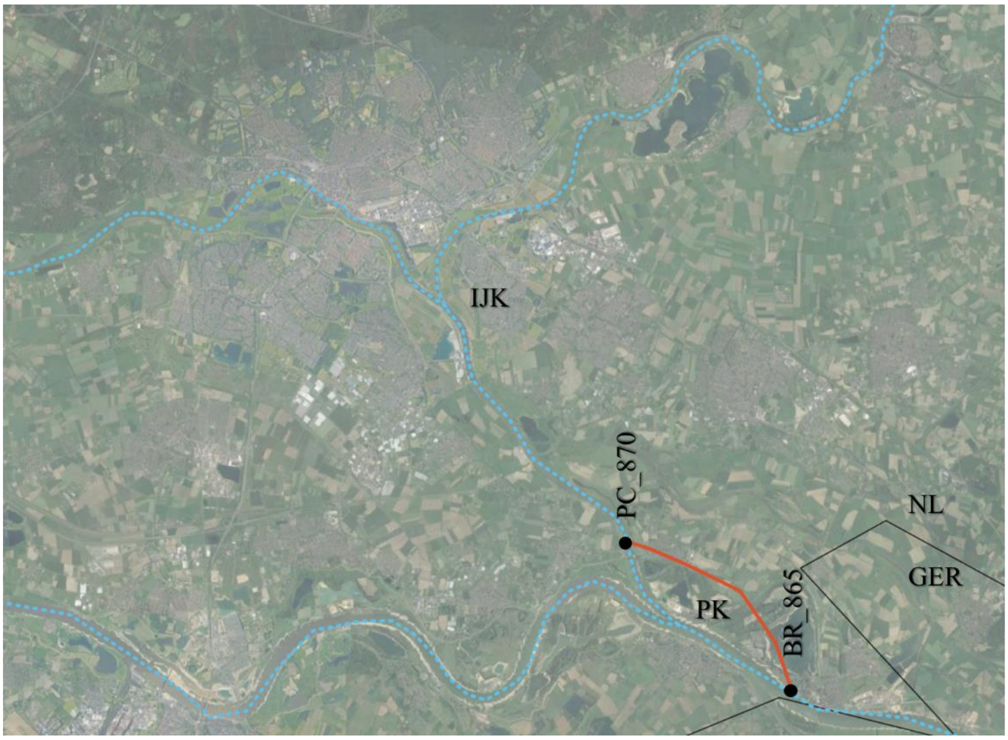

Figure B.7: Location for the side channel which runs from the Boven-Rijn to the PC. The labels indicate the river branch and the river kilometers according to the format 'riverbranch_rkm'.

C Additional plots calibration and verification

C.1 Predictive uncertainties discharge measurement instruments

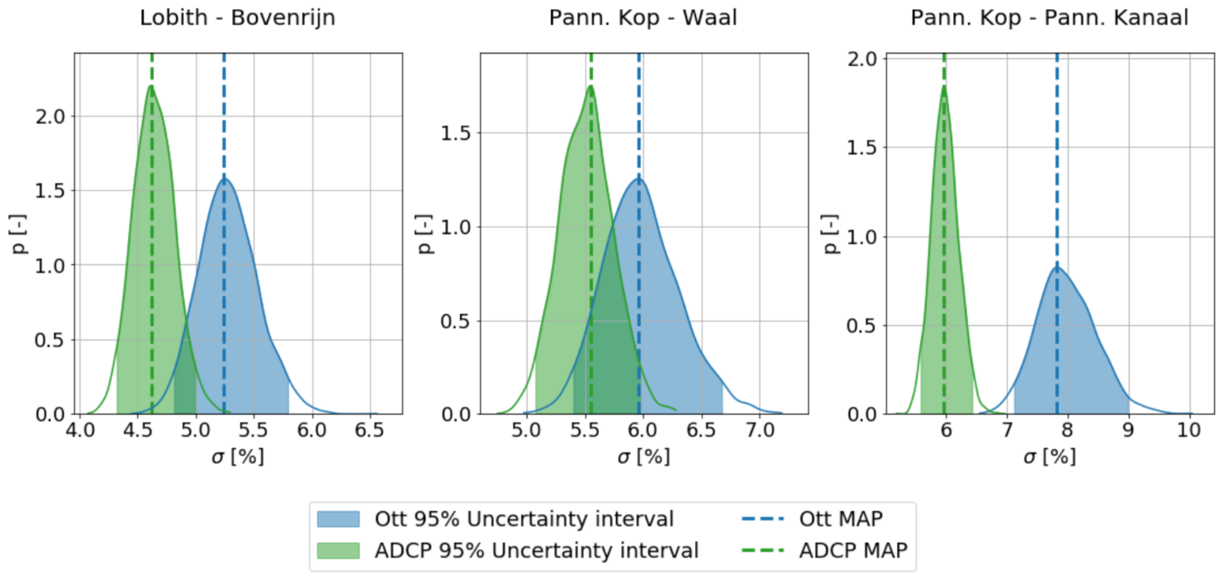

Figure C.0.1: Predictive uncertainty of Ott and ADCP measurements expressed in relative standard deviation (adapted from Twijnstra, 2020)

C.2 95% confidence interval measurement data

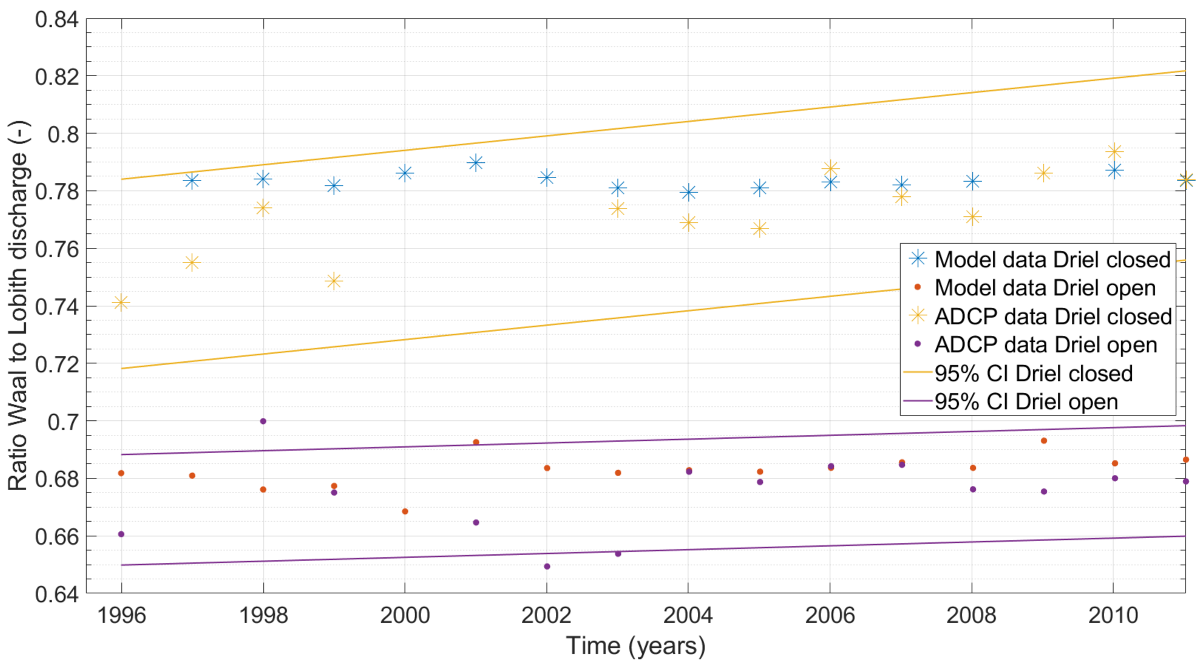

Figure C.2: Ratio of the Waal to Lobith discharge for the modeled data and the ADCP measurement data for the period of the calibration run. The 95% confidence intervals are indicated based on the assumption the measurement data is normally distributed.

C.3 Rating curve uncertainty

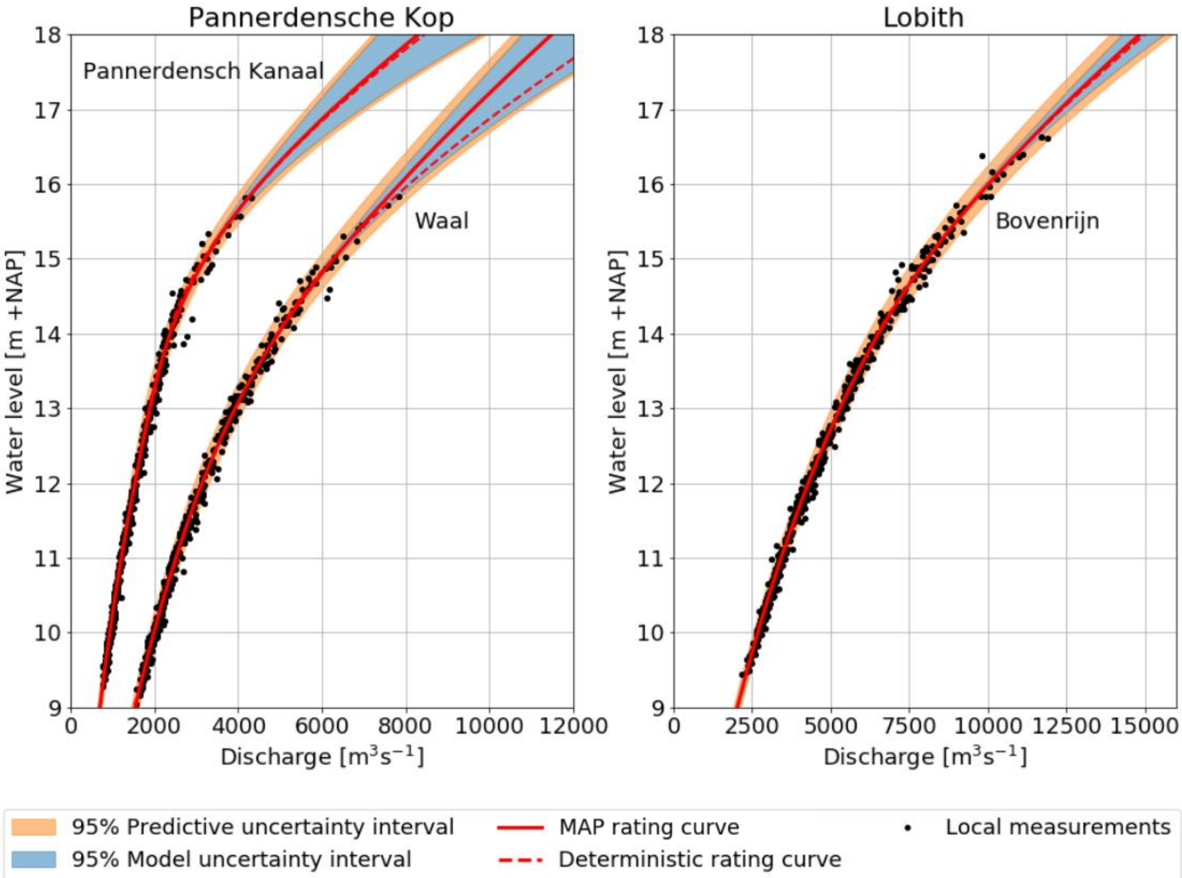

Figure C.3: Bayesian rating curve uncertainty. The total uncertainty consists of the predictive uncertainty and the model uncertainty. The MAP rating curve shows the modus curve of the total uncertainty (adapted from Twijnstra, 2020).

Table C.1: Total rating curve uncertainty bandwidths at water levels of 12 and 16 m + NAP (adapted from Twijnstra, 2020).

	Water level = 12 m +NAP	Water level = 16 m +NAP
Location	Total uncertainty bandwidth [m^3s^{-1}]	Total uncertainty bandwidth [m^3s^{-1}]
BR	430.1	1018.6
WL	364.5	1113.7
PK	199.8	727.9

C.4 Additional plots bed level development of the PC

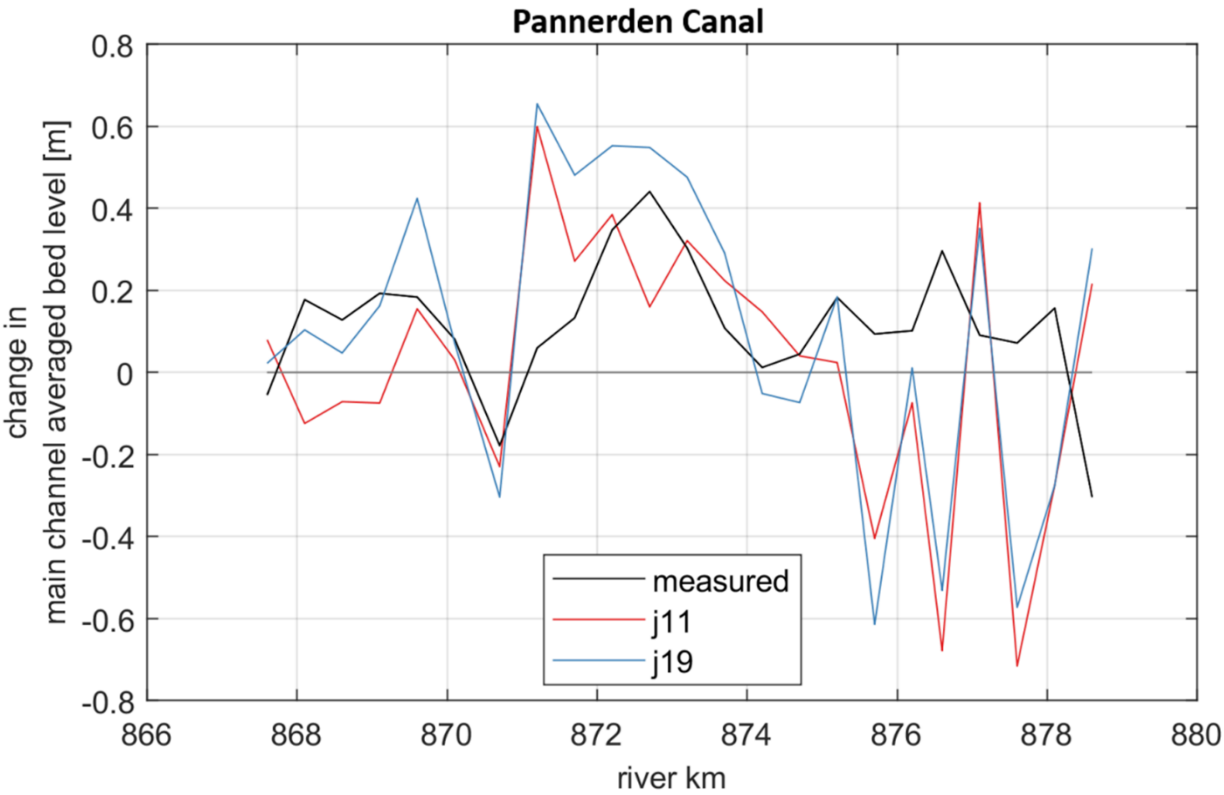

Figure C.4: Bed elevation changes for the period 2011-2019 along the Pannerden Canal. j11 and j19 respectively indicate the model data with the 2011 and 2019 initial bed levels. The 2019 bed level is subtracted from the 2011 bed level (adapted from Chavarrías et al., 2020).

