The potential of side channels to mitigate large-scale bed degradation in the Dutch Rhine distributaries: A 1D-modelling study

Master Thesis

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May 2022

UNIVERSITY OF TWENTE.

Colophon

Cover picture: Side channel in the IJssel River near Deventer (Witteveen+Bos)

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In partial fulfilment of the requirements for the degree of

Master in Science

In Civil Engineering and Management

Faculty of Engineering Technology

University of Twente

May 2022

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Preface

This thesis report is the final stage of the master track River and Coastal Engineering for the master programme Civil Engineering and Management at the University of Twente. For the past months, I studied the morphological effects that side channels have on the main channel bed of the Dutch Rhine River and its major distributaries. The project was partly executed at Witteveen+Bos in Deventer.

I learned a lot during this thesis, which is for an important part due to the supervising and guidance that I got. Therefore, I would like to thank my supervisors Leonie Straatsma and Bas Gradussen from Witteveen+Bos. Their feedback and support gave me a lot of structure during the research project, for which I am very thankful. It was a pleasure going to the Witteveen+Bos offices and it made me feel part of the team.

In addition, I would like to thank Vasileios Kitsikoudis from the department of Water Engineering and Management. His critical questions made enthusiastic to dive deeper into river modelling and the behaviour of the system of the Dutch Rhine River. I would also like to thank Denie Augustijn as the chair of the graduation committee for his feedback and for the pleasant meetings. A special thanks goes to Victor Chavarrias from Deltares, who has helped a lot with getting started and was often available to help out with model-related questions.

Lastly, I want to thank my friends and family that have supported me during this project. I am grateful for their support and availability to act as peers for me for reflection during the process.

Overall, I enjoyed the graduation period. Although the past months were not always easy, I never lost interest in the topic. On the contrary, the project really sparked my interest in the behaviour of rivers to human interference. It made me aware of the dynamics within river engineering and the uncertainties that come with it, for which a critical reflection is necessary. It also made me aware how multi-faced river engineering really is and made me enthusiastic to continue to work in river engineering projects.

I hope that you as a reader will feel the same.
Have fun reading this report!

Thorvald Rorink

May 2022

Summary

Humans have been attracted to rivers since the start of civilization. They settled along its course and modified its flow path in order to use the river for different purposes, such as agriculture and transportation. However, rivers are dynamic systems that respond to changes in forcings over very long timescales. The Rhine River is no exception. Due to historical river training from the 19th and 20th century, the Rhine River moves towards a new equilibrium which currently causes large-scale bed degradation, reaching values between 1.5 - 4 cm per year (Blom, 2016; Havinga, 2020). Bed degradation hampers the functionality of the Rhine River (Havinga, 2020; Zuijderwijk et al., 2020).

This research project investigates the effect of large-scale side channel implementation at different discharges to mitigate the ongoing bed degradation in the (Dutch) Rhine River and its distributaries. A 1D model is used to simulate morphodynamic development of the main river channel for the coming 100 years under autonomous conditions and under a changed bathymetry as a result of side channel implementation. Side channels are implemented as an extension of the adjacent main channel by 25%, which can also be seen as a partial floodplain excavation.

Based on autonomous conditions that remain as they currently are, the simulation of autonomous bed development shows various degrees of degradation and sedimentation for the Rhine River and its distributaries. Degradation in the upper reach of the Waal River reaches values op 3.5 - 4.0m, whereas the Pannerdensch Kanaal reaches values op 1.0 - 2.6 m. As a result, discharge partitioning will be skewed towards the Waal River. The middle and lower reach of the Waal River are characterized by slope decrease, leading to incision between Nijmegen (rkm 885) and Passewaaij (rkm 917) and sedimentation between Zatlbommel (rkm 933) and Hardinxveld (rkm 962). The Nederrijn, Lek and IJssel Rivers show predominantly local morphological effects that vary between 0.5 m erosion and 1.0 m sedimentation over the simulation period, with the exception of the upper IJssel river and a few minor locations. The distributaries of the Rhine River are not in equilibrium after 100 years and show high values of inter-annual change in bed level of up to 0.4 m. The degradation- and sedimentation values that are obtained from this research are in line with the current degradation rates of Blom (2016) and Havinga (2020) and are in line with projections by Ylla Arbós (2019) and simulations by Welsch (2021) and Paarlberg & Van Lente (2021).

The schematized side channels are able to reduce bed degradation rates. The effectiveness is influenced by side channel size and side channel location. In general, side channels that become active above 2800 m^3/s at Lobith (i.e. less than 20% of the year) do very little to reduce bed degradation. However, side channels that become active at 1000 m^3/s at Lobith (almost 100% of the year) are able to reduce bed degradation by 10-15% for the Waal River and 20-25% for the Pannerdensch Kanaal. A combination of side channels in both the Waal River as the Pannerdensch Kanaal is even able to reduce bed degradation rates in the Pannerdensch Kanaal by 30-35%, which is a considerable benefit regarding long-term dredging volumes (Van Vuren et al., 2015) and in line with Barneveld et al. (2019). Nevertheless, additional soft measures (such as sediment nourishments) will continue to be necessary to mitigate bed degradation rates as will dredging operations to mitigate the temporally variable initial effects (Van Vuren et al., 2015).

Since after 100 years the Dutch Rhine and its distributaries have not reached their equilibrium bed level, it is unadvisable to design interventions based on the equilibrium configuration. The long adaptation time of the main channel bed should be taken into account in the design of interventions to not overestimate the benefits. Since degradation is observed up- and downstream of the locations where side channels are implemented, strategically located side channels, i.e. upstream of fixed layers or upstream of locations where currently sedimentation is present can be of benefit with use of local dynamics to minimize dredging costs.

Contents

Colophon 2

Preface 3

Summary 4

1. Introduction 6
   - 1.1. Problem background 6
   - 1.2. Research gap 8
   - 1.3. Research objective 8
   - 1.1. Thesis outline 10
2. Theoretical background 11
   - 2.1. Schematizing rivers 11
   - 2.2. Modelling river morphodynamics 13
   - 2.3. Effect of side channels 13
   - 2.4. State of the art 14
3. Methodology 17
   - 3.1. Model choice and model description 17
   - 3.2. Model calibration and verification 19
   - 3.3. Determining autonomous bed degradation 20
   - 3.4. Determining the effectiveness of side channels in reducing bed degradation 22
   - 3.5. Overview of runs 27
4. Autonomous bed degradation in the Rhine River and its distributaries 29
   - 4.1. Verification run using a stationary upstream discharge of 2250 m^3/s 29
   - 4.2. Reference run using historical discharge time series 31
5. Bed development of the Rhine River and its distributaries under influence of side channels 37
   - 5.1. Morphological effects of side channels in one distributary of the Rhine River 37
   - 5.2. Morphological effects of side channels in multiple distributaries of the Rhine River 41
6. Discussion 43
   - 6.1. Discussion of model choices and features 43
   - 6.2. Discussion of used data 44
   - 6.3. Discussion of followed methodology 45
7. Conclusions and recommendations 47
   - 7.1. Conclusions 47
   - 7.2. Recommendations 48

Bibliography 50

Appendices 54

1. Introduction

This chapter introduces the problem that will be investigated during the research project. It starts with a description of the problem background, followed by a gap in the current research to solve the problem. Then, the research aim and research questions of the project are introduced which are followed by an outline of the remainder of the report.

1.1. Problem background

Wherever rivers flow, people make use of the services that they provide. The Rhine is no exception, and has become one of the most important rivers in Northwestern Europe, as one of the primary arteries for a region with an annual gross domestic product of US$ 1750 billion (Uehlinger et al., 2009). It provides services for power generation, industrial production, urban sanitation, drinking water for 25 million people, agriculture and tourism (Havinga, 2020). Therefore, the Rhine can be pointed out as a classic example of a 'multipurpose' waterway (Cioc, 2002). In total, the Rhine affects roughly 58 million people in their daily lives. Most of which live in crowded areas near the river banks (Frijters & Leentvaar, 2003). As the dependency of humans on rivers increases, river training becomes increasingly important in order to guarantee reliability of river functions. Therefore, rivers like the Rhine have been heavily trained from the second half of the 19th century onward to reduce the risks and increase the benefits and reliability of the river for human activities (Frings et al., 2019). The Rhine basin including the locations where river training has been implemented are given in Figure 1.1.

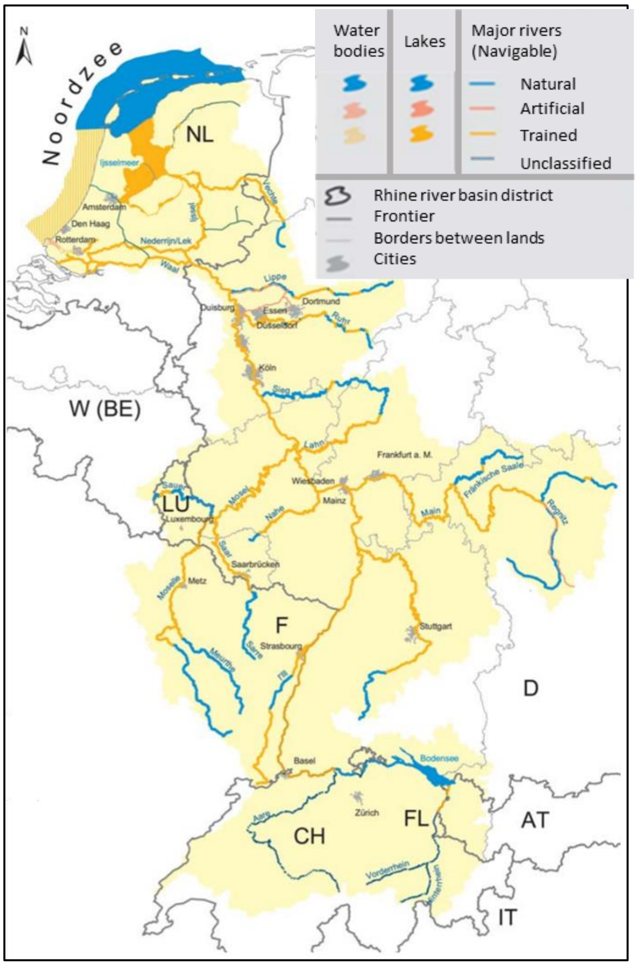

Figure 1.1: The Rhine basin including natural streaming areas (blue) and trained areas (yellow) (ICPR, 2004).

In the upper sections of the Rhine (In Switzerland and parts of Germany), there are multiple dams and weirs for hydropower generation and discharge regulation (Arnaud et al., 2019). Further downstream (In parts of Germany and the Netherlands), the river is canalized and normalized to enhance navigability (Le et al., 2020). Flow has been concentrated into one main channel and islands have been removed. Sharp meanders have been cut off and along parts of the river the eroding outer banks have been fixated (Sieben, 2009; Frings et al., 2019). Groynes have been constructed to facilitate inland navigation even during low flows as well as keeping the main river channel in its current location (Yossef, 2002). Dikes and embankments were constructed to prevent large scale flooding of the densely populated areas adjacent to the river.

Although the interventions have led to decreased risks of flooding events and increased navigability of the river, there are other consequences as well. The dams and weirs in the upstream parts of the Rhine trap around 95% of the sediment (Nienhuis et al., 2002), which reduces the sediment supply to downstream reaches. River interventions such as cutting off meanders have shortened the river severely, which has led to steeper slopes and higher flow velocities. Higher flow velocities imply a larger sediment transport capacity (Ribberink, 2011; Vermeulen et al., 2018). This is amplified by the construction of groynes in the main channel of the river, which concentrate the flow. In the past, the Rhine was also subjected to sand and gravel mining, which extracted even more sediment from the river. As a result, the sediment transport capacity of the Rhine has been increased, whereas the sediment supply has been decreased (Frings et al., 2014). Consequently, the river bed is degrading at several locations due to this imbalance in sediment budget (Frings et al., 2014). Along the Waal this degradation has been more than 1.5 meter over the last 60 years, with some locations exhibiting degradation rates between 2 cm/year (Blom, 2016) and 4 cm/year (Havinga, 2020). Degradation is observed also in parts of the IJssel, Nederrijn and Lek (Visser, 2000; Ylla Arbós et al., 2019). Spatially varying bed degradation has negative consequences for a multitude of river functions, such as navigation (Blom, 2016; Havinga, 2020), ecology (Gölz, 1994; Zuijderwijk et al., 2020), infrastructure and water safety (Gölz, 1994; Zuijderwijk et al., 2020), and water management practices resulting from the discharge partitioning at bifurcation points (Blom, 2016; Huthoff et al., 2021).

One way to counter bed degradation is to apply sediment nourishments, which have proven to stabilize the bed (Frings, 2019; Czapiga et al., 2022a). However, while this solution might look cheap compared to other types of interventions that change the river geometry (Straatsma et al., 2019; Havinga, 2020), these nourishments need to be conducted periodically to have a sustained effect on bed degradation (Visser, 2000; Havinga, 2020). Another way to counter bed degradation is to make use of river interventions, which are aimed at main channel flow velocity reduction (Blom, 2016; Havinga, 2020). One of the interventions that has proven to be promising to reduce bed degradation are side channels (Barneveld et al., 2019; Zuijderwijk et al., 2020). Side channels do not convey water during the entire year. During the lowest discharge stages the river discharge stays within the main channel. This is beneficial for several river functions (e.g. navigation, drinking water supply or nature), as during low discharge stages pressure on these functions is the most crucial. During higher discharge stages side channels become active and start conveying water, which reduces flow velocities in the main channel. Zuijderwijk et al. (2020) suggested that it is possible to implement side channels along large parts of the Dutch Rhine River distributaries in order to mitigate bed degradation. In addition, there is an ongoing political call to include (more) side channels in the main Dutch Rhine distributaries in many large-scale river management programmes, such as Integral River Management (IRM), High Water Protection Programme (HWPP),Water Framework Directive (WFD) and ‘Room for Living Rivers’ (RfLR) (Stuurgroep IRM, 2022). Side channels fit the multifunctional purpose of the Rhine as they not only reduce bed degradation, but also enhance flood safety, ecological value and offer possibilities for recreation.

1.2. Research gap

The bed degradation that is currently happening in the Dutch Rhine River and its distributaries is the result of long-term system-wide intervention. Although Rhine River and its distributaries are well-mapped regarding historic bed degradation, future prognoses are mostly based on statistical historical trends (e.g. Visser, 2000; Blom, 2016; Ylla Arbós et al., 2019) and to a limited extent based on modelling (e.g. Paarlberg & Van Lente, 2021). In addition, sediment supply in the Rhine River becomes coarser due to nourishments in Germany, leading to a degradational wave downstream of the advancing gravel front (Frings et al., 2019; Ylla Arbós et al., 2021). There is currently no quantitative indication about how the situation will develop for the coming decades: a quantification of the large-scale and long-term development of the current situation regarding bed level development under autonomous conditions is missing.

Zuijderwijk et al. (2020) suggested that it is possible to implement side channels along large stretches of the distributaries of the Dutch Rhine River in order to mitigate bed degradation. Although the development of side channels is well-studied by amongst others Mosselman (2001), Van Denderen (2019) and Meijer et al. (2020), limited research effort has been put in the development of the main channel bed as a result of side channel implementation. The contribution of side channels to mitigate main channel bed degradation depends partly on their relative positioning (Oldenhof, 2021) and on their size. Research of Rudolph (2018), Barneveld (2019) and Welsch (2021) has shown that (a combination of) interventions is effective to mitigating bed degradation, but that additional (soft) measures such as nourishments are still necessary. However, no scenario-based quantification has been made for where interventions of different sizes are implemented. A quantitative assessment of large-scale side channel implementation is necessary to determine the range of effectiveness of side channel implementation in order to mitigate bed degradation. Such a quantification is necessary to better design the river interventions (such as side channels) that are likely to be implemented through the politically driven river management programmes such as IRM and RfLR.

Research of e.g. Gensen et al. (2020) has shown that interventions close to bifurcation points have hydrodynamic effects in both the distributaries. Since hydrodynamics and morphodynamics are closely related (Janssen, 1979), it is crucial to take both distributaries into account in assessing the morphological impact of interventions close to the bifurcation points. Therefore, when assessing the long-term effects of large-scale implementation of side channels, the effects should be quantified on a system-wide scale. Such a quantification will help to understand the system behaviour of the Rhine and its distributaries and its response to human interventions.

1.3. Research objective

The first objective of this research is to quantify the long-term and large-scale morphological development of the main channel bed of the Dutch Rhine and its distributaries under autonomous conditions, while regarding the Dutch Rhine distributaries as one coherent river system. This river system spans a part of the German Rhine River from Wesel (rkm 814) up to the Waal River at Hardinxveld (rkm 962), the Lek River at Krimpen (rkm 980) and the IJssel River at the Ketelmeer (rkm 1004) as visualized in Figure 1.2.

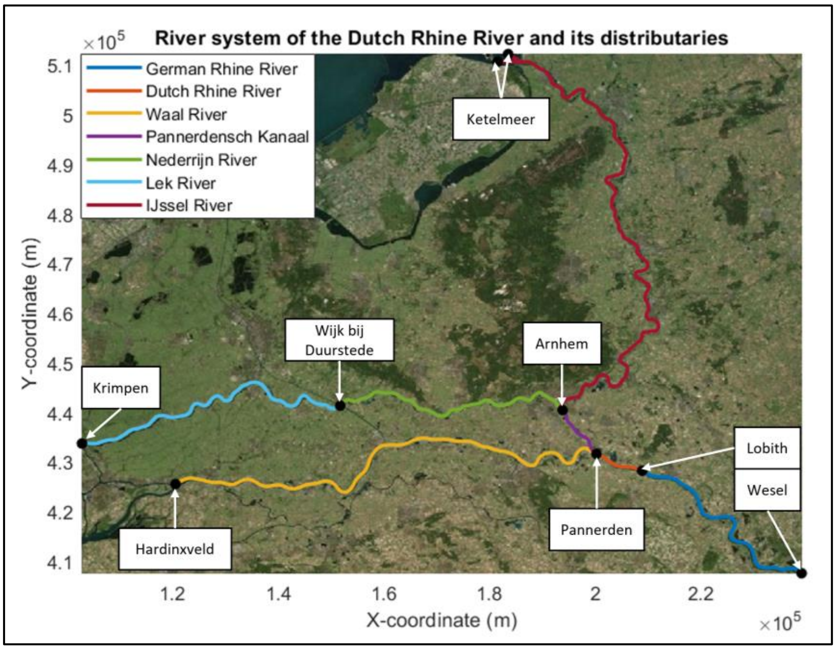

Figure 1.2: The river system of the lower German Rhine (from Wesel onward) and Dutch Rhine River including its distributaries.

Long-term morphological development includes development from the time of implementation of side channels up to 100 years after the implementation. Large-scale morphological developments are classified as morphological features with a typical length of more than several hundreds of meters and do not include local bed forms such as river dunes (Chavarrias et al., 2020). In order to run a sufficient number of scenarios within the available time frame, it is preferred to do a 1D analysis for a 100 year simulation period. A quantification of the autonomous bed development is useful to determine whether the historical bed development trends continue for the coming century and to set a reference frame to determine the effect of human intervention.

The second and main objective of this research is a quantification of the long-term and large-scale morphological effects that implementation of side channels have on the autonomous main channel bed development. By investigating the effect of several cases of side channels that become active at various discharge stages it is possible to quantify the potential of side channels to compensate for long term main channel bed degradation.

To achieve the research objectives, the following main research question has been formulated:

"To what extent can implementation of side channels reduce the autonomous long-term large-scale main channel bed degradation in the Dutch Rhine River and its distributaries?"

With the following sub research questions:

1. How does the main channel bed of the Dutch Rhine River and its distributaries develop over the coming 100 years under autonomous conditions?
2. How does the main channel bed of the Dutch Rhine River and its distributaries develop over the coming 100 years for different cases where side channels are implemented along one of the distributaries?
3. How does the main channel bed of the Dutch Rhine River and its distributaries develop over the coming 100 years for different cases where side channels are implemented along several distributaries?

1.1. Thesis outline

The thesis report is structured in the following way: Chapter 2 explains the relevant theoretical background regarding simplified river morphology as well as the state-of-the-art of ongoing research programmes. Chapter 3 structures the research methodology that was followed to formulate answers on the research questions. Chapter 4 presents the results of autonomous main channel bed development over the coming 100 years. Chapter 5 presents the results that side channels and their combinations along different distributaries have on main channel bed development over the coming 100 years. Chapter 6 discusses the methodology, results and general uncertainties. Chapter 7 lists the main conclusions and sets recommendations for further research. References provides an overview of all sources cited in this report. In the appendices additional figures are present that help to understand how the results and conclusions. The outline of the thesis report is also given in Figure 1.3 including research questions and corresponding appendices.

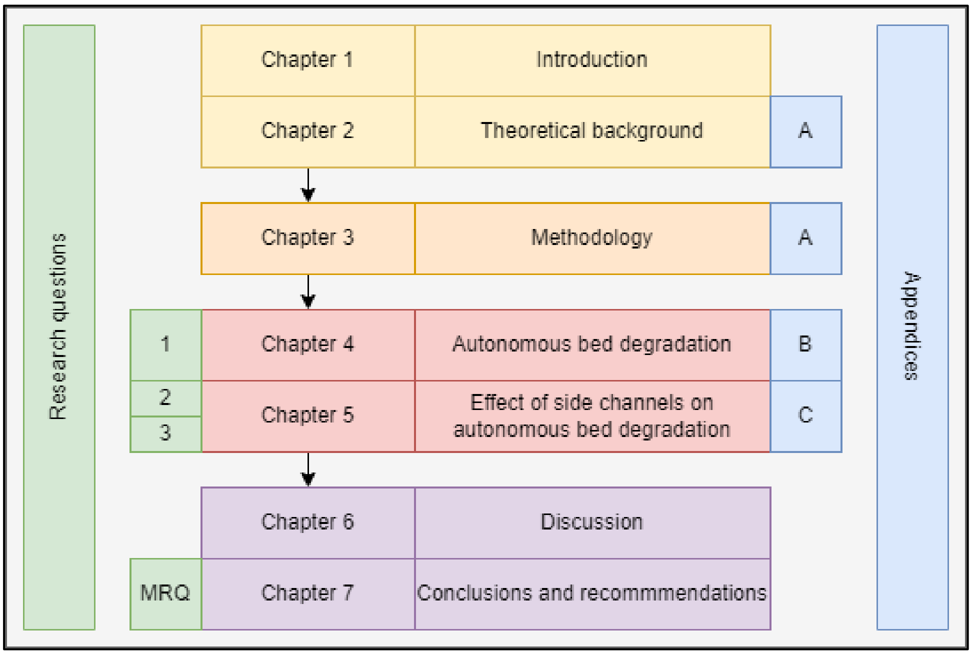

Figure 1.3: Outline of thesis report including research questions and appendices.

2. Theoretical background

This chapter explains the relevant theoretical background that is necessary to understand the followed methodology that is followed to answer the research questions. It starts by an introduction how rivers can be simplified and schematized. Next, a brief explanation about the modelling of river morphodynamics is given, followed by the short- and long-term effects of side channels on river morphology. Lastly, the chapter addresses recent river management and river research programmes and their main objectives and conclusions.

2.1. Schematizing rivers

Rivers come in all sorts and sizes, but all rivers have one thing in common. All rivers discharge water and sediments (Jansen, 1979; Ribberink, 2011). Rivers are more or less equal in the processes that influence them. All rivers have a certain channel pattern, which consists of a channel width, channel slope and bed roughness due to sediment composition and vegetation (Jansen, 1979; Ribberink, 2011). Furthermore, all rivers have a flood regime through meteorological influences that causes the discharge of water. Lastly, rivers have a sediment supply, which consists of the amount of sediment as well as sediment grain sizes of both present and incoming sediments. The relation between the discharge of water, sediments as well as the bottom profile (and channel pattern) is complex, and can be characterized in the morphodynamic loop (Figure 2.1). The flow of water initiates sediment transport along the river. Based on erosion or deposition of sediment, the channel pattern changes, which in term changes the (local) flow conditions and the sediment transport capacity of the river (Jansen, 1979; Ribberink, 2011). Therefore, the morphological loop can be considered a feedback loop.

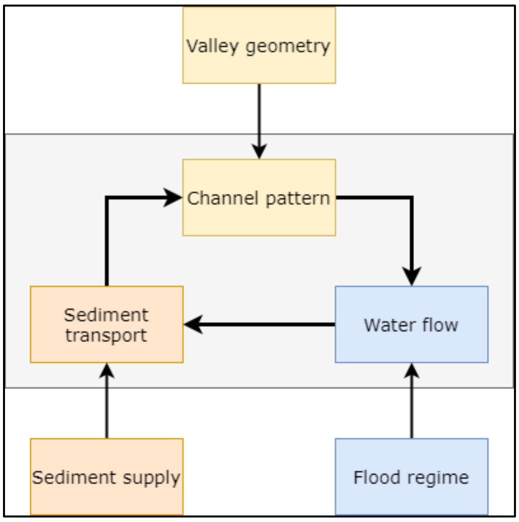

Figure 2.1: The morphodynamic loop (Adapted from Ribberink, 2011).

Cumulative and cyclic effects lead to a state of the river system. If the controls are sustained (or change slowly relative to the timescale of channel response), the channel ultimately achieves an equilibrium (or quasi-equilibrium) state (Arkesteijn et al., 2019). Interruption in one of the controls (e.g. the flood regime, sediment supply or valley geometry) leads to changes in this state. If the imposed changes are small, the river adjusts itself back to the original stable state. However, if sudden large changes in the flood regime occur (e.g. a large flood), a sudden shift in sediment supply (e.g. large structural nourishments), or structural changes are made to the river bathymetry (e.g. through human interventions), the river shifts its equilibrium and will move towards a different state. This is currently happening in the Rhine too, as a consequence of the interventions of the last two centuries, which results in the current bed degradation (Visser, 2000; Frings et al., 2014).

Rivers often have quite irregular shapes, which causes complex three-dimensional and nonlinear hydrodynamics. Together with the nonuniform sediment grains this lead to high computational demands to simulate the 3-dimensional nature of rivers. Therefore, there is a tendency to simplify the 3-dimensional nature of rivers into 2D or 1D models. A schematization in longitudinal direction and a schematization in cross-sectional direction is considered below.

Longitudinal schematization of a river

Characteristically, a rivers length is much larger than its width. Therefore, there is a tendency to neglect the width and schematize the river as links between several nodes. Bifurcations or confluences are schematized as multiple links connected to a single node, resembling the different (dis)tributaries of the river. Every link in the river is characterized by a roughness value (e.g. Chèzy, Manning or Nikoradse), a bed slope and (in case of a morphological schematization), a sediment composition (Sloff, 2006).

Cross-sectional schematization of a river

In cross-sectional direction, an engineered river can be schematized as follows. Usually, a river consists of a main channel (including groynes) and one or two floodplains followed by an embankment. Sometimes, small embankments are present in order to maintain the summer peak flow through the main channel. Figure 2.2 shows a schematization of a river with the key features and the cross-section outline in red. For most rivers, the average depth is much smaller than the width, which means that the hydraulic radius can be approximated by the average depth. A common assumption is to use compound flow resistance, where the roughness of the main channel differs from the roughness of the floodplains. This is indicated by the thickness of the horizontal red line in Figure 2.2.

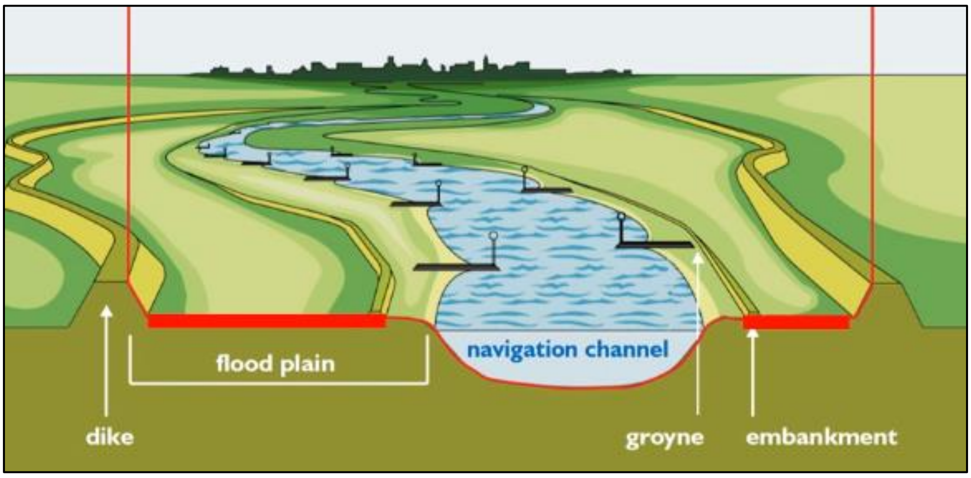

Figure 2.2: Schematization of a river in cross-sectional direction (Deltares, 2022). Thicker red lines over the floodplains indicate higher roughness values than the thinner red line over the main (navigation) channel.

A 2D approximation is obtained by either averaging the cross-section over the depth of the river (2DH) or by averaging the cross-section over the width of the river (2DV). By averaging over the entire cross-section a 1D schematization is obtained (De Vries, 1975). In practice, 1D models are broadly used in river hydraulics. 2DH models are used for water bodies where water depth is small compared to typical wavelengths, such as estuaries, fjords and the coastal near-shore. 2DH models are also used such when detailed hydrodynamics are of interest, in for example WAQUA-simulations to assess local hydrodynamic impacts of interventions. Due to the complexity involved in the calibration process and the high computational costs, 3D models are seldom used in river engineering (Winckler, 2015).