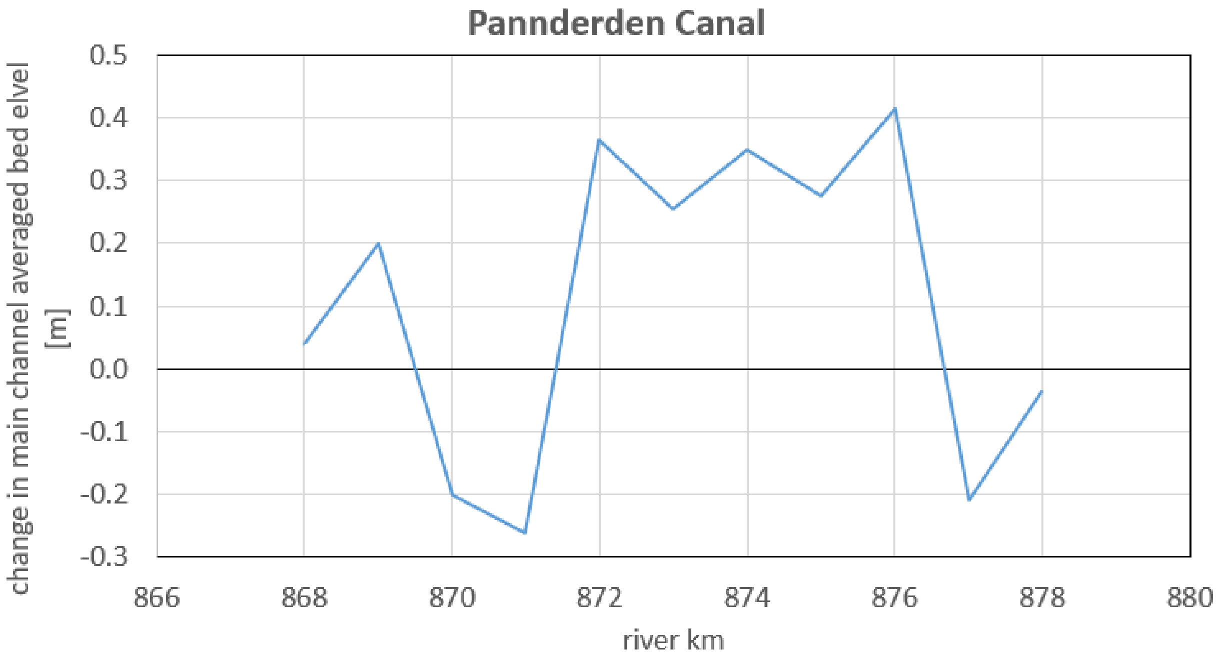

Figure C.5: Measured bed elevation change in the PC for the period of 1994-2010. The 2010 bed level is subtracted from the 1994 bed level.

D Theoretical analysis of initial and long-term effects of the interventions

D.1 Regulating structure

The idea for a regulating structure is based on the Old River Control Structure (ORCS) which controls the discharge which flows from the Mississippi to the Atchafalaya River. With the ORCS the discharge entering the Atchafalaya River can be controlled (Wang & Jun Xu, 2016). This concept can also be applied to the Pannerdense Kop bifurcation to completely control the discharge into the Waal or the Pannerden Canal. However, this would require the placement of structures inside the main channel which cause hindrance for navigation and can also damage the ecology of the river. So for this measure the question is not so much whether it could be effective but whether it is feasible. This is outside the scope of this research and therefore this measure will not be dealt with further on.

D.2 Sediment diversions

Three measures which are located in the Boven-Rijn are all aimed at diverting more sediment from the Boven-Rijn towards the Pannerden Canal. The Pannerdense Kop bifurcation is located in a river bend. The flow and bed load sediment dynamics in river bends will first be explained shortly to better understand the effects of the measures.

First of all an axial symmetry is assumed for the flow in the river bend which means that the river bend is assumed to be infinitely long and in equilibrium. With this assumption the momentum equation reduces to a balance between the transverse water level gradient and the centrifugal forces. This balance creates a secondary flow, which combined with the main flow leads to a helical flow. The helical flow leads to a transverse shear stress on the bed sediment in the direction of the inner bend. This force on the bed sediment is balanced by gravity as a result of the generated transverse slope. The cross section in the bend with the secondary flow cam be seen in Figure D.1. The magnitude of the gravity pull and the helical flow force is dependent on the sediment size. For smaller grains the helical flow force dominates while for larger grains the gravity pull dominates (Ikeda et al., 1987). Therefore coarser sediment can be found in the outer bend than in the inner bend. In the studied from Ikeda et al. (1987) and Parker & Andrews (1985) a more detailed analysis of bend flow and bend sorting can be found.

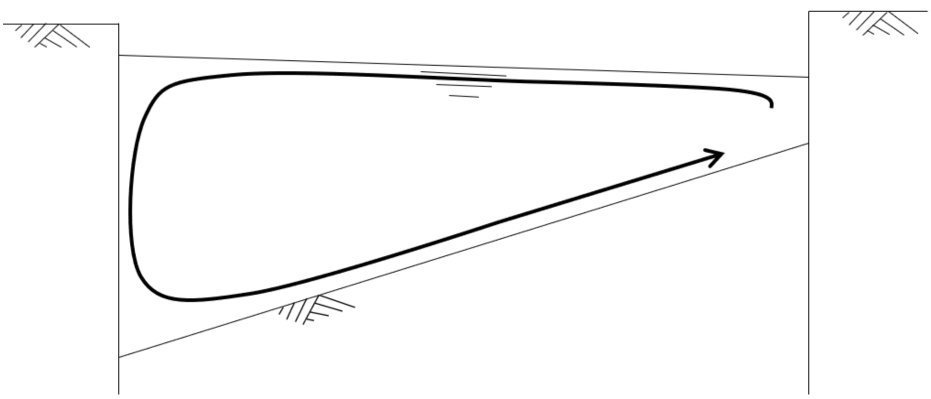

Figure D.1: Cross section of axi-symmetric river bend

Decrease of transverse slope

As explained above a balance exists between the lateral forces on the sediment particles which consist of the gravitational pull and the force due to the helical flow. By decreasing the transverse slope the gravitational pull on the particles is decreased which leads to the helical flow pushing the sediment particles towards the inner bend and thereby towards the Waal. A schematization of the process can be seen in Figure D.2.

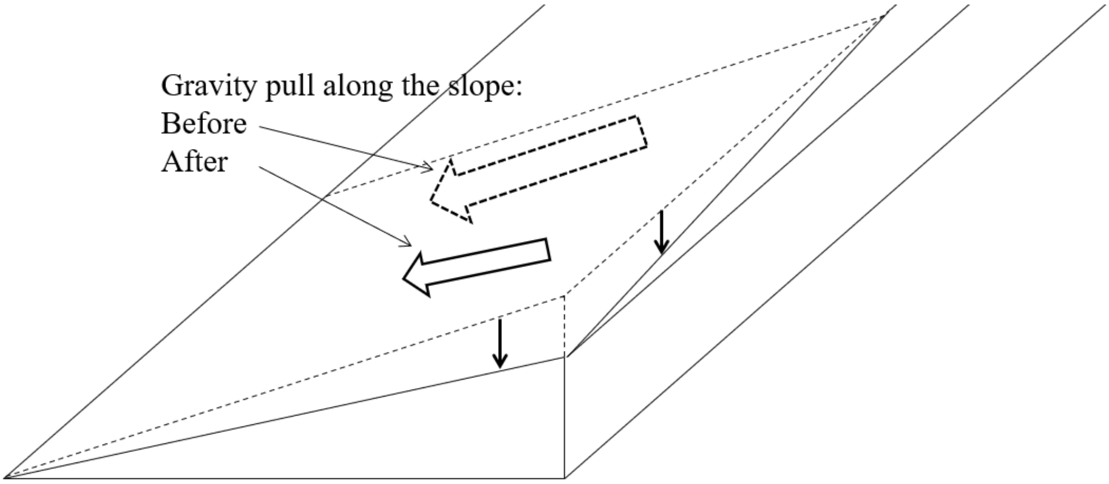

Figure D.2: A schematization of reducing the transverse slope in the Boven-Rijn just upstream of the Pannerdense Kop bifurcation

Sill

Constructing a sill in the Boven-Rijn in front of the entrance of the Pannerden Canal blocks the bed sediment load entering the Pannerden-Canal. The bed sediment load is forced around the sill which leads to more bed sediment load entering the Waal. A schematization of the process can be seen in Figure D.3.

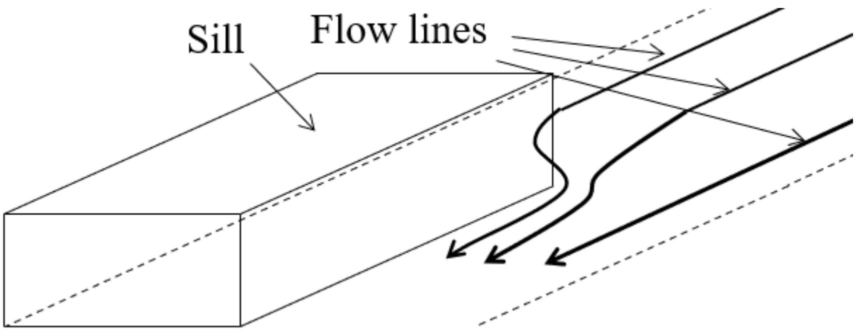

Figure D.3: A schematization of a sill in the Boven-Rijn just upstream of the entrance of the Pannerden Canal.

Bottom vanes

Bottom vanes have originally been designed to flatten the bed level in the river cross sections in bends. Bottom vanes in the outer bend placed under a small angle with respect to the main flow should generate a spiraling flow which counteracts the helical flow which is generated in the river bend (Majoor, 1995). The helical flow pushes the sediment towards the inner bend and therefore towards the Waal. So the original application of bottom vanes is unwanted here. The bottom vanes should strengthen the helical flow instead. Whether bottom vanes are capable of doing this should be studied in detail. This is outside the scope of this research and therefore this measure will not be dealt with further on.

A decrease of the transverse slope and the placement of a sill in front of the Pannerden Canal lead to more sediment being diverted towards the Waal and less sediment towards the PC. Initially no changes in the hydrodynamics occur in the bifurcates or in the Boven-Rijn as a result of the measures. Due to the increased sediment discharge into the Waal, here an aggradation wave will start and in the Pannerden Canal an erosion wave will start. The long term effect in both branches can be seen in Figures D.4 and D.5. It can be seen that the bed level in the Waal will rise and the bed level in the Pannerden Canal will drop.