2.2. Modelling river morphodynamics

The morphodynamic behaviour of rivers is of increasing interest for river managers. Therefore, a lot of research is put into developing models that accurately predict morphodynamic development of rivers (Van der Klis, 2003). It is often impossible to eliminate processes in the field. Pilots are expensive and due to the inability to replicate local conditions it is nearly impossible to optimize using different scenarios. Scale models, such as laboratory experiments, can help to minimize the variability of conditions, but the translation from a small-scale model to a large-scale field intervention is often hard. In general, time acceleration in physical (scale) models is not possible. For these reasons, river managers tend to use numerical models that simulate the relevant physical phenomena of the given situation (Jansen, 1979; De Vries, 1975).

The basis for numerical modelling are the equations that describe the processes of the morphological loop. Using the idealized 1D schematization of a river bathymetry, the hydraulic processes can be described by a momentum equation (Eq. A.1 in Appendix A.1) and a continuity equation (Eq. A.2 in Appendix A.1) (Jansen, 1979; Ribberink, 2011). Sediment can either be transported as bed load, suspended load or wash load. For all different modes of transport empirical relations exist. In this project only sediment that is transported as bed load or suspended load is considered, since wash load does not contribute significantly to bed degradation. Two widespread used formulas for sediment transport are developed by Meyer-Peter and Muller (1948) for bed load (Eq. A.3 in Appendix A.1) and Engelund and Hansen (1967) for both bed load and suspended load (Eq. A.4 in Appendix A.1). Both formulas depend on a wide number of parameters derived from spatially and temporally averaged local conditions. For channel development, the Exner equation (Eq. A.5 in Appendix A.1) is widely used (Exner, 1920).

River modelling concerns a large variety in spatial and temporal scales. Some processes such as the entrainment and deposition of individual grains have a characteristic length of a few millimeters and a characteristic timescale of a few seconds. However, large scale trends along the entire river can have a characteristic length of tens of kilometers and a characteristic timescale of decades up to centuries. Large rivers seldom attain equilibrium, because response times are much larger than changes of external controls, such as climate change, tectonics and human impacts (De Vries, 1975). This fundamental disequilibrium results in a complex alternations of erosional and depositional patterns along a river’s flow path (Frings, 2019).

2.3. Effect of side channels

Side channels are secondary channels that are connected to the main channel of a river, but are in general much smaller and convey much less discharge than the main channel. Side channels used to be part of natural river systems but have disappeared in the past centuries due to engineering measures, mainly because of canalization and the construction of embankments (Gölz, 1994; Klop, 2009). Since a few decades side channels have been reintroduced into the Dutch Rhine system as part of large-scale integral river management programmes (e.g. Kaderrichtlijn Water, Room for the River, Room for Living Rivers and Integral River Management). Side channels have multiple benefits for flood safety, ecology and can help to mitigate bed degradation (Sloff et al., 2014; Van Denderen, 2019a; Barneveld et al, 2019; Welsch, 2021; Oldenhof, 2021). The concept behind a side channel is quite simple: when side channels start to convey discharge (often only above a certain threshold), the total conveyance area of the river increases, reducing flow velocities in the main channel and therefore reducing the sediment transport capacity which leads to sedimentation in the main channel.

Figure 2.3 shows the initial and long-term morphological response of side channels. Initially, an sedimentation hump can be expected near the intake of the side channel as a consequence of a reduction in flow velocity and therefore a reduction in sediment transport capacity. Likewise, at the confluence of the side channel an initial erosion pit is to be expected due to the sudden rise in flow velocity. Due to backwater effects, initial erosion occurs over a longer reach upstream of the side channel as well as initial sedimentation parallel to the side channel as water levels, flow velocities and the corresponding sediment transport capacity gradually adapt to the new situation downstream. For a long-term equilibrium, the initial sedimentation and erosion hump will migrate downstream and slowly diffuse in space. At the same time, the gradual sedimentation parallel to the side channel will increase until the new equilibrium bed slope and bed level have been reached, while moving upstream until a solid object is reached where sedimentation cannot pass through (e.g. a dam or weir). As a consequence, the erosion that is initially present upstream of the side channel will be replaced by sedimentation in the long term.

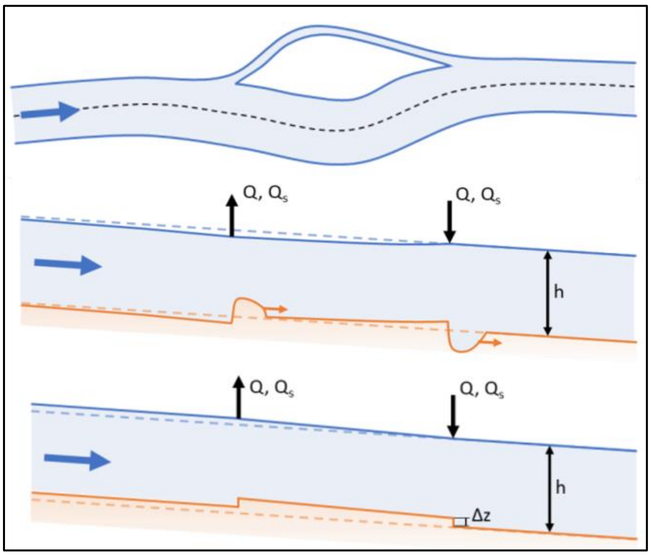

Figure 2.3: Responses of the river bed level to a side channel. Top: Schematisation of side channel. Middle: Initial morphological response of the river. Bottom: Equilibrium morphological response of a river. Adapted from Huthoff, 2020).

2.4. State of the art

Since a few years river managers have shown increasing interests in river morphodynamics. Between 2006 – 2015 a large river management programme called 'Room for the River' has been implemented to increase flood safety along the distributaries of the Dutch Rhine River as a result of the high water events of 1993 and 1995 (Zevenbergen et al., 2015). In addition, spatial quality in the riverine areas has been increased. At 34 locations along the distributaries of the Dutch Rhine River several interventions have been implemented that increased the discharge capacity of the river. However, as each individual intervention has been designed to minimize dredging operations, the combination of a chain of several interventions causes excessive local sedimentation, which increases dredging demands (Van Vuren et al., 2015). Van Vuren et al. (2015) estimates that due to the implementation of Room for the River interventions, annual dredging volumes are expected to increase by 10%. Coupled to the Room for the River programme was the research programme RiverCare, which aimed to investigate the consequences of the interventions on the river system of the Dutch Rhine River and its distributaries. The knowledge that is gained through this project is used to cut maintenance costs and better design future interventions (NCR, 2015). Among the implemented interventions were both a pilot concerning longitudinal training dams (LTD's) and side channels.

Three LTD's have been implemented in the Waal River in 2015, spanning a total of 10 km (rkm 911-921). The development of the effects of LTD's has been extensively studied by De Ruisscher (RiverCare, 2015) and Czapiga et al. (2022b). LTD's reduce water levels during high discharges and increase water levels during low discharges, enhancing both flood safety and navigability of the Waal River. In addition, LTD's contribute towards mitigation of bed degradation rates, as water is extracted from the main channel, but bed material load is not, which leads to more available sediment in the main channel Czapinga et al., 2022).

Similarly to LTD's, side channels can reduce bed degradation rates as well. The effectiveness of side channels to mitigate bed degradation depends on multiple variables. In general, side channels have a tendency to fill up with sediment and require periodic dredging, which is costly. The degree of sedimentation of secondary channels is dependent on the frequency and cumulative duration that secondary channels are active. (Meijer et al., 2020). Van Denderen (2019a) studied the behaviour and development of side channels in the Dutch rivers. He found that, amongst others, the length difference between downstream channels affects side channel development. If a side channel is much shorter than the main channel (i.e. when the channel is located on the inside of a river bend), it can develop into the dominant branch. In addition, sediment sorting at the channel intake and varying hydrodynamic conditions have large effects on side channel development as well. Van Denderen et al. (2017) also found that spiral flow may increase the sediment load to one of the channels and that the transverse bed slope upstream of the bifurcation point can stabilize a side channel system. Hydrodynamic conditions in a side channel can be altered using a discharge regulatory structure with a sill at the intake and outflow of a side channel. It is also possible to change the angle of offtake between the main channel and side channel in order to reduce discharge and sediment supply to the side channel (Hooijer et al., 2007). For side channels in the Waal it has been studied if navigation is hindered as a result of lateral currents due to in- and outflow of side channels. Despite the relatively high discharge through a side channel this does not pose a threat, which is likely due to dispersion of the flow currents into the groyne fields adjacent to the in- and outflow points of side channels (Hooijer et al., 2007). Oldenhof (2021) studied the effect of sequential and overlapping side channels. She found that two overlapping side channels create a sediment hump and that two side channels in short succession will create a scour hole. In addition, temporal fluctuations of the bed are less for two overlapping side channels than for two successive side channels. The mechanisms that define side channel behaviour are unique for each side channel and can vary in time. Van Denderen et al. (2019b) concluded that the mechanisms that affect side channels in gravel- and sand rivers are quite similar.

As successor for RiverCare, the research programme Rivers2Morrow has been started (NCR, 2018). Rivers2Morrow investigates how lowland river systems such as the Dutch Rhine River and its distributaries respond to changes in forcings. Examples of forcings are consequences of climate change (resulting in different discharge patterns and sea level rise), anthropological intervention and upstream sediment changes. Two contributors to this research programme are Gensen, who focusses on the dynamics around bifurcation points and Ylla Arbós, who focusses on sediment issues in the upper delta of the (Dutch) Rhine River (NCR, 2018).

As successor of the Room for the River programme, the Dutch government has initiated the IRM programme (Bouwplaats IRM, 2021). A key difference with the Room for the River programme is that IRM focusses on a longer timescale (at least 2050, and up to 2100) and includes more river functions than flood safety and spatial quality. Currently, several alternatives for the IRM programme are investigated without major quantification of dimensions and effects. It is expected that the preliminary investigation of these alternatives is finished at the end of 2022, and that preferred alternatives are chosen in the third quartile of 2023 (Bouwplaats IRM, 2021).

With the IRM programme coming up there is, an ongoing debate on how such an integral river management vision can be achieved. One of the visions for IRM has been developed by the World Wide Fund for Nature, which is called Room for Living Rivers. This vision includes an integral approach with a focus point on extracting discharge from the main channel if the minimum navigation depth is exceeded (Barneveld et al., 2019). As a result, sediment transport capacity is reduced, which mitigates the ongoing bed degradation rates. Preliminary studies to the effects of the chain of interventions from Room for Living Rivers show a serious reduction of the necessary dredging volume up to 33% (Barneveld et al., 2019). Currently, these studies have been limited to the middle reaches of the Waal River (Barneveld et al., 2019; Welsch, 2021).

3. Methodology

This chapter provides an overview of the followed methodology to answer the research questions. It starts with choosing a suitable model and a description of that used model. Next, the a verification is made about the quality of the model to simulate long-term morphological development of the Dutch Rhine and its distributaries. The chapter continues with the methodology followed to answer the research questions including argumentation of choices. Finally, the chapter provides an overview of the executed simulations.

3.1. Model choice and model description

The project considers numerous simulations to assess large-scale and long-term main channel bed development under influence of side channels. Due to computational and temporal constraints, it is opted to use a 1D analysis. Generally, a 1D approach is appropriate to provide a first insight into the large-scale river system response under autonomous conditions and under conditions induced by river engineering works (e.g. side channels). In a later stage, a more advanced type of model might be more appropriate at locations of special interest (Van Vuren, 2005).

In the Netherlands, the most commonly used 1D software modelling packages are SOBEK and Delft3D, both made by Deltares (Deltares, 2021). The latest generation of Delft3D software is Delft3D Flexible Mesh (Delft3D FM), which is currently under beta-release. In addition to features from SOBEK (SOBEK-Rural/Urban/River and SOBEK-RE), Delft3D FM also includes features from Duflow, Simona (Waqua, Triwaq) (Deltares, 2021). Delft3D FM is an integration software that couples modules for water flow (D-Flow FM), morphology (D-Morphology) and real time control of hydraulic structures (D-RTC) (Deltares, 2021). For this project, Delft3D FM Suite 2021.04 is used, including the modules D-Flow FM, D-Morphology and D-RTC. Delft3D FM Suite 2021.04 numerically solves the unsteady shallow-water equations and uses the hydrodynamics to calculate sediment transport and bed level development using Eqs. A.1 – A.5 from Appendix A. (Chavarrias et al., 2020). Real-time feedback mechanisms are available to simulate the operation of major hydraulic structures, such as weirs at Driel, Amerongen and Hagestein (Chavarrias et al., 2020).

The model of choice is a 1D-model of the Dutch Rhine River distributaries. This 1D model has been created by Deltares to specifically evaluate the long-term and large-scale morphological effects of interventions and changes in forcing in the Rhine River distributaries in the Netherlands, such as climate change and changes in upstream sediment composition (Chavarrias et al., 2020). The interest of the model is to predict morphodynamic change in the main channel. Depositional processes in the floodplain are out of the model scope. Physically, the assumption that morphodynamic development is only occurring in the main channel translates to permanent dredging of the side channels and floodplains to prevent any sedimentation.

The model consists of the three main Rhine River distributaries in the Netherlands; the Waal River, Nederrijn and Lek Rvers and IJssel River. Furthermore, the Pannerdensch Kanaal and part of the German Rhine Riverare included in the model as well. The upstream boundary is located at the confluence of the Rhine River and the Lippe River, near Wesel (Germany) and downstream boundaries are formed near Hardinxveld (Waal River), Krimpen a/d Lek (Lek River) and the Keteldiep and Kattendiep just downstream of Kampen (IJssel River). Furthermore, the model has lateral inflows from smaller streams at 20 locations, most of which flow into the IJssel River. The domain of the model is given in Figure 3.1. In addition, the model includes the bifurcations near Pannerden and Arnhem as well as the weirs near Driel, Amerongen and Hagestein. Bathymetry of the model is derived from SOBEK-3 schematizations which represent the situation of 2019 for the Dutch parts of the model and the situation of 2012 for the German part of the model. These schematizations have been simplified by removing flood channels, structures and retention areas. The features 'extra resistance' and the D-RTC parameters have been corrected as well. After that, the schematizations have been merged into one large schematization where space steps have been increased to approximately 500 m and the model has been converted to D-Flow FM 1D. In addition to the simplifications and merging, the model also has been straightened. D-Flow FM 1D uses a 2D numerical solver, which causes energy losses due to streamline curvature. The 2D solver requires a large amount of grid cells per bend to not simulate unrealistically high energy losses. By straightening the model both the unrealistic high energy losses as well as the small space step are prevented. Chavarrias et al. (2020) also adjusted the Chézy and Manning friction values (for respectively floodplains and main channel) as well as the main channel width and storage area, as there were problems with the numerical schemes between SOBEK 3 and D-Flow FM 1D. Morphological parameters have been implemented according to the schematizations of Sloff (2006). Hydrodynamic parameters have been calibrated using a comparison with steady-state WAQUA simulations from 1995-2011 and validated using simulations from 2011-2019 (Chavarrias et al., 2020). Because the model focus lies on simulating accurate morphological development of the main channel, the calibration of hydrodynamic parameters has only been done to mimic the important hydrodynamic parameters for sediment transport. Therefore, inaccuracies in water level of several centimeters up to a decimeter are common (Chavarrias et al., 2020).

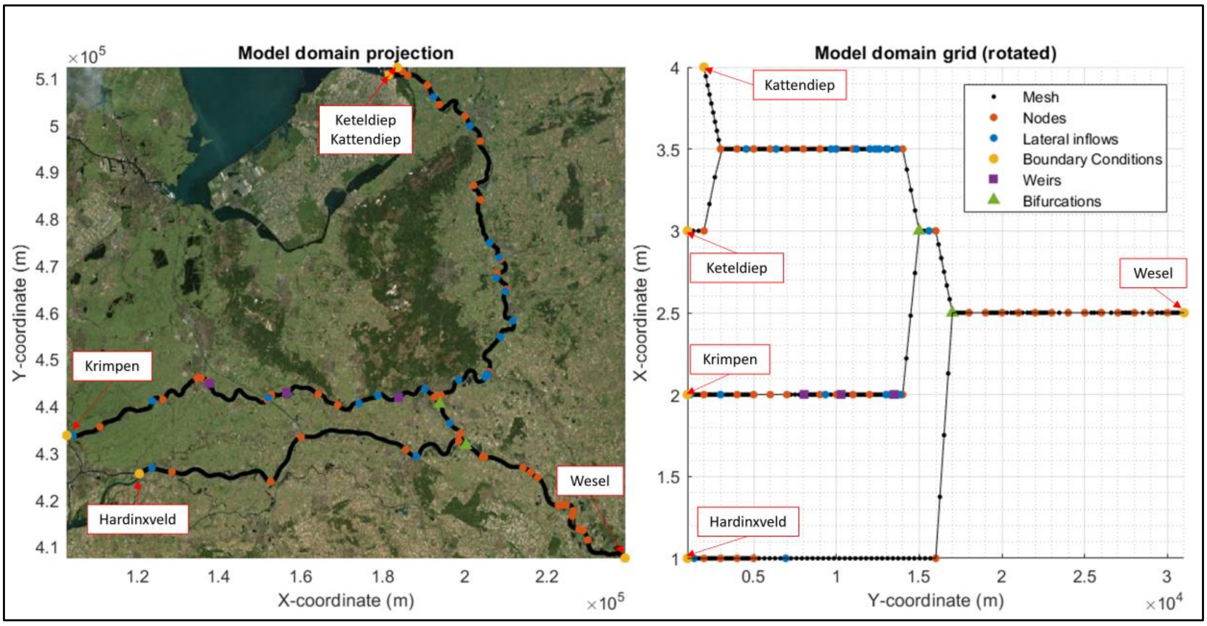

Figure 3.1: Domain of the model including boundaries and key locations. Left side: Projected model domain on a spatial map. Right side: Actual model domain. Figure created from model projections on Google Maps.

By default, 16 different sediment fractions are present in the model based on Sloff (2006). 8 fractions are modelled as sand and 8 fractions are modelled as gravel. Grain sizes of the sediment fractions are given in Figure 3.2. The smallest fraction has a characteristic grain size which is near the silt range ($D = 7.5 * 10^{-5}$ m) and the largest fraction has a characteristic grain size which is towards the cobble or boulder range ($D = 1.8 * 10^{-1}$ m). For the gravel fractions, the Meyer-Peter and Muller (1948) bed load transport formula is used (Eq. A4a). For the sand fractions, the Engelund and Hansen (1967) bed material load formula is used (Eq. A3a), which includes both bed load transport and suspended load transport. However, since the focus of the model lies on main channel morphological development and excludes floodplain- or side channel dynamics, the sediment transport resulting from this formula is modelled as bed load transport (Chavarrias et al., 2020).

For the bifurcations at the Pannerdensche Kop and IJsselkop a nodal point relation is used to determine the ratio of sediment partitioning as a function of discharge partitioning, where discharge partitioning is calculated as a function of local water levels and cross-sectional flow area. By default, the nodal-point relation from the original schematization of Sloff (2006) is used, which is given in Eq. A.6 in Appendix A.1. The nodal point relation has been calibrated by Chavarrias et al. (2020) for both sand and gravel fractions at each bifurcation to mimic the estimated annual sediment transport loads from Frings et al. (2019), which stem from a long-term analysis of the Rhine River's sediment budget. It is noted that the nodal-point relations are unstable for a steady-situation, as described in Wang et al. (1995) and Schielen & Blom (2018).

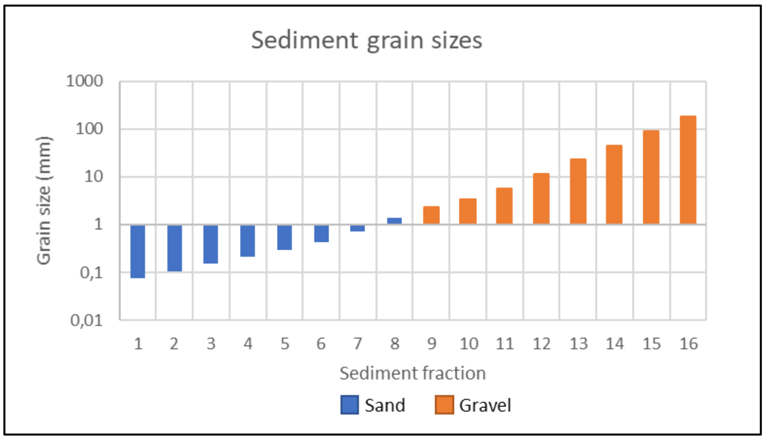

Figure 3.2: Default modelled sediment fraction grain sizes (based on Sloff, 2006).

The default initial bed composition is made up of 10 layers, of which the top layer has a thickness of 0.5 m and the underlayers each have a thickness of 0.4 m. Grain sizes of the top layer based on Sloff (2006) is used. Data about the substrate was not available, so it is assumed that the underlayers have the same grain size distribution as the top layer (Chavarrias et al., 2020). Fixed layers are prescribed by a lack of available sediment, which is simulated by setting the thickness of the substrate layers to 0.0 m. The model uses an active layer thickness of 1.0 m, meaning that only sediment from the layers which are less than 1.0 m below the top of the bed can be set in motion (Chavarrias et al., 2020). The default morphological boundary condition of the model is that the bed level position and the bed level composition at Wesel is fixed. Chavarrias et al. (2020) and Paarlberg & Van Lente (2021) notet that for long-term morphological simulations the model becomes unstable due to the combination of morphology and weir operation. To stabilize the model, a condition is imposed around the weirs that limits morphological development. Physically, the condition comes down to permanent dredging around the weirs to prevent erosion or sedimentation.

3.2. Model calibration and verification

Chavarrias et al. (2020) have calibrated the model thoroughly in order to reproduce mean annual sediment transport load as well as bed level elevation. Two sets of simulations are performed by Chavarrias et al. (2020) to calibrate, finetune and validate the model. The first set of simulations focusses on large-scale morphodynamic trends (for a period of 10-20 years) using the observed discharge time series at Lobith from 1994-2011 and both the schematization based on the bathymetry in 1995 (excluding 'Room for the River'-interventions) and the bathymetry in 2011 (including 'Room for the River'-interventions). Aim of the simulation was to calibrate the nodal point relations as well as the sediment transport equations to mimic the annual sediment transport load and sediment distribution at the bifurcation points based on Frings et al. (2019). Additionally, the main channel bed evolution and grain size changes (geometric grain size and D_{50}) were used as calibration objectives as well. Both the bathymetry of 1995 as well as 2011 has been used to separate the large-scale morphodynamic trends from local interventions. The second set of simulations focusses on the effects of interventions, such as the large scale ‘Room for the River’-project using both the schematization based on the bathymetry in 2011 and in 2019 as well as the observed discharge time series at Lobith from 2011-2019. Aim of these simulations is to validate the trends observed in the first set of simulations and apply local fine tuning at locations where ‘Room for the River’-interventions have been implemented. Like for the first set of simulations, main output consisted of main channel bed evolution, annual sediment transport loads at bifurcations and grain size changes.

As verification of the correct model settings, the second set of simulations using the 2011 – 2019 Lobith discharge time series and 2019 bathymetry has been re-run. No significant differences were found. Furthermore, several runs were conducted using a stepped hydrograph, fixed downstream water level as well as removing the lateral inflow discharges as means of sensitivity analysis. The tidal range is approximately 2.0 – 2.5 m. Lateral inflow sources generally make up less than 5% of the total (cumulative) discharge.

No significant differences in bed level development were found between the tidal time series and fixed water level. Minor differences were found between simulations with and without lateral inflow discharges, which were mostly located in the IJssel River (up to 0.20 m), as it discharges most of the water that lateral inflow sources provide. Significant differences in bed level evolution (up to 0.60 m) were found when changing the upstream time series hydrograph to a stepped hydrograph. The conclusion of this simulation is that the system of the Rhine River and its distributaries is dominated by the upstream boundary condition for short to mid-term analysis

Since the start of the research project no long-term simulations have been performed by Chavarrias et al. (2020) and the study of Paarlberg & Van Lente (2021) was not publicly available. Therefore, a verification run has been done to assess the long-term behaviour of the system and to gain insight in the effect of the initial conditions on the long-term model results. For this run a stationary upstream discharge of 2250 m^3/s has been used, as it is the long-term annual average discharge near Lobith for the period of 1994-2020. Downstream boundary conditions consist of the long-term average water levels of the Waal River (0.93 m+NAP), Lek River (0.80 m+NAP) and Ketelmeer (0.0 m+NAP) of the same period. Lateral inflows have been ignored in this run. The initial bathymetry is represented by the 2019 schematization.

3.3. Determining autonomous bed degradation

To answer the first research question the model has been set up to simulate the autonomous bed degradation of the Dutch Rhine River and its distributaries over the coming 100 years if no further human interventions are implemented. For this, the default model settings of Chavarrias et al. (2020) were used. However, boundary conditions are slightly changed to obtain settings that span a 100 year period.

The default boundary conditions near the upstream model boundary consists of a historical discharge time series of the Rhine near Lobith with an interval of 24 hours. The measurements of the hydrograph originate from the Landelijk Meetnet Water (Chavarrias et al., 2020). Since there are no major inflows between Wesel and Lobith, it was deemed sufficient to use this hydrograph. Lead time is ignored, since daily discharge values are used and the distance between Wesel and Lobith is not that large (ca. 50 km). In addition, flood wave propagation is not of interest for this research project. The upstream hydrograph is given in Figure 3.3. In total, four cycles of the observed time series have been used in order to obtain boundary conditions that span a 100 year period.

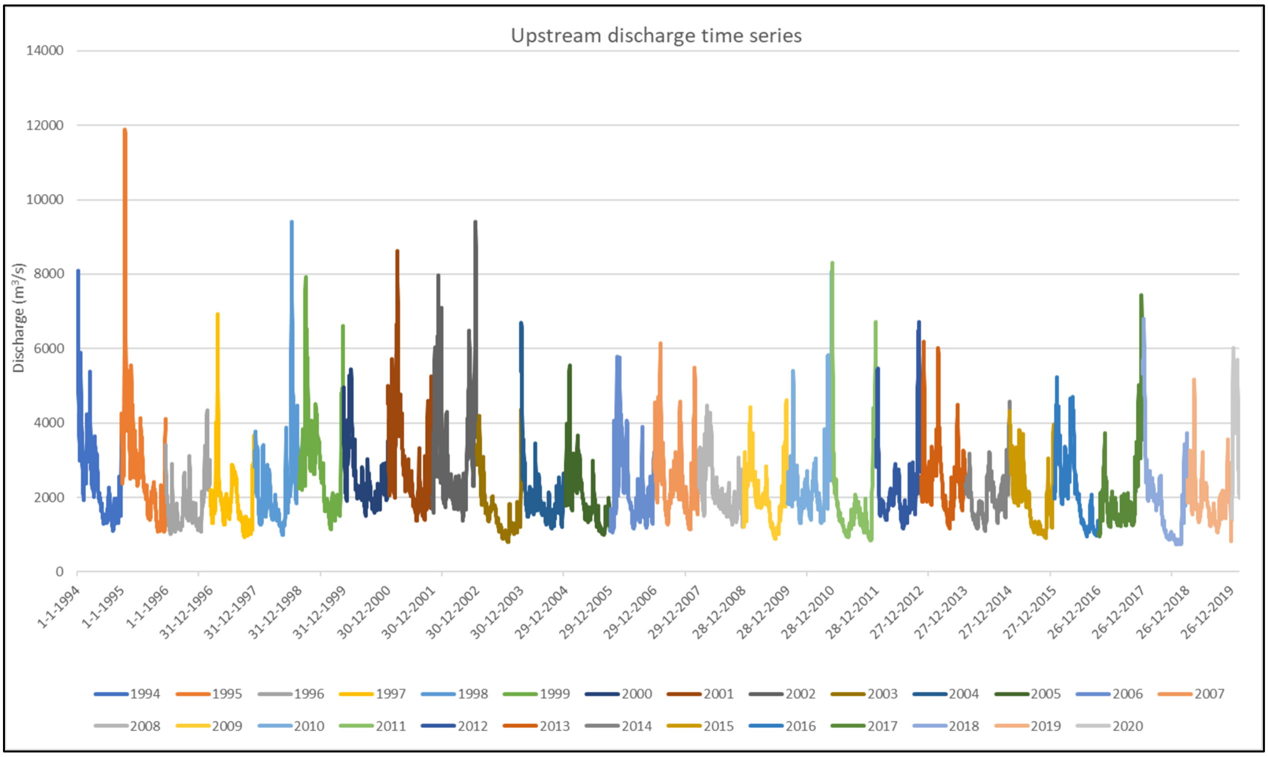

Figure 3.3: Upstream observed discharge time series at Lobith from 1994 – 2020.

Downstream boundary conditions consist of corresponding historical water level measurements near Krimpen a/d Lek (Lek), Hardinxveld (Waal) and Keteldiep and Kattendiep (both IJssel). Measurement frequency of the water level time series are 10 minutes for tidal boundaries (Waal and Lek) and 12 hours for non-tidal boundaries (IJssel). Lateral boundaries consist of 20 different discharge time series with constant intervals between 60 and 720 minutes. Like with the upstream boundary, four cycles of the downstream water levels and lateral discharge time series have been used to obtain boundary conditions that span a 100 year period. Climate change effects such as sea level rise and long-term discharge variability are not taken into account, since inclusion of several climate change scenarios would lead to a disproportional amount of simulations for the available time frame of the research project.