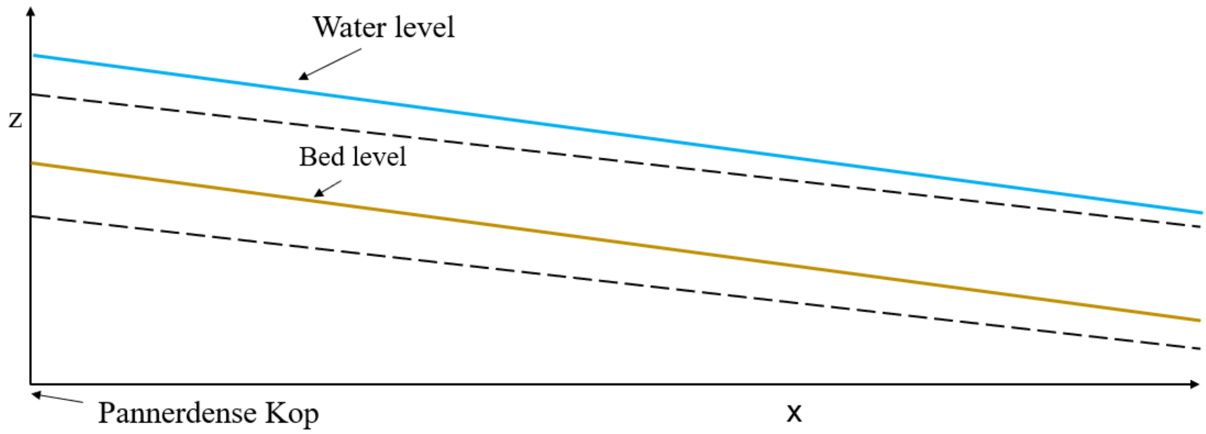

Figure D.4: Long-term effect of diverting more sediment towards the Waal

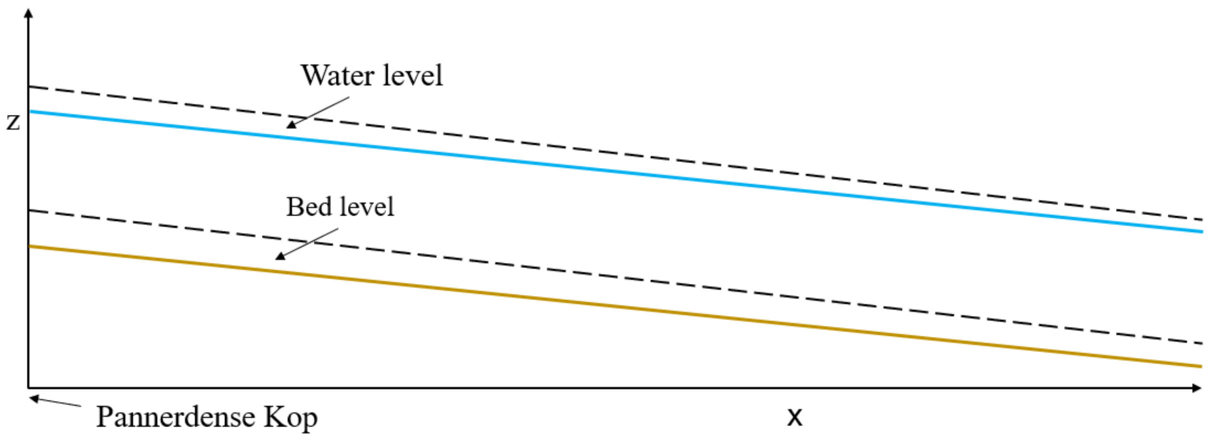

Figure D.5: Long-term effect of diverting less sediment towards the Pannerden Canal

D.3 Water offtake

Two measures which are located in the Boven-Rijn are aimed at directly diverting more water discharge from the Boven-Rijn towards the Pannerden Canal.

Flow screens

The concept originates from bandals used in Jamuna river to protect the river bank and divert the flow away from the river bank (Rahman et al., 2020; Teraguchi et al., 2011). The studies from Rahman et al. (2020) and Teraguchi et al. (2011) show that bandals succeed at diverting the flow away from the bank. The flow screens should be wide enough in order to divert the flow towards the Pannerden Canal instead of only away from the left bank of the Boven-Rijn. The flow screens will be a bandal-like structure where screens are placed on piles such that the top half of the structure becomes impermeable for water while the bottom half of the structure is permeable. This way the bed sediment load remains untouched such that only the water flow will be altered. A schematization of the flow screens can be seen in Figure D.6.

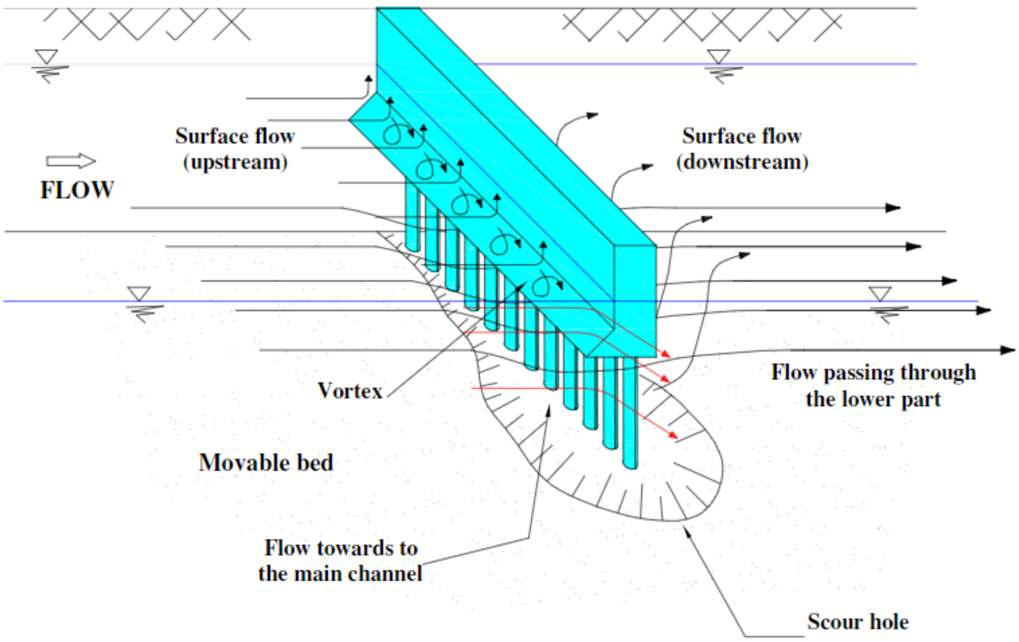

Figure D.6: A schematization of the flow around a bandal-like structure.

However, even though the flow screens can change the flow in the cross-section upstream from a bifurcation, nothing changes to the water levels or geometry of the bifurcation. This means that the discharge diversion of the flow screens will be counteracted by the bifurcation leading to no net discharge difference in the bifurcates.

Water offtake channel from the Boven-Rijn to the Pannerden Canal

By constructing a channel which runs from the Boven-Rijn to the Pannerden Canal extra water discharge can be transferred from the Boven-Rijn to the Pannerden Canal. A sill will be located at the entrance such that the bed sediment load which enters the offtake channel is limited. It is assumed to be zero here. Initial and long-term response to water offtake and addition in the Pannerden Canal and Boven-Rijn can be seen in Figures D.7, D.9, D.9 and D.10.

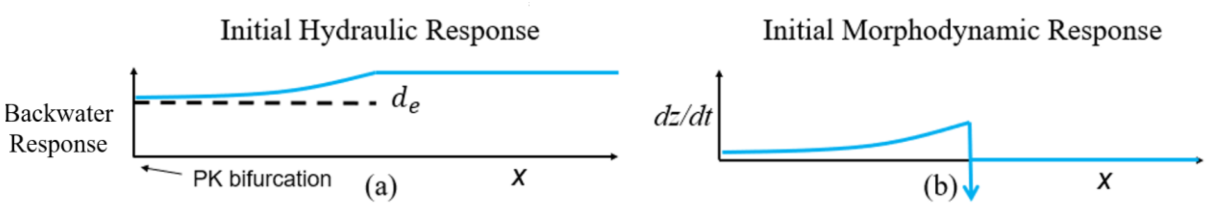

Figure D.7: Initial hydraulic (a) and morphodynamic (b) response. The Backwater response due to a water addition on the Pannerden Canal is shown (a and b).

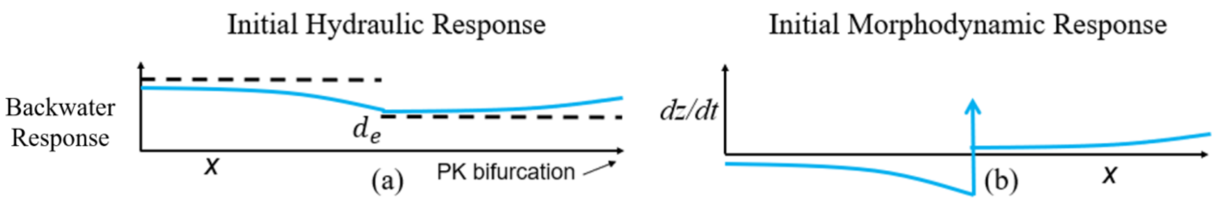

Figure D.8: Initial hydraulic (a) and morphodynamic (b) response. The Backwater response due to a water extraction on the Boven-Rijn is shown (a and b).

From the initial hydraulic response it can be seen that there is a M1 backwater curve in the Pannerden Canal. The water level is therefore above the equilibrium water depth upstream in the Pannerden Canal. This effect continues over the bifurcation which leads to a M1 backwater curve as well in the downstream part of the Boven-Rijn. From the initial morphodynamic response it can be seen that sedimentation occurs upstream from the water inlet in the Pannerden Canal and downstream from the water outlet in the Boven-Rijn. Upstream from the outlet in the Boven-Rijn erosion occurs. At the water outlet a sedimentation wave arises and at the inlet an erosion wave starts.

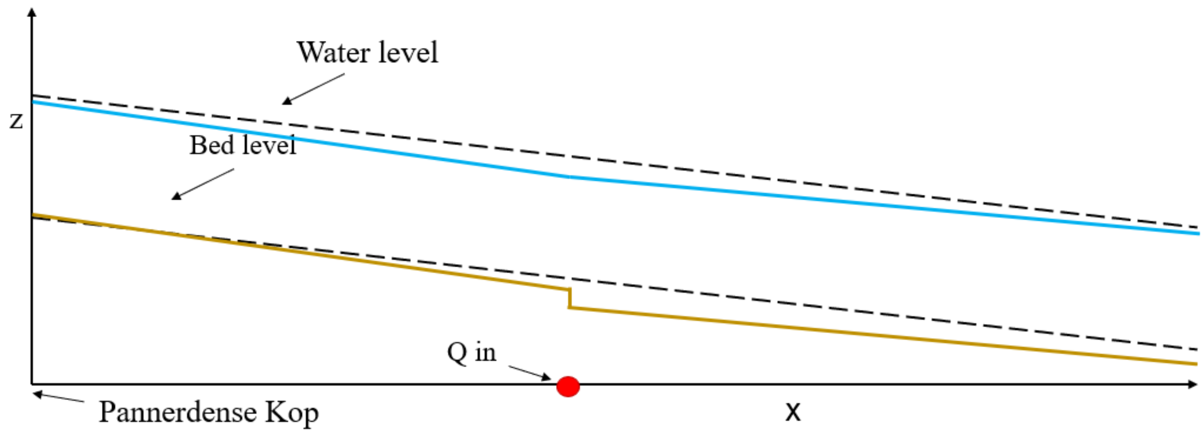

Figure D.9: Long-term effect of adding water to the Pannerden Canal

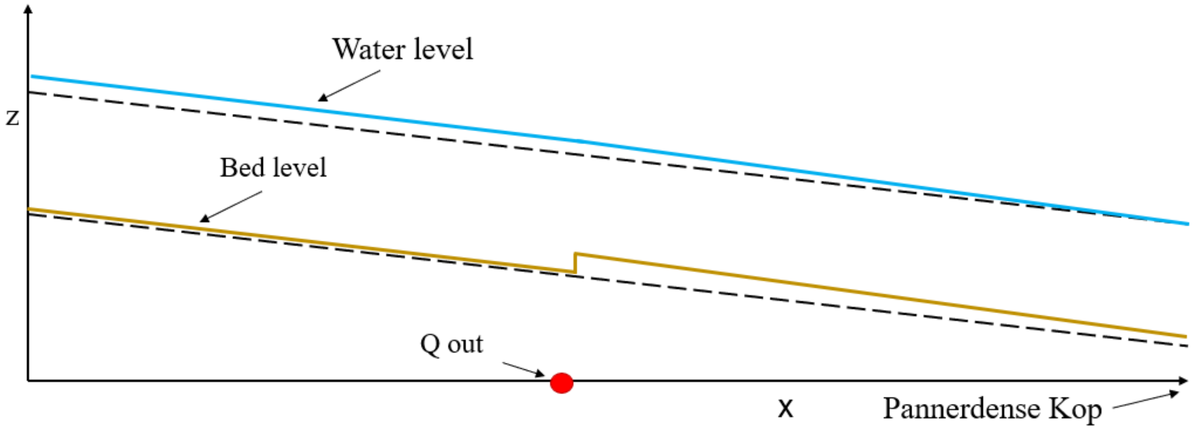

Figure D.10: Long-term effect of extracting water from the Boven-Rijn

Downstream of the discharge inlet in the Pannerden Canal the discharge is increased with respect to the reference case and upstream it is decreased. This leads to a larger slope and smaller depth downstream of the inlet and a smaller slope and larger depth upstream of the inlet. These effects counteract each other. Whether or not the bed level at the upstream end of the Pannerden Canal will rise or fall depends on the relative increase and decrease of the discharge with respect to the reference situation.
The slope increases and aggradation takes place downstream of the water outlet in the Boven-Rijn. Due to the increased slope of the widened section the bed level upstream of this section will also move up.

D.4 Nourishments

First of all the sediment nourishments will be studied. Czapiga et al. (2022) divided the initial effect of sediment nourishments in 4 different effects. (1) Due to the increased bottom height of the nourishment submerged weir flow occurs. (2) The increased bottom height leads to backwater effects. When the sediment composition of the nourished sediment differs from the original bed sediment composition, (3) the roughness of the bed changes and (4) the mobility of the sediment changes. In Figure D.11 the initial hydraulic effects in terms of flow depth and the initial morphological effects of the four different factors can be seen. For the latter two effects it is assumed that the nourishments are courser than the original bed surface texture.
The combined initial hydraulic effect of the measures is a water level increase at the upstream end of the Waal since the different contributions either leave the water level unchanged upstream of the nourishment or a M1 backwater curve occurs upstream of the nourishment. The combined morphological response of the Waal depends on the relative magnitude of the different effects.