Initial conditions consist of the bathymetry schematization of 2019, which includes the interventions of the 'Room for the River'-programme. The schematization is identical as the one that Chavarrias et al. (2020) used to calibrate and validate the model.

Model output consists of the main channel average bed level values at roughly every 500 meters. In addition, grain size data of the 10th (D_{10}), 50th (D_{50}) and 90th (D_{90}) percentile as well as the mean (D_m) and geometric grain sizes (D_g) are computed. In addition, the model computes sediment transport values of all sediment fractions. Output frequency has been set to store model output once per simulated year in order to prevent the output files from becoming excessively large. Some of the model output variables (e.g. water levels and flow velocities) show large fluctuations between the years as a result of their short adaptation time. Therefore, these variables can only be used to compare between scenarios, but not to assess the development over time within a single simulation.

The averaged main channel bed level development can be compared against bed level trends of Ylla Arbós et al., (2019), which has also included an extrapolation of the bed level position in 2050 based on trends of the past 5, 10 and 20 years as a means to obtain insights in the development of long-term large-scale bed degradation patterns. In addition, results are compared to the study of

Paarlberg and Van Lente (2021), who have conducted a similar analysis using the same bathymetry schematization, but different boundary conditions. They used a 100 year observed discharge time series (1916 – 2016) as upstream boundary and corresponding non-tidal rating curves as downstream boundary. Lateral inflows were ignored in this study. Comparison to both studies strengthens the credibility of the model to translate the current state of the river system into a long-term state as well as a partial sensitivity analysis into variables that dominate the river system for longer timescales.

3.4. Determining the effectiveness of side channels in reducing bed degradation

To answer the second and third research questions, the initial bathymetry of the reference run is changed to include side channels. The following sections explain: 1) how side channels are schematized in the model; 2) how the width and depth of side channels are parametrized in order to obtain side channel schematizations that become active at different discharge stages; and 3) how suitable locations are determined based on suggestions of Zuijderwijk et al (2020). There are multiple ways of implementing side channels in the model. This chapter only treats the schematization procedure that was followed in this research project and the procedure followed by Paarlberg & Van Lente (2021), as they used the exact same model as is used in this study. Other possible ways to implemented (and their effects on the results) are treated in the discussion.

3.4.1. Schematization of side channels

Cross-sections in a the model are divided in a main channel and a floodplain. Side channels can be implemented by changing the cross-sectional geometry of the river. In the field, part of the floodplain is excavated to form a side channel. This can be done for model cross-sections too. When this is continued for any number of cross-sections and foreseen with a start and end point that are attached to the main channel, a side channel is created.

Paarlberg & Van Lente (2021) have drawn side channels in GIS and exported these drawings to Baseline. From Baseline, they conducted 2D simulations using WAQUA to determine flow velocities and water levels for different discharges. In addition, they determined roughness values from the Baseline schematizations as well, which were exported to 1D SOBEK-profiles. From SOBEK, the profiles were converted to 1D Delft3D FM schematizations.

However, for this thesis project there is only a limited amount of time available and due to a large number of side channels following the same procedure is unfeasible. Therefore, it has been chosen to directly change the Delft3D FM 1D-profiles. Cross-section profiles in the field (Figure. 3.4, left side) are different from cross-section profiles in Delft3D FM 1D (Figure 3.4, right side). Delf3D FM 1D uses a flow width - flow depth diagram that must be monotonic (i.e. it is not possible to schematize cross-sections that lie entirely in the floodplain). To model side channels, the main channel is extended with a smaller depth, as it was a partial floodplain excavation. The flow area of the side channel in the model should represent the flow area of the side channel in the field.

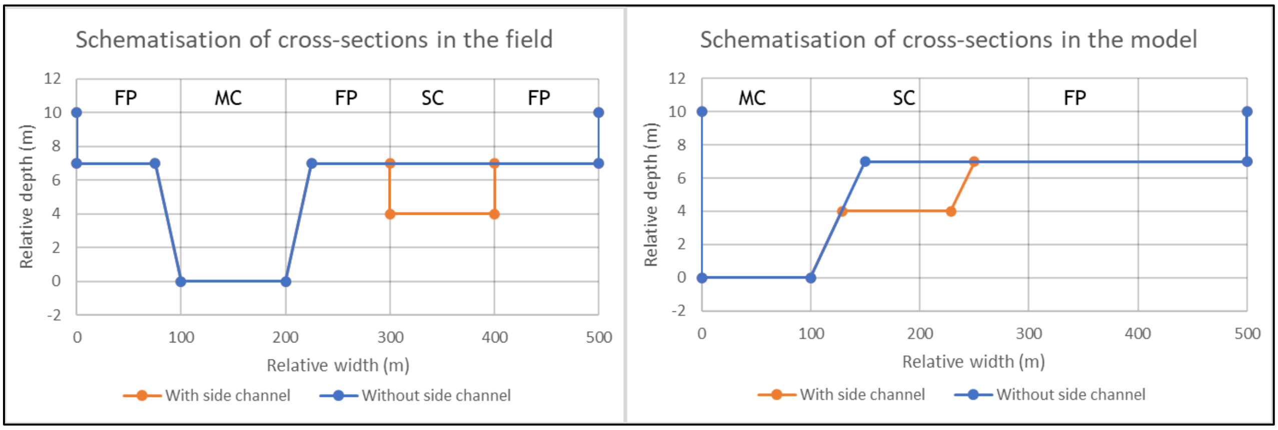

Figure 3.4. Schematization of cross-sections in the field and in the model (including side channels). FP=Floodplain, MC=Main channel and SC=Side channel.

In order to validate the schematization of side channels using this procedure, the cross-sections in the bathymetry schematizations of 1995 and 2019 are compared to each other. Apart from general bed level changes, the main differences in bathymetry between both schematizations are the implementation of the 'Room for the River'-interventions, which included the implementation of side channels at several locations (Chavarrias et al., 2020). There were differences in dimensions found, but the general appearance of side channels implemented in the Room for the River project matches the result that the followed methodology generated to schematize side channels.

The model uses separate roughness values for main channel and floodplains depending on the actual discharge stage. For this project, roughness values in side channels were not changed, as these values are both depending on location and on discharge stage. It was not possible within the available time frame to realistically change roughness values for all cross-sections that were changed in order to simulate side channels. As a result, roughness values of side channels are overestimated as floodplains generally have higher roughness values than side channel. Overall, less water will be extracted by the side channels in the model than would be the case in reality. This is slightly countered by the underestimation of the wetted perimeter, but still a net underestimation of inflow in the side channels is expected than would be the case in reality, resulting in higher flow velocities in the main channel and smaller mitigation of main channel bed degradation.

Due to the monotonic character of the flow width – flow depth diagram, it is impossible to model excessive aggradation in the main channel (Chavarrias et al., 2020). Part of the floodplains is excavated to simulate side channels, resulting in higher flow depths and less opportunity for main channel aggradation. Realistically, excessive aggradation is unrealistic as dredging operations keep the main channel at a minimum depth to facilitate navigation.

Overall, schematizing side channels using the aforementioned schematization is not completely accurate to represent side channels in the field and is likely to generate conservative results that overestimate bed degradation rates. However, within the available time frame and scope of the project, this way of schematizing side channels gives freedom to generate multiple scenarios for side channels that become active at several discharge stages. The parameters that are altered to obtain side channels that become active at different discharge stages are side channel width and side channel bed elevation.

3.4.2. Dimensioning side channels

Altering side channel width and side channel bed elevation can be done in multiple ways. Zuijderwijk et al. (2020) has used standard dimensions set by Rijkswaterstaat in their analysis of possible locations for side channels. All side channels in the Rhine River distributaries have a standard depth of 2.0 meters and a standard width of 100 meters (150 for the Waal River). However, an inspection of the cross-sectional profiles of the model shows that main channel width at some locations (mostly in the IJssel River) does not exceed 100 meters. The inspection of the differences in cross-sections between 1995/2011 and 2019 at locations where side channels were implemented through Room for the River did not show constant side channel widths. This is likely due to the conversion from SOBKEK to Delft3D FM profiles.

Given that the inspection of Room for the River side channels did not result in a constant width and that standardized dimensions set by Rijkswaterstaat are not possible to implement at all locations, it has been chosen to make side channel widths depending on adjacent main channel width. Setting the side channel width comes with a trade-off, since not all floodplains have space for large side channels. Therefore, if side channel width is set too large, it is physically unrealistic to implement longer stretches of side channels, which limits their effectiveness to reduce bed degradation. If side channels width is set too small, it is expected that the contribution of side channels to mitigate bed degradation is negligible. A rather arbitrary value of 25% of the adjacent main channel width has been chosen, which resulted in side channels of 68 - 76 meter wide for the Waal River, 30 - 40 meter wide for the Pannerdensch Kanaal River, and 20 - 35 meter wide for the IJssel River. Side channels in the Nederrijn and Lek Rivers are not necessary, since bed degradation is not problematic in those rivers (Zuijderwijk et al., 2020).

To create scenarios of side channels that become active of different discharges, side channel bed level is set equal to water levels that are exceeded a certain percentage of time. This implies that side channels in the model are schematized without a sill. In reality, side channels usually have a sill in order to prevent excessive sediment transport towards the side channel, resulting in side channel aggradation. However, since the model only focusses on main channel bed development and ignores sediment dynamics within side channels, it is impossible for side channels in the model to aggrade.

Water levels that are exceeded a certain percentage of time are obtained from a cumulative distribution function (CDF), that is constructed using the recorded upstream boundary discharge time series near Lobith from 1994 – 2020. For practical reasons, lateral inflows are ignored as these make up a small percentage of the total discharge. For downstream reaches in general and the the IJssel River in particular, this results in side channels that are active slightly more time than is initially aimed, as most of the lateral inflows are discharging into the IJssel River. Afterwards, discharge values that are exceeded a certain percentage of time are determined that span the entire CDF. As reference, the steps of the standard hydrograph of the DVR model used by Sloff (2011) is used, which are given in Table 3.1. The result are a wide range of side channels that have relatively equal discharge steps, but also a wide range of exceedance frequencies for a sensitivity analysis (see also Figure 3.5). Discharges that occur less than seven days per year (i.e. 6200 m^3/s and ≥8000 m^3/s) are ignored to reduce the number of scenarios, as it is expected that these side channels would do more towards flood safety than to counter bed degradation rates. Quasi-stationary simulations are set up for all discharges to determine the corresponding water levels at all locations in the model. Chavarrias et al. (2020) notes that the inaccuracy of water level prediction can be up to a decimeter. The discharge inaccuracy resulting from this water level inaccuracy is not investigated, since the interest is to obtain a rough idea about the range in which side channels can contribution to mitigation of ongoing bed degradation in the main channel.

Table 3.1: Exceedance frequencies of observed discharges at Lobith between 1994 – 2020.

Upstream discharge (m^3/s)	Percentage of time exceeded (%)	Average number of days that side channel flows (days/year)
1000	97,1	354,6
1600	70,7	285,3
2000	46,3	169,2
2800	20,3	74,1
3600	10,2	37,2
4400	5,0	18,3
5300	2,5	9,2
6200	*1,2*	*4,3*
≥8000	*0,03*	*1,0*

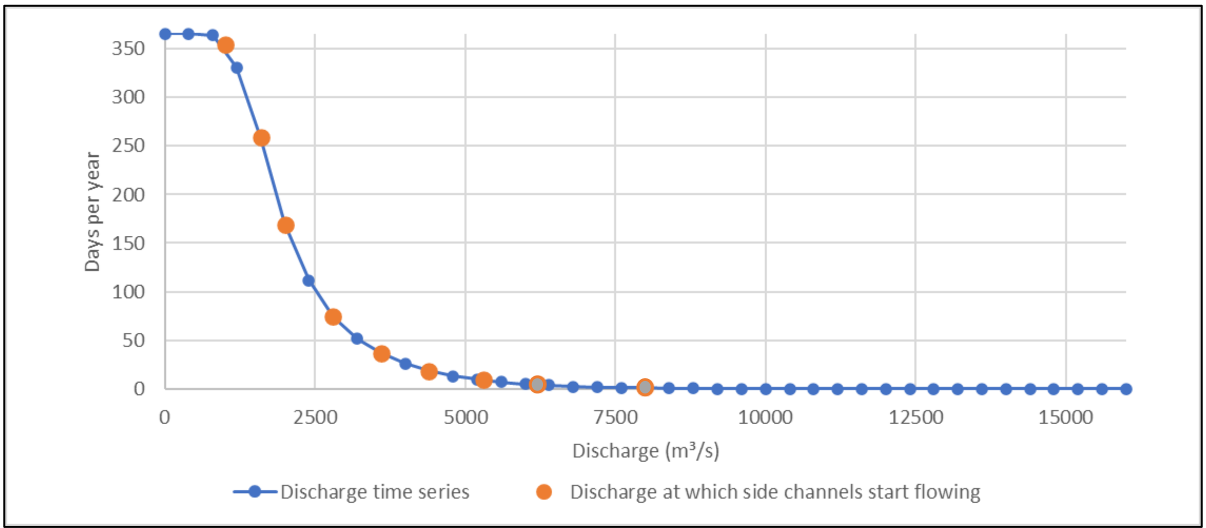

Figure 3.5: CDF of the discharge at Lobith including the chosen discharges for side channels. Grey points indicate discharges that are not taken into account in this analysis.

A parametrization script is used to implement side channels in the cross-sections in the model by excavating part of the floodplain corresponding to 25% of the main channel width to a depth that corresponds with one of the water levels mentioned above. The lowest and highest points of the flow width – flow depth diagram have been interpolated in order to ensure the monotonic character of the cross-section and to maintain the original bank slope.

The current parametrization of side channel schematization implies that discharge in the side channels is not constant over the reach of the side channels. Water levels (and therefore side channel bed elevation) is more or less constant, but main channel width exhibits small variations between cross-sections. As a result, discharge within side channels changes every cross-section. Physically, this comes down to new intake and outflow points for side channel(s) at every cross-section, which is roughly every 500 meters. This would result in a braided pattern of side channels, or that side channels function more like longitudinal training dams with frequent openings. Alternatively, this schematization of side channels can be regarded as a partial (nonuniform) floodplain excavation. An inspection of the width differences between consecutive cross-sections has shown that the differences are generally around 10%, with the exception of the bifurcation areas.

3.4.3. Location of side channels

According to Zuijderwijk et al. (2020), it is not necessary to construct side channels along the entire Rhine River and its distributaries. First of all, bed degradation is not problematic in all reaches of the distributaries of the Rhine River (Table A.3 in Appendix A.2).Recent trends show that in the downstream regions no bed degradation is present but that the bed is stable or even aggrades (Visser, 2000; Ylla Arbós, 2019; Ten Brinke, 2019). It wouldn't be advisable to implement side channels at this location, since any additional aggradation would result in an increase of dredging operations (Zuijderwijk et al., 2020). In addition, at some locations there is not enough physical space in the floodplain to excavate side channels, there are obstructions such as bridges, or there have been previous interventions that make the implementation of (additional) side channels not a realistic option.