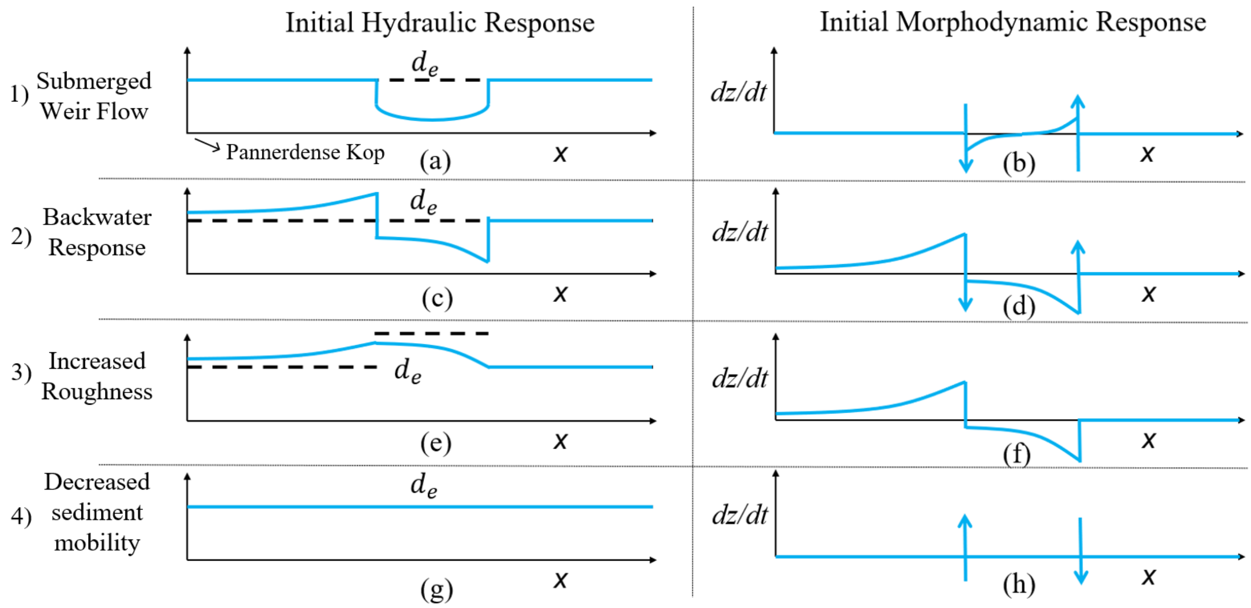

Figure D.11 : Initial hydraulic (a, c, e, g) and morphodynamic (b, d, f, h) response. Adapted from (Czapiga et al., 2022). The initial response is divided in 4 different effects: (1) Submerged weir flow due to increased bed elevation (a and b); (2) backwater response due to increased bed elevation (c and d); (3) increased hydraulic roughness due to an increased bed surface grain size (e and f); (4) decreased sediment mobility due to an increased bed surface grain size.

Sediment nourishments can be executed in different ways as the sediment grainsize distribution, the applied volume and the dumping location all influence the efficiency of the nourishment (Czapiga et al., 2022). Czapiga et al. (2022) studied the effects of different deposition methods, sediment compositions and nourishment volumes. They found that widespread erosion can be mitigated through sediment nourishments by either coarsening the sediment flux, increasing the sediment flux or both. Therefore coarse sediment should be dumped in sufficiently large volumes. Dumping all the coarse sediment in one location leads to propagating degradation pits downstream of the nourishment due to the reduced sediment mobility over the nourished section. By doing distributed nourishments this problem disappears. Since the aim is to mitigate erosion of the upstream part of the Waal in the long-term, the large volume, distributed coarse sediment nourishments seem to be a strategy for sediment nourishments in the upstream part of the Waal.

From the theory on the long-term effects of interventions it can also be seen that widespread erosion in the upstream part of the Waal can be mitigated through distributed coarse nourishments. It should be mentioned that the nourishments should be repeated since the effects of a single nourishment will disappear eventually. The sediment supply is increased and the sediment flux and therefore the bed sediment composition is coarsened. A coarser bed means the mobility of the finer sediment in the bed is decreased. Also more coarse sediment has to be entrained due to a coarser sediment flux and coarse sediment is less mobile than fine sediment. So the supply of sediment is increased while the capacity is decreased. This will lead to aggradation until a higher slope is reached to be able to transport the increased and coarsened sediment flux downstream, see Figure D.12. The nourishments are schematized as a single nourishment.

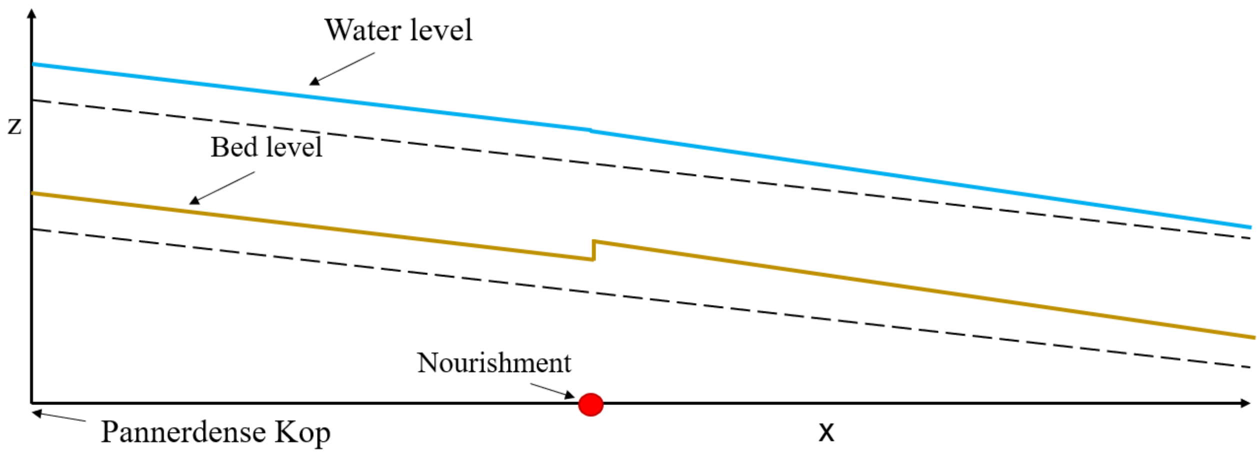

Figure D.12: Long-term effect of coarse sediment nourishments in the Waal

D.5 Dredging

Next dredging is studied. The dredging site is located upstream in the Pannerden Canal. Due to the decreased bottom height backwater effects arise. In
Figure D.13 the initial hydraulic effects in terms of flow depth and the initial morphological effects can be seen.

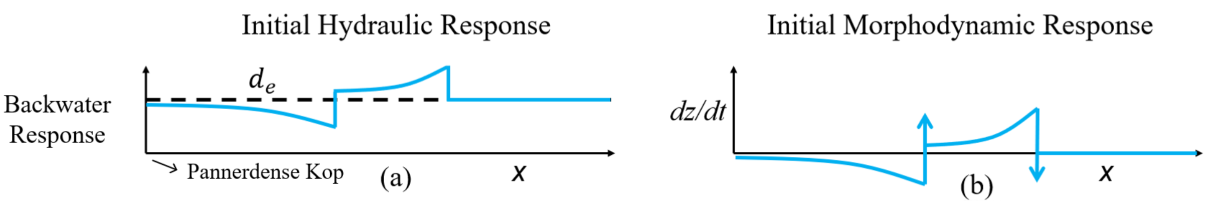

Figure D.13: Initial hydraulic (a, c, e) and morphodynamic (b, d, f) response. Adapted from (Czapiga et al., 2022). The initial response is divided in 3 different effects: (1) Backwater response due to increased bed elevation (a and b); (2) decreased hydraulic roughness due to an decreased bed surface grain size (c and d); (3) increased sediment mobility due to an decreased bed surface grain size (e and f).

By maintaining the dredged profile, sediment is continuously extracted from the dredging site. This way the sediment transport is decreased downstream. A lower sediment supply means that erosion will take place until the slope is low enough such that the sediment transport capacity matches the supply. This is illustrated in Figure D.14 where the dredging is schematized as a sediment extraction.

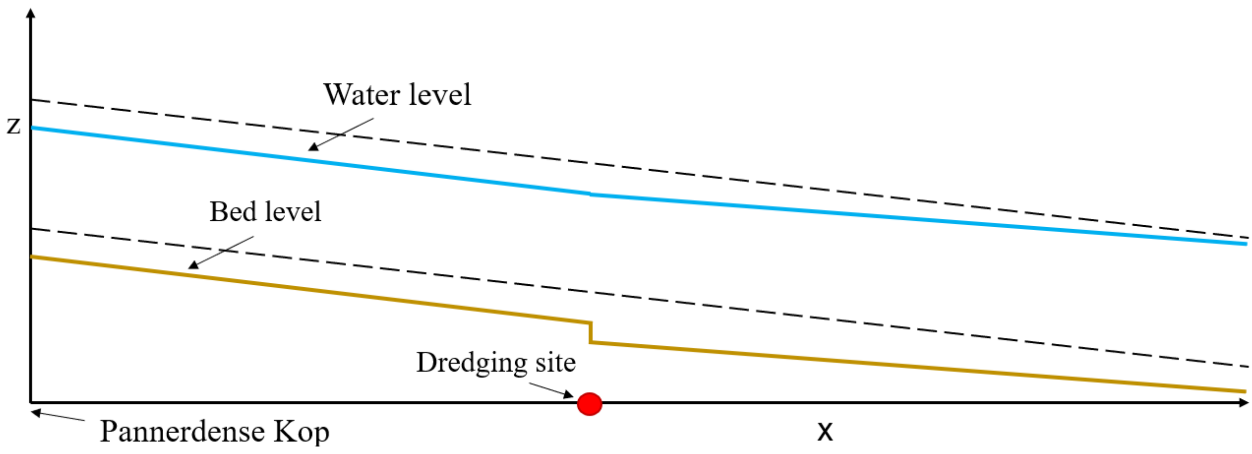

Figure D.14: Long-term effect dredging in the Pannerden Canal

D.6 Longitudinal walls

The last intervention which is assessed are longitudinal walls. Longitudinal walls separate the river into a main channel and a side channel. At the inlet there is a weir which controls the inflow of water and sediment into the side channel. Except for the in- and outflow openings, longitudinal walls can also contain multiple openings along its length through which water and sediment can be exchanged between the main channel and the side channel. For simplicity it is assumed that the additional openings are closed and that there will be no exchange of water and sediment between the main channel and the side channel during high flow conditions.

The longitudinal wall is regarded as a combination of different interventions which are active at different flows. Longitudinal walls reduce the width of the main channel with respect to the situation with groynes for low flows. Furthermore longitudinal walls divert water and sediment from the main channel into the side channel and reintroduce it at the end. They also reduce the friction which the flow experiences with respect to the situation with groynes

Reduction width

A reduction of the width leads to the exact opposite initial and long-term effects of widening, see Figure D.15 Initially the water level at the Pannerdense Kop will rise and degradation will take place in the smaller section and aggradation upstream of it. An erosion wave starts at the upstream end of the smaller section and an aggradation wave starts at its downstream end.

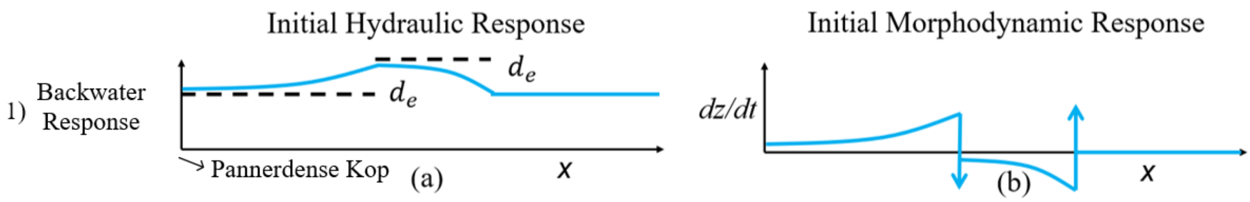

Figure D.15: Initial hydraulic (a) and morphodynamic (b) response. The Backwater response due to a narrowed section is shown (a and b).

On the long term the slope of the smaller section will go down as the sediment transport capacity over the smaller section increases due to a higher flow velocity while the supply remains the same. Due to the reduced slope the part of the Waal upstream of the intervention will experience degradation, see Figure D.16.

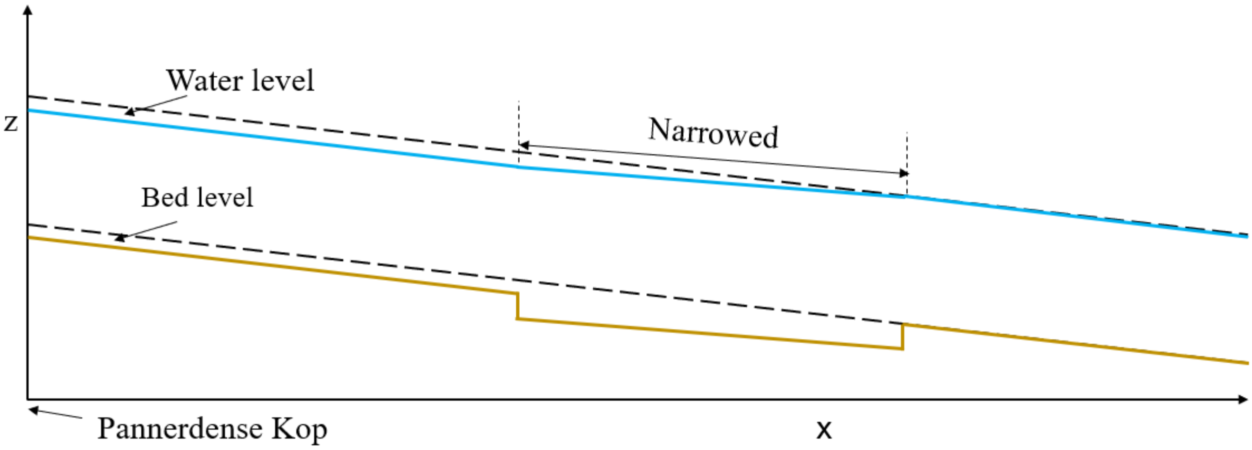

Figure D.16: Long-term effect of narrowing a river section

Water offtake

The initial and long-term morphodynamic response to water offtake and reintroduction after a certain length is equivalent to widening a part of the river. In Figure 4.1 and Figure 4.2 the initial and long-term morphodynamic response can be seen.

Reduced friction

The reduced friction leads to a lower equilibrium flow depth and therefore the initial response is equivalent to widening a river section, see Figure 4.1. The long-term response is different from widening as a lower friction needs a milder slope to transport the same amount of sediment downstream. The long-term effect is comparable to narrowing a river section, see Figure D.16.

Sediment offtake

Initially the sediment offtake and re-introduction have no hydraulic effect. The initial morphodynamic effects are an erosion wave at the inlet of the longitudinal wall and an aggradation wave at the outlet. The equilibrium response to the offtake of sediment and its reintroduction downstream is equivalent to narrowing a river section. The long-term effect can be seen in Figure D.16.

The combined effect of the interventions depends on the relative contributions of the different effects. The contribution of the individual effects differs with water discharge. An inlet step is present at the inflow which causes a concentration of water and sediment discharge into the main channel for low water discharges. This means that the reduction in width effect is dominant over the sediment and water offtake effects which leads to higher water levels during low flow to aid navigation. For higher flows a larger fraction of the water and sediment discharge is diverted towards the side channel which increases the width of the river and therefore leads to a increase in the contributions of the sediment and water offtake effects and a decrease of the reduction in width effect.
For low flows the initial morphodynamic response is degradation in the main channel next to the longitudinal wall and on the long-term also the river bed upstream will lower. Whereas for higher flows the higher relative contribution of water offtake can lead to aggradation in the short and long term.
A study by Berkhof et al. (2018) showed that the combined effect of longitudinal walls can slow down degradation. This can be explained by the fact that the low flows, for which

degradation would occur, are morphologically less relevant. A study by de Ruijsscher (2020) furthermore showed that the sediment and water discharge into the side channel can be effectively steered by the sill geometry which means that the degradational effects of the sediment offtake can be limited.

D.7 Groyne lowering/increase

By changing the groynes height constriction of the flow is changed. The flow only experiences a different constriction when there is flow over the groynes. Lowering the groynes leads to less constriction and increasing the groynes leads to more constriction. Therefore, lowering of the groynes is comparable to widening of a river section and increasing the groynes is comparable to narrowing a river section.

D.8 Weirs fully open

By fully opening the weirs, the water can flow freely through the Nederrijn and Lek for the lower Lobith discharges. It is assumed that the equilibrium depth is reached and therefore no changes in the sediment flux and bed level occur. For a closed weir, and for low flows, a M1 backwater curve arises which leads to aggradation. Averaged over all discharges at Lobith, the water level at the downstream end of the Pannerden Canal is lowered. A lower downstream water level eventually leads to a lower bed level as well. More water is attracted to the Pannerden Canal this way initially. However, also more water is attracted to the Nederrijn and Lek. The water level difference at the IJsselkop will be larger than the water level difference at the PK. Therefore it is expected that less water will reach the IJssel. This can lead to problem with the freshwater supply of the IJsselmeer and therefore additional interventions may be required to take care of this.

E Quantitative analysis initial response of the opposing bifurcate

From the initial response it remains uncertain whether or not an aggradation or erosion wave occurs in the untouched bifurcate. Therefore a quantitative analysis is made where the change in sediment transport capacity is compared to the change in sediment supply for the untouched bifurcate.

Initially it is assumed that the sediment supplied to the bifurcates matches the sediment transport capacity in the bifurcates. Therefore nothing happens upstream in the bifurcates. Due to interventions in the bifurcates, the discharge partitioning at the PK changes. This also changes the sediment partitioning at the PK. In the new situation, just as before the interventions, the sediment transport capacity in the bifurcates remains equal along the river so no aggradation or erosion will occur, see Figure 4.3. However, the sediment supply to the bifurcates does not necessarily match the sediment transport capacity upstream in the bifurcates anymore. This can lead to a degradation or aggradation wave in the bifurcates starting from the PK.

Therefore a calculation is made where the sediment supply and the sediment transport capacity of the untouched bifurcate are compared after the implementation of a intervention. When the capacity increases more than the supply, an erosion wave occurs and when the supply increases more than the capacity, an aggradation wave occurs.

For simplicity, the sediment is assumed to be unisize. Since the transport of sand over the Pannerdense Kop bifurcation is higher than the transport of gravel the sediment is assumed to be sand with a diameter of 1.5 mm. For sand the Engelund-Hansen formula can be used to determine the sediment transport capacity, Q_s, see equation D.1 (Engelund & Hansen, 1967). The depths and water discharges from before and after the implementation of the intervention from Table are used to determine the sediment transport capacity.

$$Q_s = Bmu^n \tag{E.1}$$

Where, n =5

$$m = \frac{0.05c_f^{\frac{3}{2}}}{(\Delta g)^2 D}$$

Δ = the submerged specific density: $\frac{\rho_s - \rho}{\rho}$

ρ = density
D = grainsize

The sediment supply from the Boven-Rijn is taken from Frings et al., (2019). The division of sediment over the bifurcation is determined with a nodal point relation. The same nodal point relation as used in the 1D Rijntakken model is chosen, which can be seen in equation E.2 (Chavarrías et al., 2020). Using equation E.3 this can be rewritten to equation E.4 to calculate the sediment supply to the Waal and then the sediment supply to the Pannerden Canal is calculated using equation E.3.

$$\frac{Q_{s,1}}{Q_{s,2}} = 1.79\frac{Q_1}{Q_2} \tag{E.2}$$

$$Q_{s,BR} = Q_{s,1} + Q_{s,2} \tag{E.3}$$

$$Q_{s,1} = \frac{1.79\frac{Q_1}{Q_2}}{1 + 1.79\frac{Q_1}{Q_2}}\,Q_{s,BR} \tag{E.4}$$

Since the calculated sediment supplies and transport capacities do not match initially, the absolute values are not used for comparison. Instead the relative values which present the increase or decrease with respect to the initial situation are used to compare the sediment transport capacity and supply after the implementation of an intervention. The results can be seen in Table E.1. The subscripts n and o represent new and old which respectively indicate the situation after and before the implementation of an intervention.

Table E.1: The relative difference in sediment transport capacity and supply for the Waal and the Pannerden Canal for two different Lobith discharge values as a result of the required water level difference at the Pannerdense Kop.

	$Q_{s,1,n}/Q_{s,1,o}$ Cap.	$Q_{s,1,n}/Q_{s,1,o}$ Supply	$Q_{s,2,n}/Q_{s,2,o}$ Cap.	$Q_{s,2,n}/Q_{s,2,o}$ Supply
Q_0=1851 (m^3/s)	0.34	0.96	1.51	1.31
Q_0=6421 (m^3/s)	0.43	0.95	1.26	1.18

It can be seen that after a water level increase in the Waal, the sediment transport capacity in the Pannerden Canal increases relatively more than its sediment supply for both Lobith discharge values. Therefore an erosion wave is expected in the Pannerden Canal after a water level increase on the Waal. After a water level decrease in the Pannerden Canal, the sediment transport capacity in the Waal decreases relatively more than its sediment supply for both Lobith discharge values. Therefore an aggradation wave is expected in the Waal after a water level decreases on the Pannerden Canal.

F Notes on schematizing

The most simple way for implementing the interventions is by changing the cross sections in the model. In Figure F.1 a simplified cross section of a river is seen. In this cross section changes are made which are indicated with the arrows to model for example changes in width or depth of the main channel, a change in length or height of the groynes or a change in width or height of the floodplains. Furthermore discharges may be added and subtracted to the model as a means to schematize interventions and changes can be made to the model parameters to schematize interventions. The floodplain friction values can for instance be changed to schematize floodplain maintenance and the constant in the nodal point relation can be changed to influence the sediment partitioning at the bifurcations.

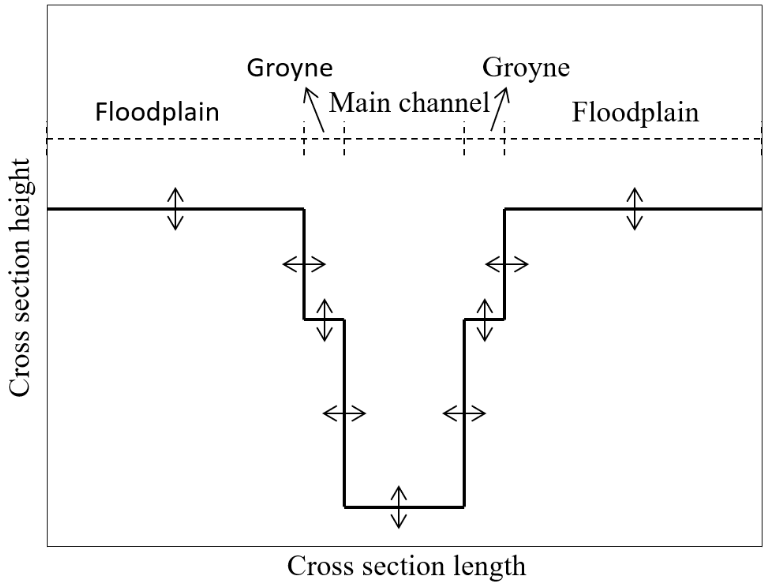

Figure F.1: Simplified river cross-section and the changes in the cross-section belonging to different river interventions.

Two simple tools have been developed to aid with the schematization. The tools help in determining the dimensions of the interventions. One tool determines the initial water extraction or addition to the main channel as a result of the interventions and the other tool determines the initial water level difference at the PK as a result of the interventions. The tools are further explained below.

Water extraction tool

The river is split in three different sections, namely: the main channel, the groynes and the floodplains. The flow velocity in each section is calculated separately with the normal flow equation:

$$u_i = \sqrt{i_b R_i C_i^2} \tag{F.1}$$

where i_b [-] is the river bed slope. R [m] is the hydraulic radius defined by $R=A/O$, where A [m^2] is the flow area and O [m] is the wetted perimeter. C [$m^{1/2}/s$] is the Chézy value. For a given range of depths, the flow velocities can be calculated. The total discharge is then calculated as a sum of the discharges in the river segments.

$$Q = \sum_{i=1}^{n} u_i A_i \tag{F.2}$$

As a result of an intervention in the river, water is added or subtracted from the main channel. This can be expressed with an extraction curve, where the difference in percentage of the flow through the main channel is plotted against the total discharge.

Water level difference at the Pannerdense Kop

For this tool the interventions are schematized as changes in the width or depth, or changes in the discharge through the main channel, or both. As a result of the interventions, backwater effects arise which alter the water level at the PK. The backwater effects can be easily quantified using the empirical fit to the Bresse's analytical solution of the backwater equation. The empirical fit is seen in equations F.3 and F.4 below.

$$d(s) = d_e + (d_0 - d_e) * 2^{\frac{s-s_0}{L_{\frac{1}{2}}}} \tag{F.3}$$

$$L_{\frac{1}{2}} = 0.24 \frac{d_e}{i_b} \left(\frac{d_0}{d_e}\right)^{\frac{4}{3}} \tag{F.4}$$

where s [m] is the distance along the river axis. d_e [m] is the equilibrium depth and d_0 [m] and s_0 [m] are respectively the depth and the location of the upstream end of the backwater curve. Given the extraction curve from the extraction tool, the water level difference as a result of the interventions can also be plotted as a function of discharge.

G Quantitative analysis required water level lowering at the Pannerdense Kop

The required water level change at the PK determines the size of the interventions. From the paper by Chowdhury et al. (2023) it can be seen that the ratio of discharge to the Waal has increased by about 5% since the peak flows of 1993, 1995 and 1998 in both cases when the Driel weir is opened and closed. So to restore the discharge partitioning to the situation before the peak flows, a reduction in the discharge ratio to the Waal of 5% is aimed for. It can be calculated what the increase in water level in the Waal or the decrease in water level in the Pannerden Canal should be to reach this goal. The difference in water level can be obtained hydraulically in the short term through backwater effects and it can be obtained morphologically in the long term through adjustments of the bed.
The required water level difference is calculated for two different discharges. One for which all weirs are closed and one for which they are open as this has an impact on the water depth gradient which is important for the determination of the depth. The discharges in the Boven-Rijn are selected from the 2018 water level data from Rijkswaterstaat and have a magnitude of $1.85*10^3$ and $6.43*10^3$ m^3/s.

At the Pannerdense Kop the water level is continuous such that $h_0 = h_1 = h_2$, where h_0 is the water level of the Boven-Rijn, h_1 the water level of the Waal and h_2 the water level of the Pannerden Canal. From this it can be deduced that the water depth in the Waal equals the depth in the Pannerden plus the bed level difference between the Pannerden Canal and the Waal (where z (m+NAP) denotes the bed level height):

$$d_1 = d_2 + \Delta z. \tag{G.1}$$

At the Pannerdense Kop it also holds that the discharges of the bifurcates add up to the discharge of the Boven-Rijn such that: $Q_0 = Q_1 + Q_2$, where Q_0 is the water discharge of the Boven-Rijn, Q_1 the water discharge of the Waal and Q_2 the water discharge of the Pannerden Canal. Rewriting it gives:

$$Q_2 = Q - Q_1. \tag{G.2}$$

The depths in the branches can be computed from the backwater equation $S_d = \frac{S-S_f}{1-Fr^2}$, where S_d is the streamwise gradient in water depth d, S the channel bed slope and S_f the friction slope which is equal to $c_f F_r^2$. Replacing Fr^2 by $\frac{Q^2}{gB^2d^3}$ (where g is the standard gravity and B the width of the main channel) gives the following formula for the water depth after rewriting:

$$d = \sqrt[3]{\frac{Q_w^2}{gB^2}\frac{c_f - S_d}{S - S_d}} \tag{G.3}$$

By combining equations G.1, G.2 and G.3, equation G.4 is obtained.

$$\sqrt[3]{\frac{Q_1^2}{gB_1^2}\frac{c_{f,1} - S_{d,1}}{S_1 - S_{d,1}}} = \sqrt[3]{\frac{(Q_0 - Q_1)^2}{gB_2^2}\frac{c_{f,2} - S_{d,2}}{S_2 - S_{d,2}}} + \Delta z \tag{G.4}$$

By filling in all variables except for the discharge in the Waal, the discharge division can be found for which equation G.4 holds. The initial values for the non-dimensional friction coefficients and the widths are taken from Sloff & Mosselman (2012). The slopes of the branches, the bed steps and the depth gradients follow from the 2020 bathymetric survey and the water level data of 2018 of Rijkswaterstaat (Chowdhury et al., 2022). Input can be found in Table G.1. Two values are given for the streamwise gradient in water depth because it changes when the discharge changes. Due to M1 and M2 backwater effects for respectively low and high flows, the streamwise gradient in flow depth is positive for low flows and negative for high flows.