Lastly, modelled interventions must have a minimum length to have meaningful effects, as the model is unsuited for modelling morphological effects of interventions that span less than a few hundred meters (Chavarrias et al., 2020) and side channel effectiveness generally increases if side channels are implemented along larger stretches of the river (Van Denderen, 2017; Rudolph, 2018). Paarlberg & Van Lente (2021) used a length of 1.5 – 3 km, which corresponds to 5 – 6 cross-sections. However, this results in a spatial high variable pattern of upstream sedimentation humps and downstream scour holes (Oldenhof, 2021) that would increase dredging costs (Van Vuren et al., 2015). For a proper assessment of the effects of large-scale side channel implementation it is desired to implement longer chains of side channels where it is assumed that there is no gap, nor overlap between sequential side channels.

The following criteria were used to determine the locations where side channel implementation would be viable:

- Side channels can only be implemented along river stretches that suffer from bed degradation according to Zuijderwijk et al. (2020);
- Side channels can only be implemented along river stretches that have enough space in the floodplains to accommodate an additional 25% of the local main channel width, while still maintaining the necessary safety margin of 100 meters towards the nearest dike toe as well as an additional 50 meters to set the main channel and side channel apart (Hooijer et al., 2007);
- A chain of side channels must cover a minimum length of 5 km (10 cross-sections) to ensure that the effects are noticeable on a large scale. This length was chosen rather arbitrary.

In total, 11 chains of side channels are implemented in the Waal River, Pannerdensch Kanaal and IJssel River (Figure 3.6). Side channels have been grouped by river into three cases, i.e. Waal River, Pannerdensch Kanaal and IJssel River (Table 3.2). For every case, seven scenarios have been created where the side channels start becoming active at a corresponding upstream discharge at Lobith (or Wesel). Individual cases are compared to the reference run to answer the second research question. A combination between individual cases is compared to the reference run to answer the third research question.

Since no side channels are implemented in the Nederrijn and Lek Rivers, a combination between side channels in the Waal River and Pannerdensch Kanaal is taken to answer this research question. Using the procedure mentioned above, an additional fourth scenario is created using the largest four side channels, which flow if the discharge at Lobith exceeds 1000 m^3/s, 1600 m^3/s, 2000 m^3/s, or 2800 m^3/s. Side channels that become active at higher discharges than 2800 m^3/s are only active for less than 10% of the time. To reduce the number of cases that will be investigated, these combinations have been excluded, as the general effect is likely to be visible using only the four most active side channels.

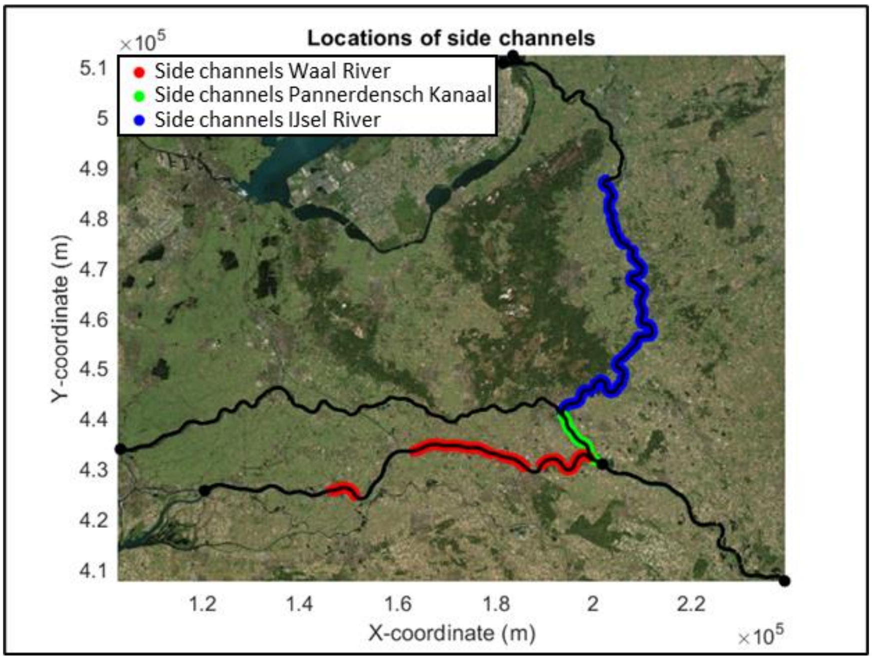

Figure 3.6: Locations where side channels can be implemented, given the used schematization and restrictions.

Table 3.2: Details of the implemented chains of side channels.

River	Start of first side channel (rkm)	End of last side channel (rkm)	Length (km)	Trajectory
Waal River	868,6	881,7	13,1	Pannerden - Nijmegen
	886,2	891,8	5,6	Nijmegen - Bridge of the A50 (Erwijk)
	893,8	909,9	16,1	Bridge of the A50 (Erwijk) - Beneden-Leeuwen
	927,7	933,3	5,6	Rossum - Zaltbommel
Pan. Kanaal	867,1	878,6	11,5	Pannerden - Arnhem
IJssel River	878,6	889,1	10,5	Westervoort - Rheden
	890,6	911,2	20,6	Rheden - Dieren
	911,7	927,8	16,1	Dieren - Zutphen
	928,8	944,0	15,2	Zutphen - Deventer
	946,0	961,6	15,6	Deventer - Veessen

3.5. Overview of runs

In total, 27 runs were executed, as described in Table 3.3. A distinction is made between one verification run, one reference run, 21 runs with side channels in a single distributary of the Rhine River and four runs with side channels in multiple distributaries of the Rhine River. Simulation time is per run estimated to be around 60 hours. Results of the verification and reference runs are described in Chapter 4. Results of the runs using side channels in single or multiple distributaries of the Rhine River are described in Chapter 5.

Table 3.3: Overview of executed runs that are elaborated in the results

Simulation(s)	Case(s)	Description	Results
1	Verification run	Verification case using Q_{Lobith} = 2250 m^3/s	4
2	Reference run	Reference case without side channels	4
3 - 9	Waal River	SC[1] in Waal River at Q_{Lobith} = 1000, 1600, 2000, 2800, 3600, 4400 or 5300 m^3/s.	5.1
10 - 16	Pannerdensch Kanaal	SC[1] in Pannerdensch Kanaal at Q_{Lobith} = 1000, 1600, 2000, 2800, 3600, 4400 or 5300 m^3/s.	5.1
17 - 23	IJssel River	SC[1] in IJssel River at Q_{Lobith} = 1000, 1600, 2000, 2800, 3600, 4400 or 5300 m^3/s.	5.2
Combinations			
24 – 27	Waal River – Pannerdensch Kanaal	SC[1] in Waal River + Pannerdensch Kanaal at Q_{Lobith} = 1000 m^3/s, 1600 m^3/s, 2000 m^3/s or 2800 m^3/s.	5.2

[1] SC stands for side channel. The discharge at Q_{Lobith} indicates the discharge at Lobith for which the side channel becomes active.

Boundary- and initial conditions for all cases are the same as the boundary- and initial conditions for the reference run, with the exception of the cross-sections at locations where side channels have been implemented. By evaluating the main channel bed level in cases with side channels to the main channel bed level in the reference case, it is possible to evaluate the effectiveness of side channels in reducing main channel bed degradation. Complementary variables, such as sediment transport or grain size changes are of secondary importance, but provide useful aid in explaining the patterns that are visible in the main channel bed level as a result of side channel implementation.

4. Autonomous bed degradation in the Rhine River and its distributaries

This chapter provides a summary of the results that were generated by the verification run using a stationary upstream discharge. The verification run provides useful information to investigate the long-term behaviour of the model. In addition, results for the more realistic reference run are presented. Main interest in the results is the large-scale evolution of the main channel averaged river bed level(simply called 'bed level') over time.

4.1. Verification run using a stationary upstream discharge of 2250 m^3/s

Results based on a constant upstream discharge of 2250 m^3/s show that the main channel averaged bed level of the Rhine River and its distributaries is experiencing varying degrees of change over time. The German and Dutch Rhine River and Waal River are highlighted in more detail, as these convey most of the discharge. Figure 4.1 and Figure 4.2 show the elevation change of bed level over time, the elevation change of the bed level with respect to the initial elevation of the bed and the elevation change of the bed level with respect to the elevation of the be in the previous year respectively. Development of the Pannerdensch Kanaal, Nederrijn- and Lek Rivers and IJssel River is briefly discussed and figures are included as Figures B.1 to B.6 in Appendix B.

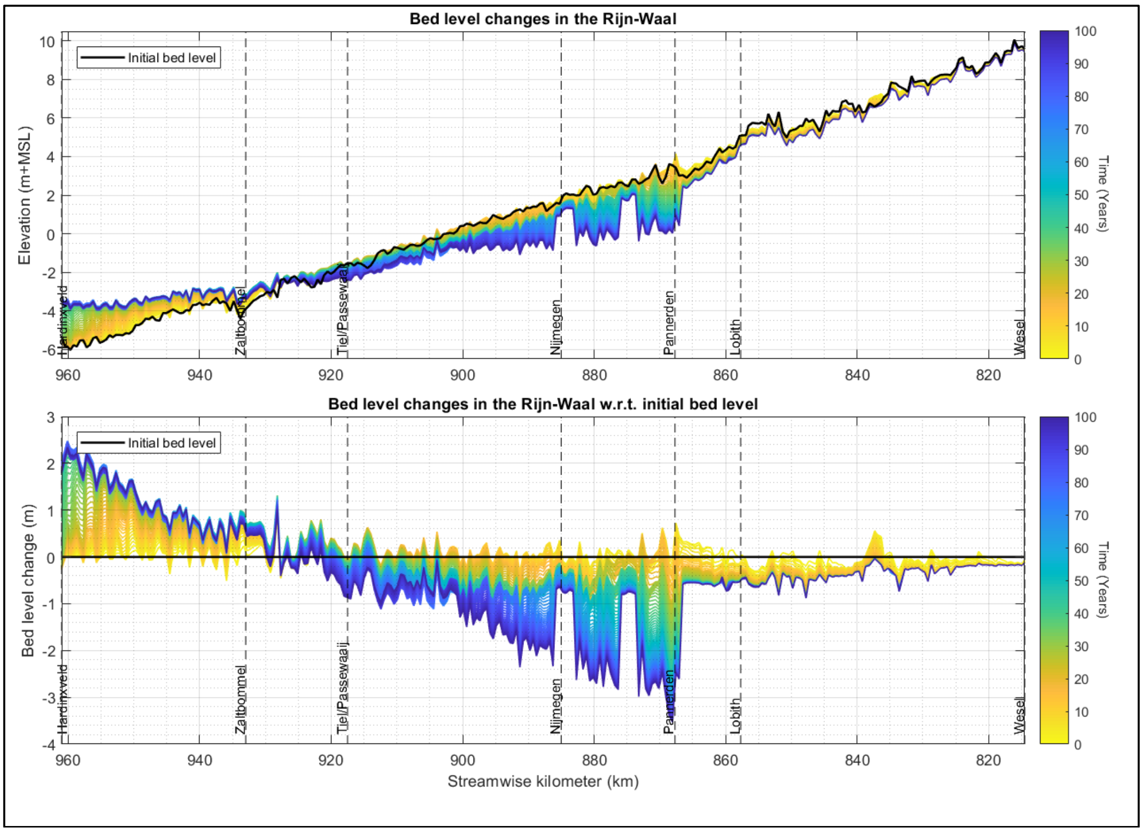

Figure 4.1: Simulated bed level changes in the Rhine and Waal Rivers for a period of 100 years using a stationary discharge of 2250 m^3/s. Top: Position of the bed level over time. Bottom: Change of bed level w.r.t. the initial bed level position.

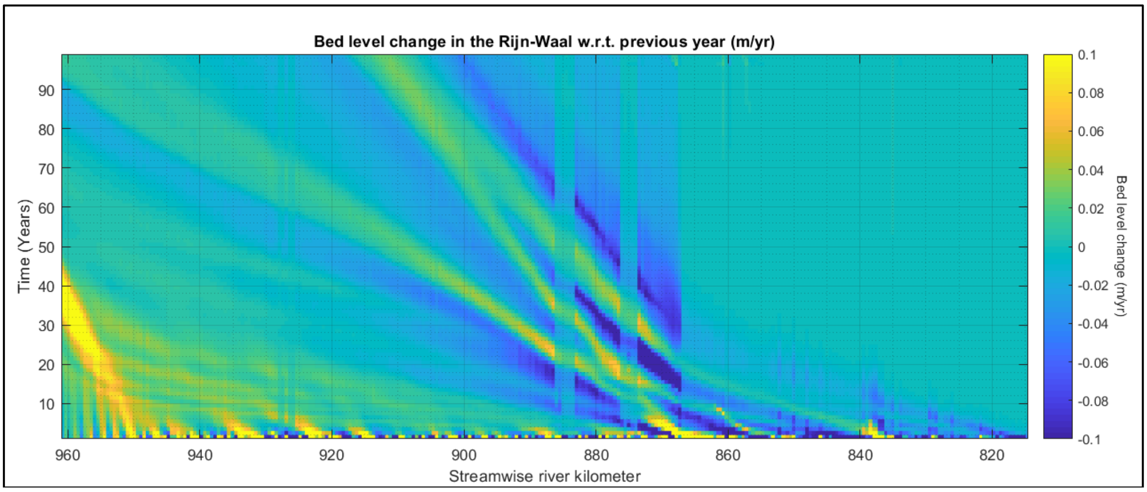

Figure 4.2: Simulated bed level changes in the Rhine and Waal Rivers w.r.t. the previous year for a period of 100 years using a stationary discharge of 2250 m^3/s.

From Figure 4.1 and 4.2, it becomes apparent that the Rhine River moves towards a morphological equilibrium, where there is no change in bed level over time. Depending on the location, this morphological equilibrium will be reached in approximately 5 to 30 years at the upstream and downstream reaches respectively. The Waal River shows no such behaviour, as continuous bed level changes are observed between Pannerden and Hardinxveld. Figure 4.2 shows that these continuous bed level changes in the Waal River result from the advection and diffusion of bed perturbations resulting from the relatively high initial bed level changes in the first 2 - 5 years. This was also observed by Welsch (2021). He notes that this is likely due to the transport of very fine sediment that is almost permanent in motion. A closer inspection of sediment transport of the finer fractions confirms this statement, which is shown in Figure B.10 in Appendix B. Figure 5.2 also shows that the celerity with which the bed perturbations travel differs between the Rhine River (2 km/year) and Waal River (0.5 - 1 km/year). Furthermore, the magnitude of the celerity decreases over time and space. An explanation for this could again be that the finer sediments are transported more quickly than the coarser sediments. Sieben et al. (2005) notes that for the Rhine River and Waal River the celerity of perturbations is in order of 1 km/year, which is in line with our findings.