Equation G.4 is modified by adding the water level difference resulting from the interventions, Δh, to obtain equation G.5.

$$\sqrt[3]{\frac{Q_1^2}{gB_1^2}\frac{c_{f,1}-S_{d,1}}{S_1-S_{d,1}}}+\Delta h=\sqrt[3]{\frac{(Q_0-Q_1)^2}{gB_2^2}\frac{c_{f,2}-S_{d,2}}{S_2-S_{d,2}}}+\Delta z \qquad \text{(G.5)}$$

Q_1 is changed now such that the discharge ratio of Waal to Lobith is 5 % lower. The equation is solved to obtain the required water level lowering of the Pannerden Canal or the water level increase of the Waal. The results can be seen in Table G.2. The water level difference as a results of the intervention is not equal to the change in depth in the bifurcates as the discharge partitioning changes at the Pannerdense Kop as a result of the water level difference from the interventions. The changes in depth in the Pannerden Canal and the Waal can also be seen in Table G.2.

Table G.1: Input variables for the calculation of the required water level difference that should be obtained by the interventions.

	$Q_0 = 1.85*10^3$ (m^3/s)	$Q_0 = 6.43*10^3$ (m^3/s)
$c_{f,1}$ (-)	0.004	0.004
$S_{d,1,old}$ (-)	7.41E-06	-9.60E-06
$S_{d,1,new}$ (-)	7.73E-06	-7.75E-06
S_1 (-)	1.07E-04	1.07E-04
B_1 (m)	260	260
$c_{f,2}$ (-)	0.01	0.01
$S_{d,2,old}$ (-)	3.90E-05	-5.46E-05
$S_{d,2,new}$ (-)	2.95E-05	-7.43E-05
S_2 (-)	6.12E-05	6.12E-05
B_2 (m)	135	135

Table G.2: The discharge in the Waal, the depth in the Pannerden Canal and the Waal before and after the implementation of the interventions and the required water level difference for the two different Lobith discharges.

	$Q_{1,old}$ (m^3/s)	$Q_{,1,new}$ (m^3/s)	$d_{1,old}$ (m)	$d_{1,new}$ (m)	$d_{2,old}$ (m)	$d_{2,new}$ (m)	Δh (m)	Δd (m)
$Q_0 = 1.85*10^3$ (m^3/s)	1.53E+03	1.44E+03	5.19	4.99	4.67	4.92	0.45	0.24
$Q_0 = 6.43*10^3$ (m^3/s)	4.37E+03	4.04E+03	9.93	9.48	9.41	9.85	0.88	0.44

So the water level differences as a result of the interventions for low flows and high flows should respectively be 0.45 and 0.88 m which leads to a difference in flow depth of 0.24 m and 0.44 m. For the high flows this seems to be too high. An explanation for this might be that for high flows the effect of the flood plains is neglected. Therefore the width is too small which leads to too large flow depths.

H Additional plots reference simulation

H.1 Reference simulation

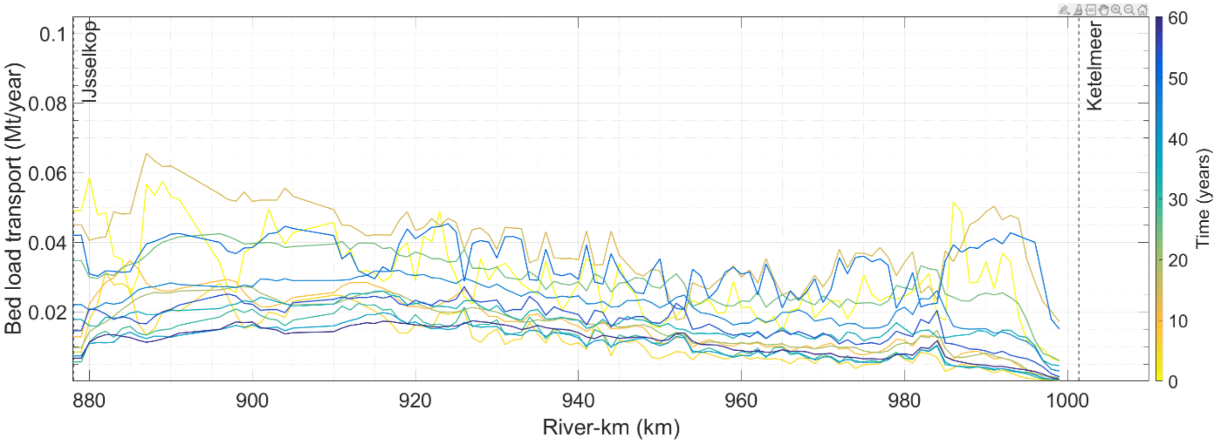

Figure H.1: Yearly bed load sediment transport in time for the IJssel

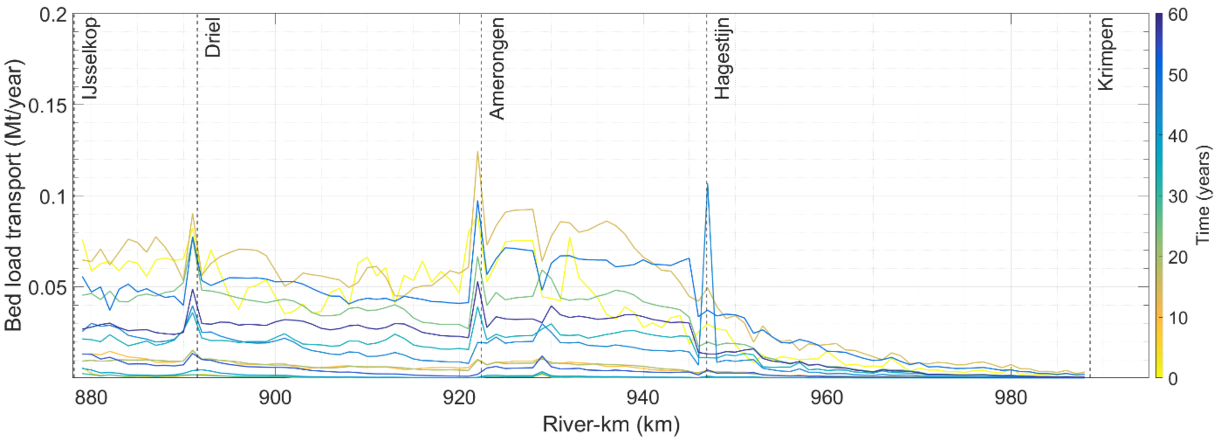

Figure H.2: Yearly bed load sediment transport in time for the Nederrijn-Lek

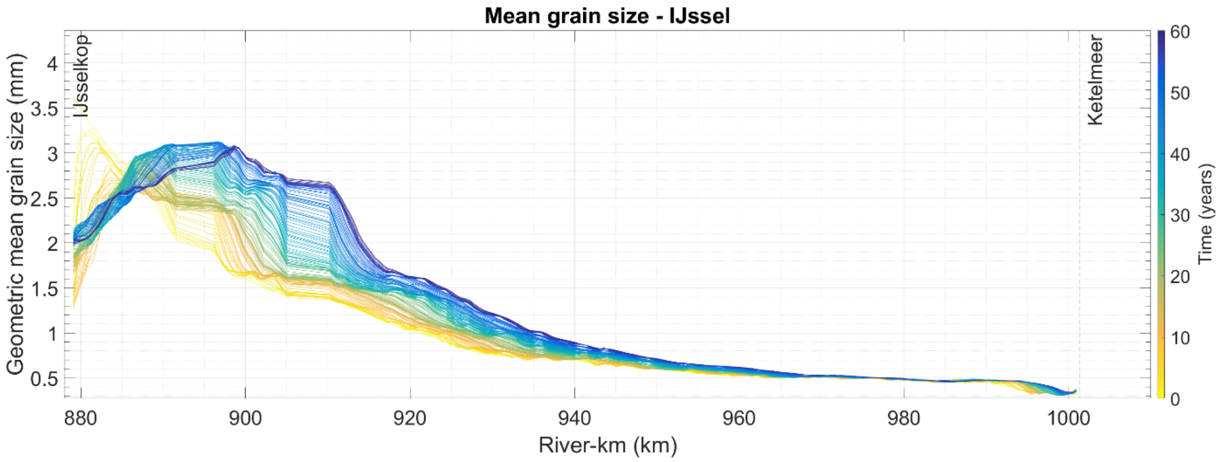

Figure H.3: Geometric mean grain size development for the IJssel

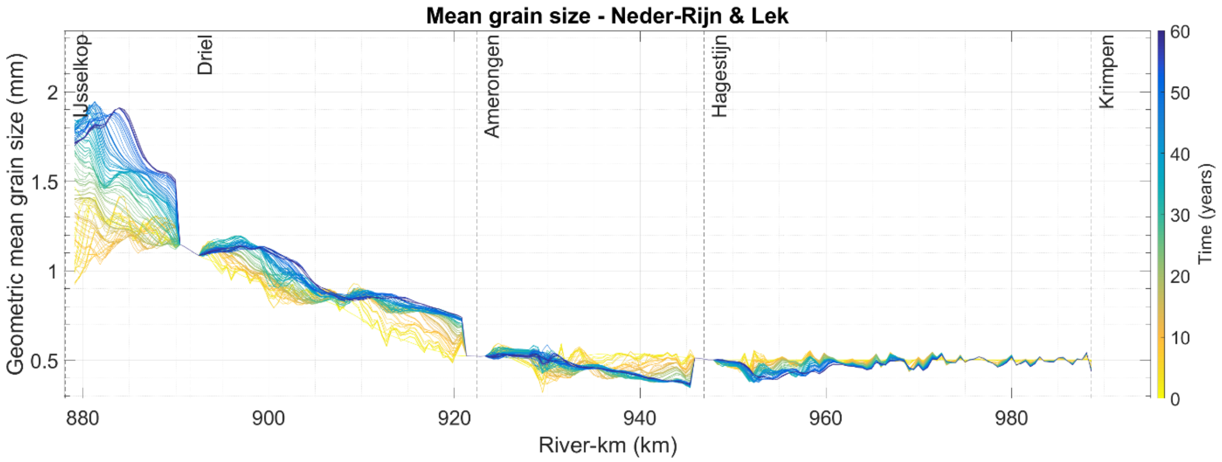

Figure H.4: Geometric mean grain size development for the Nederrijn-Lek

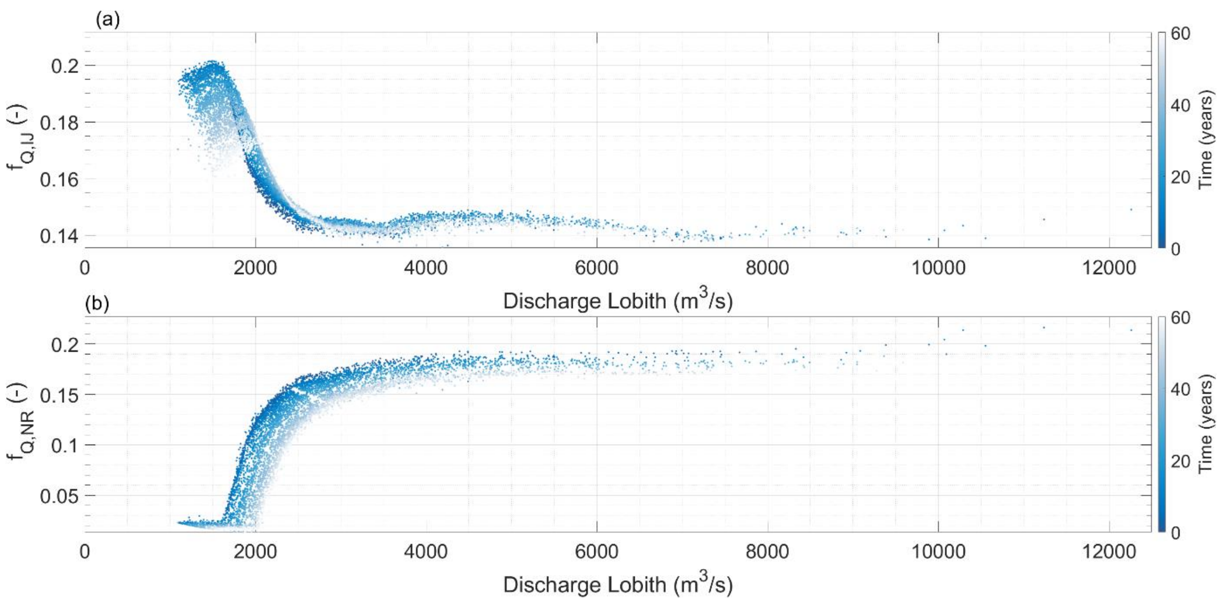

Figure H.5: a) IJssel discharge fraction relative to the Lobith discharge for the reference simulation as a function of the Lobith discharge. b) Nederrijn-Lek discharge fraction relative to the Lobith discharge for the reference simulation as a function of the Lobith discharge.