Two clear disruptions of the bed level are visible in the Waal River, between rkm 873-876 and rkm 882-885. These features are the fixed layers of Erlecom and Nijmegen, which have a lack of sediment and therefore cannot erode beyond the (active) top layer. At Erlecom, bed degradation cannot occur due to the bottom groynes that are currently present. At Nijmegen, the outer bend of the main channel is protected from erosion by a fixed layer. In reality, no erosion is observed here and only the inner bend can erode. A similar effect is also visible at St. Andries (rkm 925-928), but this is much less profound.

Verification of the imposed morphological condition that prohibits bed level changes around structures becomes apparent from Figure B.2 in Appendix B, as bed level changes around the weirs of Driel (rkm 891), Amerongen (rkm 922) and Hagestein (rkm 947) equal zero for all years. In addition, the bed level position and sediment composition (D_{50} and ratio D_{90}/D_{10}) at the upstream boundary should remain fixed. However, the most upstream node appears to be a ghost cell, which does not store output data. Figures B.7 to B.9 in Appendix B show a sudden increase in grain size just after the upstream boundary (~rkm 816). This sudden increase can be considered a direct result of the fixation of the sediment composition of the upstream boundary, as from this node onward there is no net equilibrium in sediment transport gradient and thus the D_{50} can change based on the available sediment.

It appears that the nodal point relation in the model indeed becomes unstable for stationary discharges as suggested by Chavarrias et al. (2020). In Figure B2 and B3, it is visible that the IJssel River shows severe erosion and the Nederrijn River shows severe aggradation, resulting in the eventual closing of the Nederrijn River if the simulation would have been extended to include a longer simulation period. However, during a discharge of 2250 m^3/s near Lobith, the weirs of Driel, Amerongen and Hagestein are not (fully) open, which is likely to influence the discharge partitioning in favor of the IJssel River. For the Waal River and Pannerdensch Kanaal the effect of the nodal point relation is less pronounced, but still large asymmetry in the bed degradation between Waal (-3.6 meter over 100 years) and Pannerdensch Kanaal (-2.6 meter over 100 years) is observed.

To conclude, the model is able to simulate a period of 100 years without instabilities. The morphological condition that prevents morphological changes around weirs is working as intended. Results following the verification run seem plausible, but for the upper reach of the Waal River show excessive bed degradation in combination with the fixed layers. The Rhine River, Nederrijn- and Lek River seem to be in equilibrium after 100 years. The Waal River, IJssel River and Pannerdensch Kanaal are not yet in equilibrium. The calibrated nodal-point relation behaves as expected for the IJsselkop bifurcation, but the effects are less noticed for the bifurcation at the Pannerdensche Kop.

4.2. Reference run using historical discharge time series

Results based on observed discharge and water level time series show that there is a clear distinction in the behaviour between the Rhine River and its different distributaries (Figure 5.3). A few things become apparent when looking at the bed level change between the initial bed level and the bed level after 100 years. Bed degradation in the upper and middle reaches of the Waal River is in the order of 2.5 – 4.0 m over a 100-year simulation. This corresponds to degradation rates of 2.5 – 4 cm/year on average, which is on the high end of the spectrum of current bed degradation rates (Blom, 2016; Ylla Arbós et al., 2019; Havinga, 2020). In addition, the extreme bed degradation in the upper Waal River is interrupted by the presence of fixed layers that only degrade between 0 and 1.5 m, which causes large sills (rkm 873-876 at Erlecom and rkm 882-885 at Nijmegen). The presence of these kinds of sills is expected to cause severe restrictions for navigation during low flows (Havinga, 2020). Large amounts of sedimentation is simulated at the mouths of the Waal River and IJssel River, pressing the need for (additional) dredging. Chavarrias et al. (2020) notes that the present-day dredging is not taken into account in the model, but that it would be possible to do so.

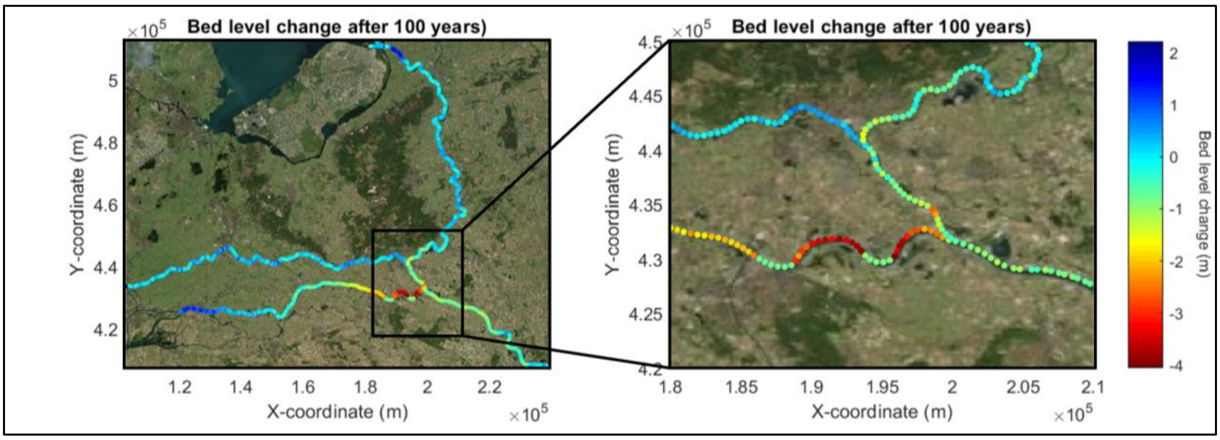

Figure 5.3: Simulated main channel averaged bed level changed over 100 years for the entire model domain (left) and for the bifurcation area (right).

Bed degradation in the bifurcation areas is quite different in the downstream branches (Figure 5.3, right side). The Waal River notes much more bed level change than the Panennerdensch Kanaal (–4.0 versus –2.5 m) and the IJsssel River notes much more bed level change than the Nederrijn River (-1.7 versus +0.9 m). This stresses the importance of updating the operational water management in order to guarantee the discharge partitioning as set by law (Havinga, 2020). As with the verification run, the German Rhine, Dutch Rhine and Waal Rivers are discussed in more detail. Figures on the other distributaries are given as Figure B.13 to B.18 in Appendix B.

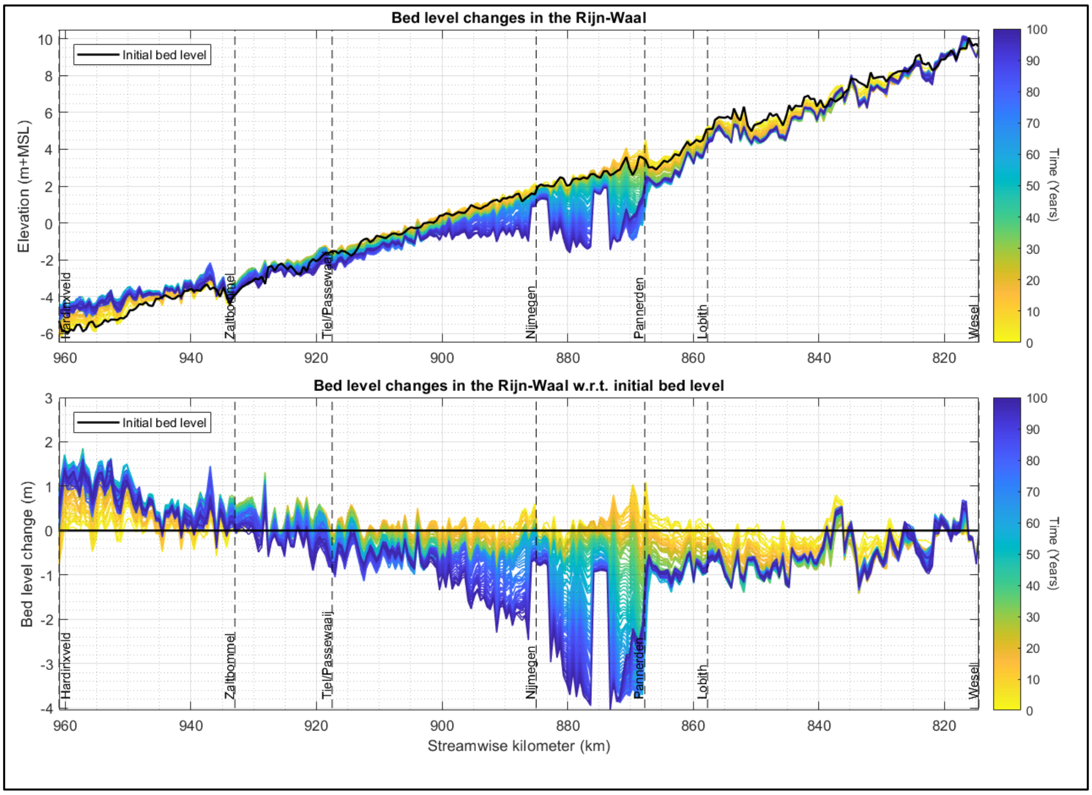

Figure 5.4: Simulated bed level changes in the Rijn and Waal Rivers for a 100 year period using a historical discharge time series. Top: Position of the bed level over time. Bottom: Change of bed level w.r.t. the initial bed level position.

The German and Dutch Rhine Rivers are characterized by mild degradation of up to 1.0 meter over 100 years, with relative morphological stability. As with the verification run, the observation can be made that the Rhine River moves towards an equilibrium, but with a dynamic component due to discharge variability between the years. Again, as with the verification run this equilibrium is obtained between 5 - 30 years for upstream and downstream reaches of the Rhine River respectively. However, whereas the verification run moved towards a static equilibrium, the reference run moves towards a dynamic equilibrium, as defined by Arkesteijn et al. (2019). This is visible by the deviation from the average bed level position given by Figure B.16 to B.18 in Appendix B. Here, the variation from the equilibrium position at most locations is around 10 cm/year with some locations showing more than 40 cm/year variation and a three year moving average that exceeds more than 15 cm/year. At Rees (rkm 835-840), a side channel has been implemented specifically to mitigate bed degradation (WSV, 2017). At this location around 50 cm sedimentation is simulated over the coming 100 year period, which breaks up the erosional pattern of the Rhine River.

The Waal River is characterized by a slope decrease. The upper- and middle reaches of the Waal River are characterized by large degradation, leading to incision of the bed. The downstream reach of the Waal River is characterized by sedimentation. Degradation in the upper Waal River reaches values of up to 4.0 m over 100 years, which is almost identical to Paarlberg & Van Lente (2021).

Interestingly, it appears that during the final years of the simulation the bed level between Pannerden and Erlecom (rkm 873-876) starts aggrading, which slowly moves downstream. Between Nijmegen and Tiel degradation slowly decreases from 2.0 m to 0.5 m and the bed level stabilizes. Between Tiel and Zaltbommel, the behaviour of the Waal River changes and the upstream erosional trend shifts to a downstream sedimentary trend. At the downstream boundary, total sedimentation equals roughly 1.5 m over the 100 year period. In reality, present-day maintenance dredging activities are not taken into account in the simulation. After 100 years of simulation, it appears that the bed in upper and middle reaches of the Waal River has not reached an equilibrium position given the continuous change.

The Pannerdensch Kanaal shows morphological behaviour of slightly less magnitude than the Waal River, which is given as Figure B.13 and B.14 in Appendix B. Initial sedimentation turns into severe degradation after 30 - 60 years and after 100 years around 1.2 - 1.4 m of degradation is simulated for the upstream reach of the Pannerdensch Kanaal, with a maximum degradation of 2.60 meters. Given that the degradation in the downstream reach of the Pannerdensch Kanaal starts later (after 50 - 60 years) and has a smaller magnitude (up to 1.0 m), it appears that the upstream erosional front is travelling downstream.

The Nederrijn and Lek Rivers show predominantly sedimentation which is visible in Figure B.13 in Appendix B. Sedimentation is generally less than 1.0 m over the coming 100 years. At one location the total sedimentation exceeds 2.0 m, which is mostly due to very high initial sedimentation in the first 2-5 years. In addition, the modelled changes are local and show no large-scale trends. The same can be said for the IJssel River (Figure B.14 in Appendix B), with the exception of an erosional trend in the upstream segment (until rkm 891), which is likely due to continuation of the degradation of the Pannerdensch Kanaal. In addition, a large amount of sedimentation is visible just before the Ketelmeer. The downstream boundary of the IJssel River ends in the Ketelmeer, where the flow velocity is almost zero. Therefore, flow velocities just upstream of the Ketelmeer reduce, which reduces the sediment transport capacity and results in sedimentation. The local morphological effects in the Nederrijn, Lek and IJssel Rivers can partly be explained by the interventions of the 'Room for the River'-programme, as Chavarrias et al. (2020) state that these interventions have been implemented in the schematization that has been used in the model.

Ylla Arbós et al. (2019) has determined the expected bed level of the Dutch section of the Rhine River and its distributaries in 2050 based on 5, 10 or 20-year average degradation rates. For most locations, the estimation of the position of the bed in 2050 is quite similar to our modelled position after 30 years (which is also in 2050). The situation for the Rhine and Waal Rivers is given in Figure 5.5 and the situation for the other distributaries is given by Figure B.20 and B.21 in Appendix B. Only for the lower Waal River the situation shows differences up to 1.0 m, which can be explained by the fact that the model does not include dredging activities. At the fixed layers, the projections by Ylla Arbós et al. (2019) even underestimate the bed level position compared to the simulation.

However, after 30 years the majority of the Waal River and other Rhine River distributaries are clearly not in equilibrium and show continuous erosion until at least 50 years into the simulation or even until the very end of the simulation. The model shows degradational values after 30 years that are disproportionally low compared to the degradational values after 100 years. One explanation could be that the initial sedimentation that is present in the upper reaches of the Waal River first has to erode too and that the modelled bed level position is overestimated. Another explanation could be the inter-annual variability of the modelled (and measured) the bed level position, which is quite substantial. The simulated bed level development is on par with trends observed by Welsch (2021) and Paarlberg & Van Lente (2021), but higher than Barneveld et al. (2019).