H.2 Reference simulation dredge and dump

For the dredge and dump simulation the D-Flow FM version 1.2.102.66429M is used and for the other simulations the D-Flow FM Version 1.2.110.67553M is used.

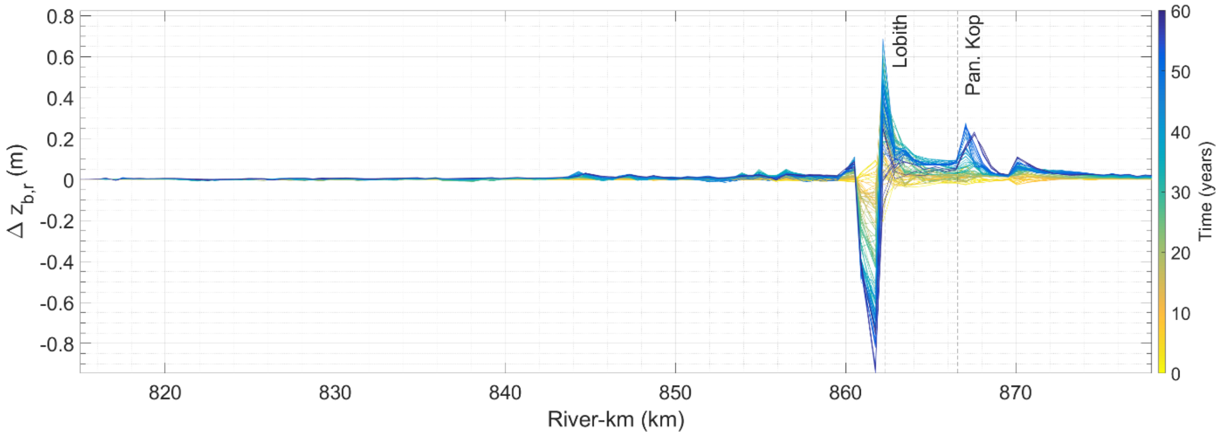

Figure H.6: Difference in bed level of the Niederrhein, Boven-Rijn and Pannerden Canal between the reference simulation for the dredge and dump intervention and the original reference simulation.

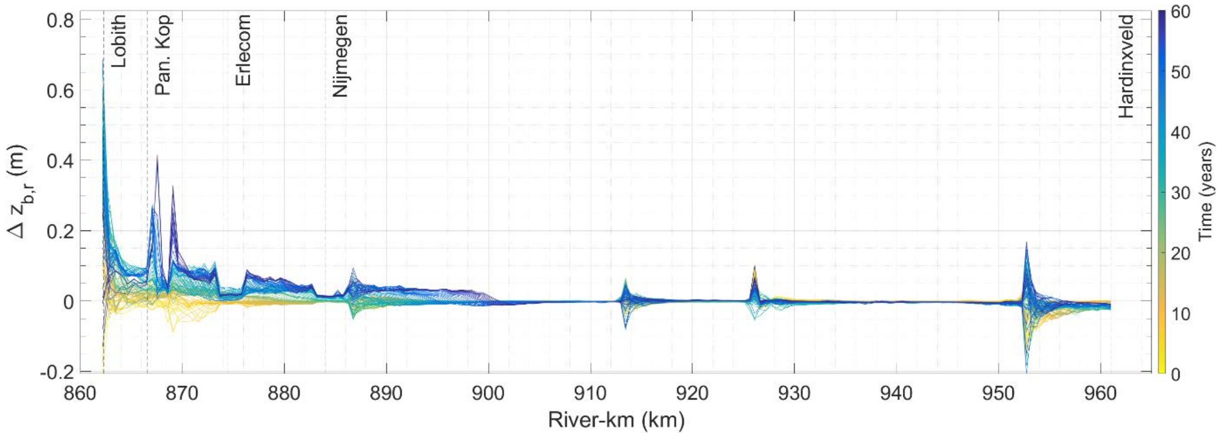

Figure H.7: Difference in bed level of the Boven-Rijn and Waal between the reference simulation for the dredge and dump intervention and the original reference simulation.

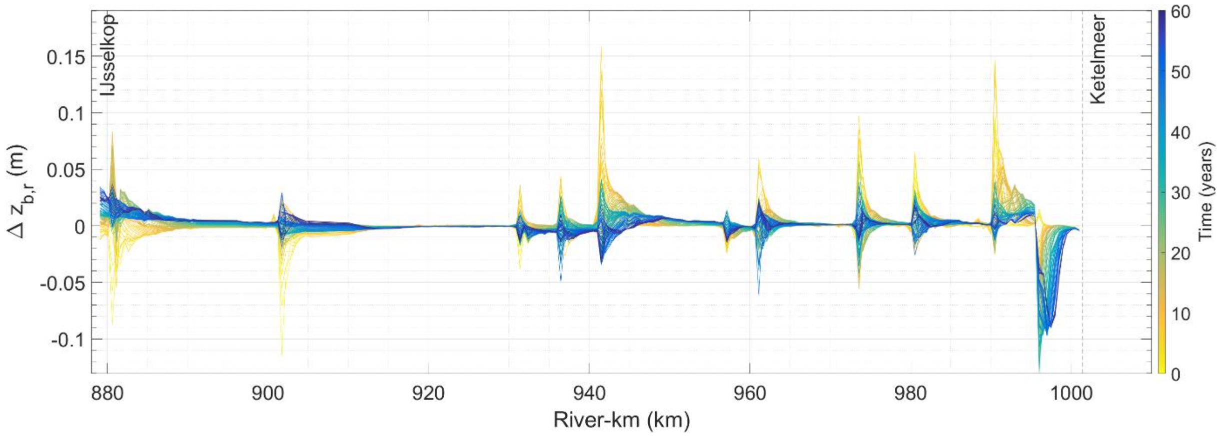

Figure H.8: Difference in bed level of the IJssel between the reference simulation for the dredge and dump intervention and the original reference simulation.

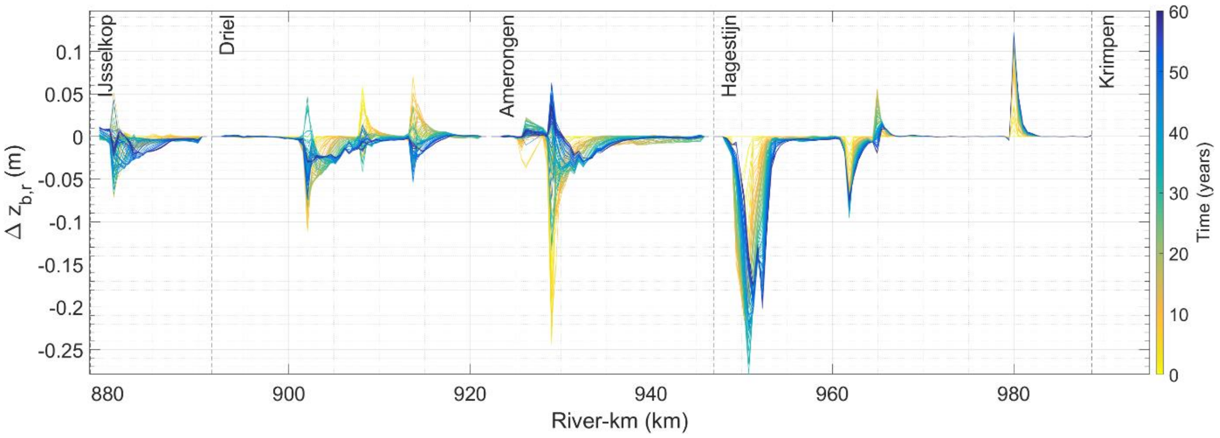

Figure H.9: Difference in bed level of the Nederrijn-Lek between the reference simulation for the dredge and dump intervention and the original reference simulation.

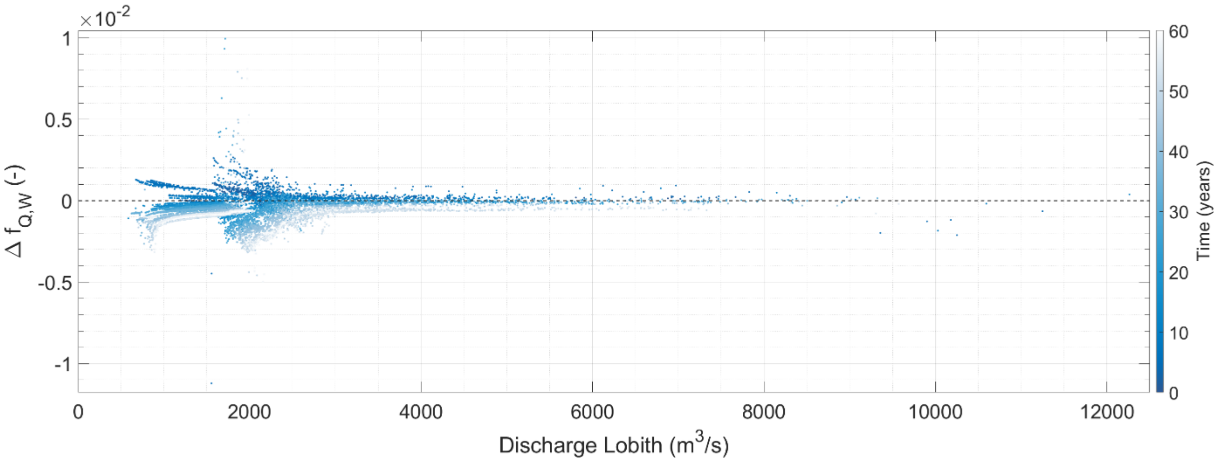

Figure H.10: Difference in the Waal discharge fraction between the reference simulation for the dredge and dump intervention and the original reference simulation.

I Additional plots interventions

I.1 Side channel from the Boven-Rijn to the Pannerden Canal

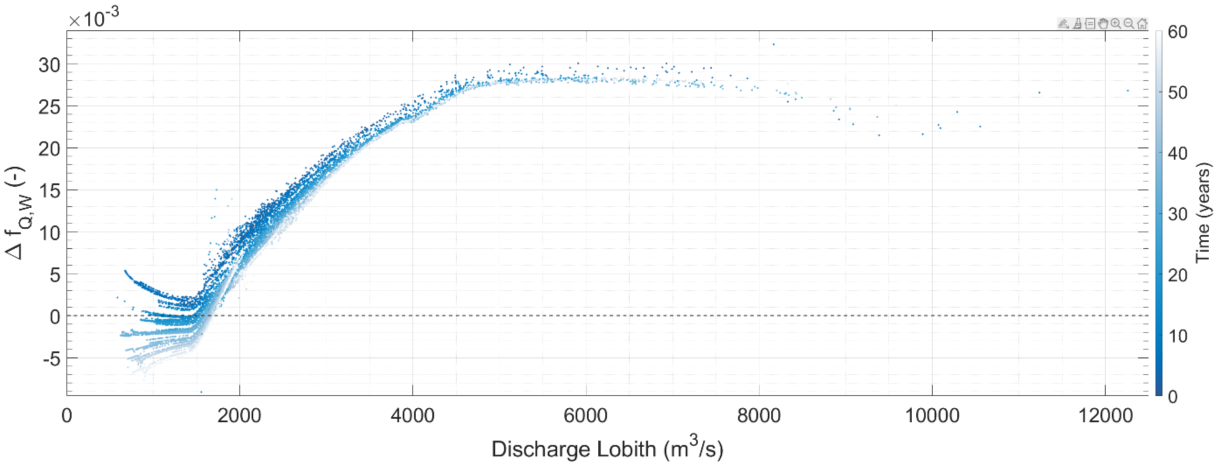

Figure I.1: Difference in Waal discharge fraction between the simulation with the side channel intervention and the reference simulation. The Boven-Rijn discharge just upstream of the Pannerdense Kop is used to compute the Waal discharge fraction.

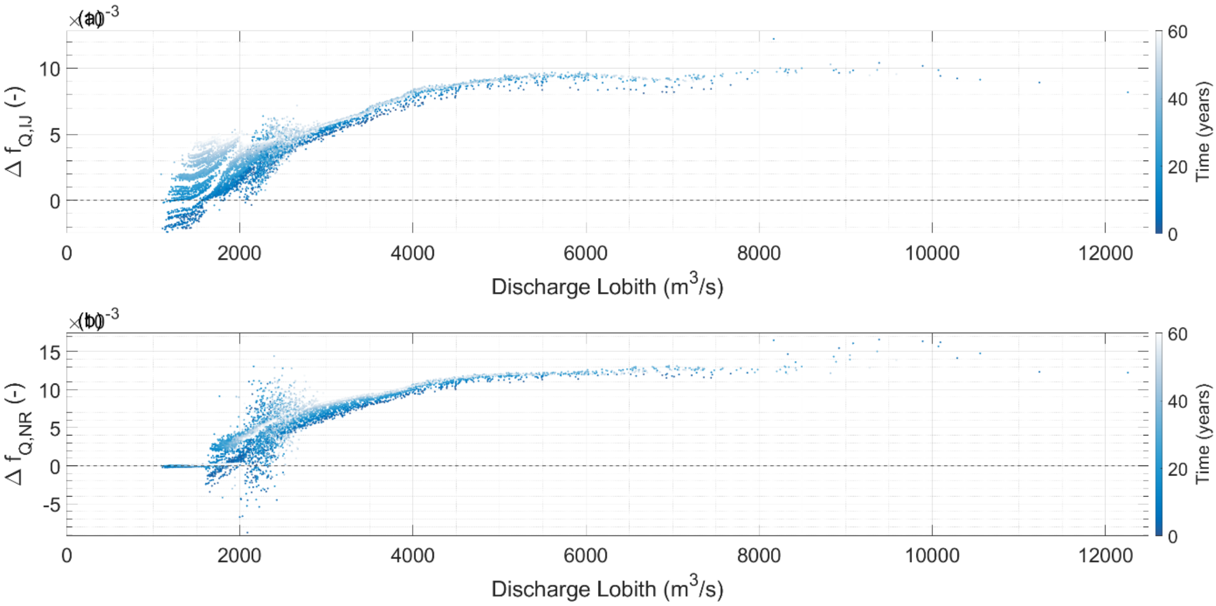

Figure I.0.2: a) Difference in IJssel discharge fraction relative to the Lobith discharge between the simulation with the side channel and the reference simulation as a function of the Lobith discharge. b) Difference in Nederrijn-Lek discharge fraction relative to the Lobith discharge between the simulation with the side channel and the reference simulation as a function of the Lobith discharge.

I.2 Opening of weirs

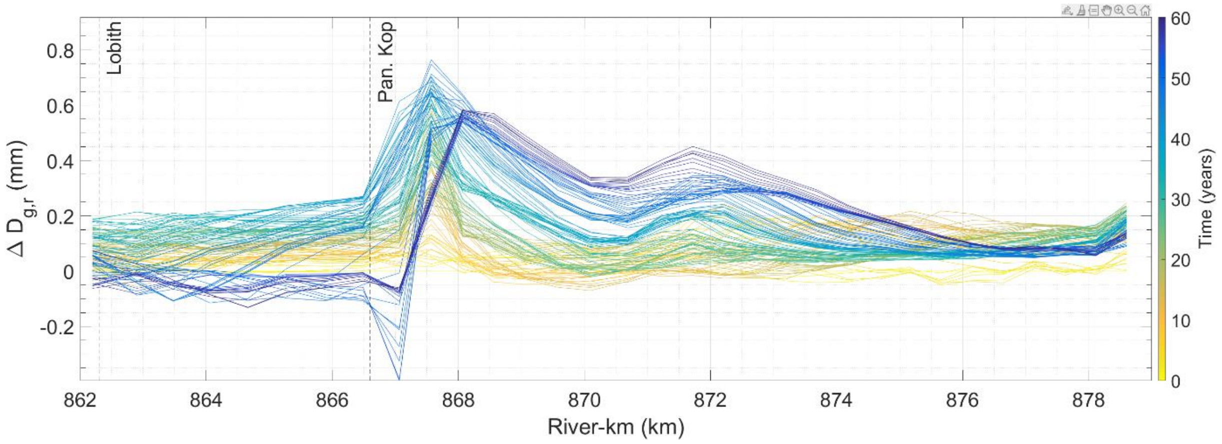

Figure I.0.3: Difference in geometric mean grain size of the Boven-Rijn and Pannerden Canal between the simulation with the open weirs and the reference simulation.

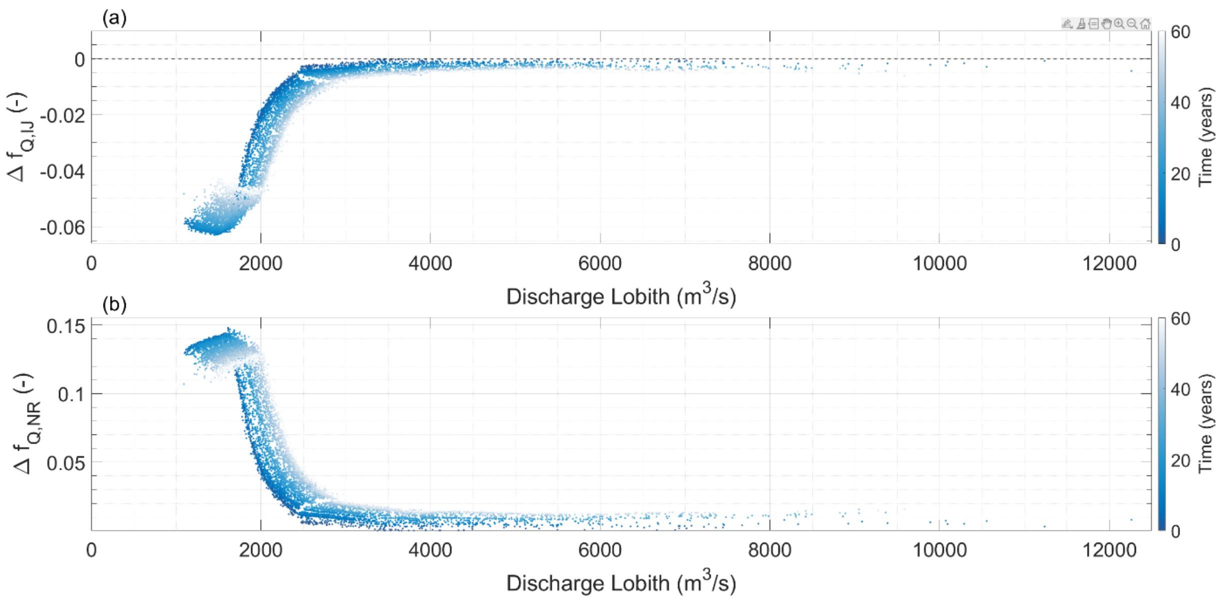

Figure I.4: a) Difference in IJssel discharge fraction relative to the Lobith discharge between the simulation with opened weirs and the reference simulation as a function of the Lobith discharge. b) Difference in Nederrijn-Lek discharge fraction relative to the Lobith discharge between the simulation with opened weirs and the reference simulation as a function of the Lobith discharge.

I.3 Widening on the IJssel

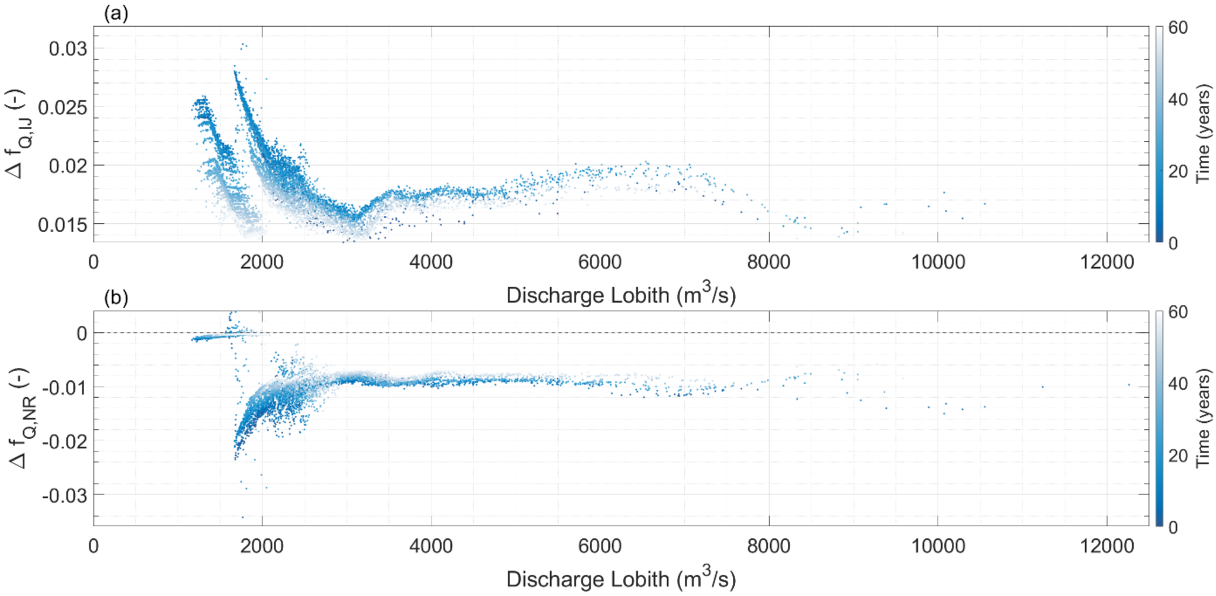

Figure I.5: a) Difference in IJssel discharge fraction relative to the Lobith discharge between the simulation with the widening on the IJssel and the reference simulation as a function of the Lobith discharge. b) Difference in Nederrijn-Lek discharge fraction relative to the Lobith discharge between the simulation with the widening on the IJssel and the reference simulation as a function of the Lobith discharge.

I.4 Directly steering the sediment partitioning at the PK

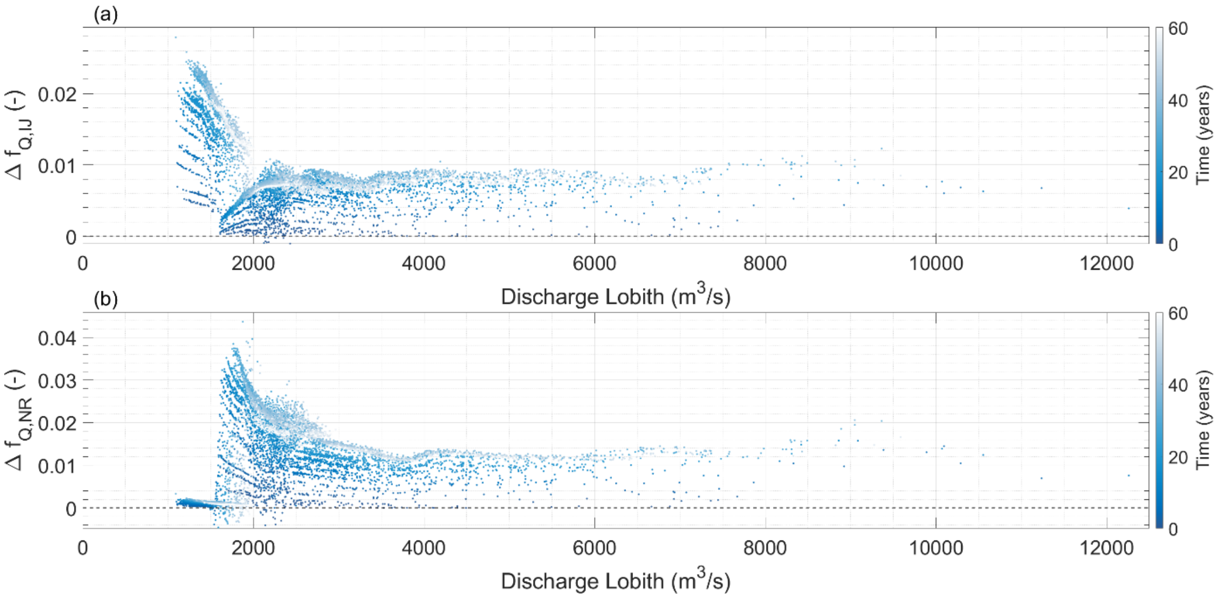

Figure I.6: a) Difference in IJssel discharge fraction relative to the Lobith discharge between the simulation with the changed sediment partitioning at the PK and the reference simulation as a function of the Lobith discharge. b) Difference in Nederrijn-Lek discharge fraction relative to the Lobith discharge between the simulation with the changed sediment partitioning at the PK and the reference simulation as a function of the Lobith discharge.

I.5 Dredging in the PC and dumping in the Waal

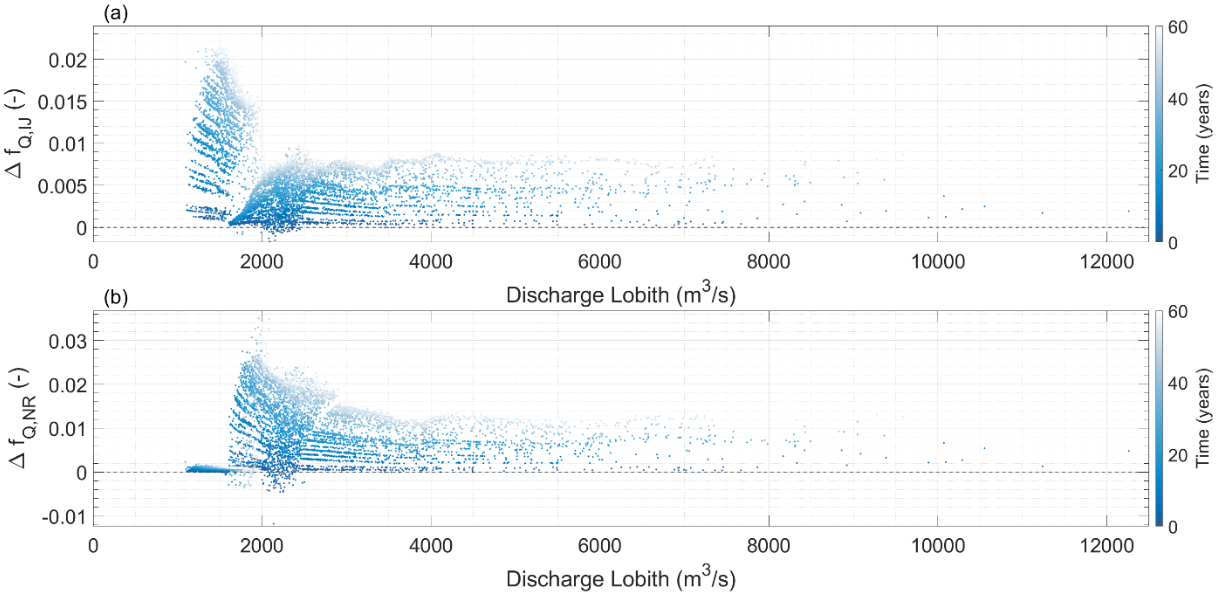

Figure I.7: a) Difference in IJssel discharge fraction relative to the Lobith discharge between the simulation with the dredging and dumping and the reference simulation as a function of the Lobith discharge. b) Difference in Nederrijn-Lek discharge fraction relative to the Lobith discharge between the simulation with dredging and dumping and the reference simulation as a function of the Lobith discharge.