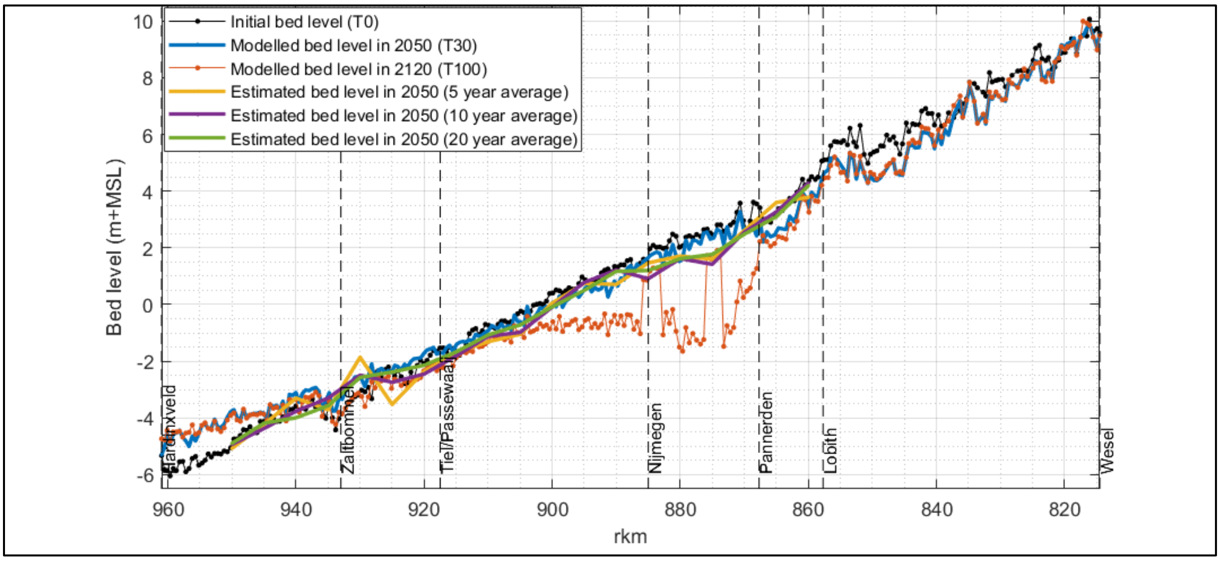

Figure 5.5 Comparison of the simulated bed level of the Rhine and Waal Rivers to the expected bed level in 2050 based on historic 5- 10- and 20-year averaged bed degradation rates by Ylla Arbós et al. (2019).

When looking at sediment transport (Figures B.25 to B.27), is becomes apparent that sediment transport in the Rhine River becomes larger towards the bifurcation at Pannerden. Here, a discontinuity in sediment transport is present, which is a result of part of the discharge and sediment being partitioned towards the Pannerdensch Kanaal. Most of the sediment transport happens in the Waal River: up to 3.1•10^7 ton over 100 years after the bifurcation and 6.1•10^7 ton over 100 years at the maximum location (around rkm 933). Sediment transport to the Pannerdensch Kanaal equals 0.6•10^7 ton over 100 years at the bifurcation from the Rhine River and 0.8•10^7 ton over 100 years at the bifurcation near Arnhem. We observe that around 20% more sediment is transported into the Nederrijn River than into the IJssel River. Figure B.26 in Appendix B shows that around the weirs of Driel, Amerongen and Hagestein large discontinuities in sediment transport are present that only happen a few times during the simulation, but at every occurrence becomes larger. An explanation could be the interaction between the imposed morphological condition in combination with a (very) high discharge event that opens the weir for a short time. The imposed morphological condition requires the sediment transport along the weir to be constant, resulting in large gradients up- and downstream of the weir. The exact reason is not further investigated as the Nederrijn and Lek Rivers are not experiencing problematic bed degradation.

It is noted that sediment transport in the Rhine River flattens over the years, which is in line with the degradational patterns moving towards equilibrium. For the Waal River, the sediment transport increases in downstream direction. However, there are strong fluctuations between different years as a consequence of the inter-annual discharge variability.

Figures of grain size changes of the Rhine River distributaries are given in Figures B.22 to B.24 in Appendix B. Grain sizes in the Rhine River and Pannerdensch Kanaal (ca. 10-15 mm) are much larger than in the Waal, Nederrijn or Lek Rivers (ca. 1-5 mm). In addition it is noted that grain sizes in the Rhine River start becoming coarse right away, which is visible as an increase in D_{50} and a decrease in the ratio between D_{90} and D_{10}. This indicates that predominantly fine sediments are transported that are not replaced from upstream. The model has a fixed upstream bed composition that happens to be very coarse. Over time, the system lacks finer sediments and gets dominated by the coarse upstream sediment load. After 50 years, the D_{50} in the Waal River becomes as large as the D_{50} in the Rhine River, which is approximately 10 mm. This coarse gravel front is slowly moving downstream, with around 0.5 - 1.0 km/year, which is in line with Sieben et al. (2005). Interestingly, the D_{50} in the Pannerdensch Kanaal starts increasing as well. However, after 50 years this increase stops. One explanation might be that since the Waal River is eroding faster than the Pannerdensch Kanaal, it receives exponentially more sediment. After 50 years the system has predominantly coarse sediments, which cause a degradational wave travelling downstream into the Waal River.

Since four cycles of the observed discharge and water level time series from 1994-2020 are used, it is expected to see some repetition in the results. When looking at the development of the bed level at some key locations (Figure 5.6), it is indeed visible that in year 1, 27, 53 and 79 repetitive fluctuations occur. At Hardinxveld and Zaltbommel, these fluctuations are visible as erosion. At Lobith, Pannerden and Nijmegen, these fluctuations are visible as sedimentation. A closer inspection of the time series notes that this phenomenon is likely caused by the very high discharge event in 1995 (reaching up to 12.000 m^3/s). What further stands out is that the initial sedimentary development at Pannerden is reversed after 5 years into an erosional trend that lasts almost 50 years. At some point, the bed elevation of the Waal River near Pannerden is even lower than the bed elevation near Nijmegen, which is more than 15 km downstream. At 54 years, the erosional trend reverses back to a sedimentary trend for another 40 years and the bed level stagnates after 90 years until the end of the simulation. An explanation could again be the advection of sedimentary humps from upstream, which take some time to reach Pannerden. This trend is also visible in Figure B.16 in Appendix B, where the advection of the sedimentary humps reaches Pannerden between 5 – 50 years.

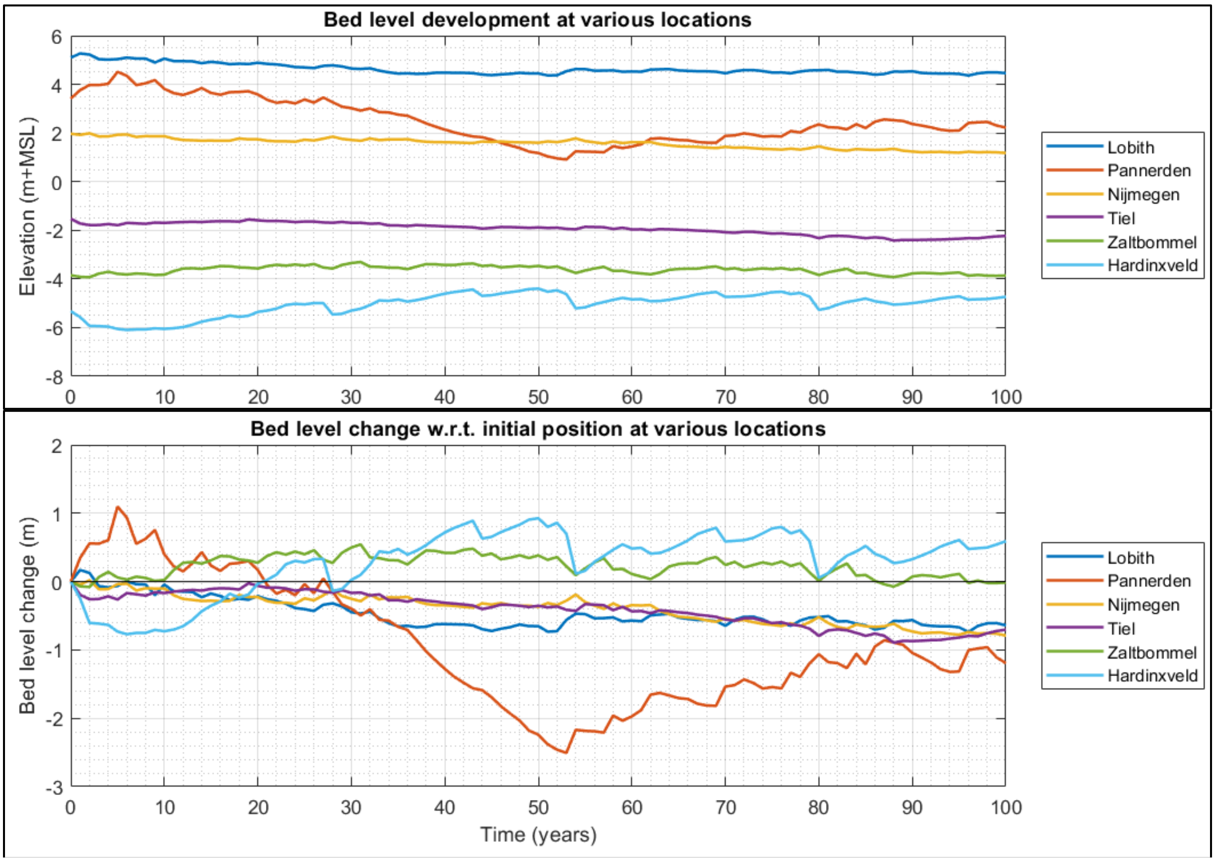

Figure 5.6: Bed level development at various locations along the Rhine and Waal Rivers. Top: Bed level position over time. Bottom: Bed level change w.r.t. the initial position.

To conclude, the simulation shows varying degrees of degradation and sedimentation for the Rhine River and its distributaries, which is a continuation of the patterns described in Ylla Arbós et al. (2019). For the Rhine River, degradation of the bed over a 100 year period is roughly 1.0 m compared to the present-day bed level position. For the Waal River, degradation varies between 3.5 - 4.0 m in the upper reach (upstream of Nijmegen) and a continuous decrease of 2.0 m degradation downstream of Nijmegen to 1.5 m aggradation near Hardinxveld. Fixed layers at Erlecom and

Nijmegen are degrading to a limited extent. The Pannerdensch Kanaal also exhibits degradation, varying between 2.6 m at Pannerden to 1 m at Arnhem. The IJssel shows degradation of 1.3 m for its upstream reach (until Rheden) and sedimentation near the Ketelmeer boundary. The rest of the IJssel River as well as the Nederrijn and Lek Rivers show predominantly local morphological changes that range between -0.5 and +1.0 m, with some small exceptions.

Generally, there is high morphological development for the first 2-5 years (up to 0.8 m) and a substantial inter-annual variability in bed level position (ranging from -0.4 to +0.4m). For longer timescales (more than 50 years), the system gets dominated by the composition of the upstream node, which happens to contain relatively coarse sediments. There is a significant increase in D50 and decrease between the D_{90}/D_{10} ratio for the majority of distributaries.

5. Bed development of the Rhine River and its distributaries under influence of side channels

This chapter shows the effect that the implementation of side channels has on the main channel bed level change. Firstly, the extent to which side channels can mitigate bed degradation if they are implemented along one of the distributaries is discussed. After that, results are presented that contain side channels in both the Waal River and the Pannerdensch Kanaal.

5.1. Morphological effects of side channels in one distributary of the Rhine River

Compared to the reference scenario, side channels are able to reduce bed degradation. Results of the seven different sized side channels at the four locations for the Rhine and Waal Rivers are given in Figure 5.1. Results are given as a three-year average of the final three years of the simulation to account for the high inter-annual variability.

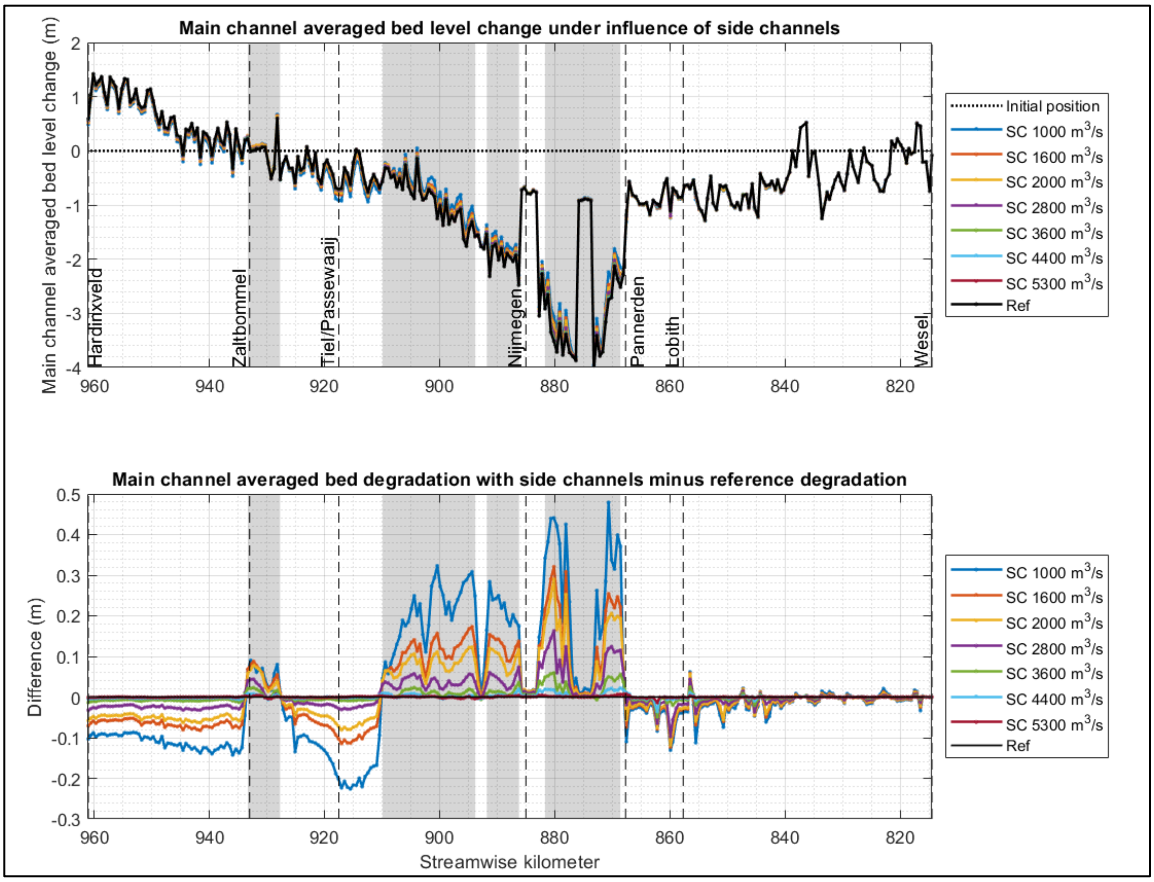

Figure 6.1: Effects of side channels on main channel bed degradation in the Rhine and Waal Rivers after 100 years. Colors indicate the starting discharge for side channels to flow (m^3/s at Lobith). Locations are indicated by grey bands. Top: Bed level change w.r.t. initial position. Bottom: Bed level change w.r.t. reference bed level change. Results are averaged over the final three years of the simulation.

At the locations of the side channels themselves, a reduction in degradation of up to 0.48 m compared to the reference case is present, which is a reduction of around 10-15% after 100 years. For the most upstream side channel, this sedimentation pattern is broken up by the fixed layer at Erlecom, where the model does not simulate any sedimentation. It is expected that flow velocities at this bottleneck are that large that no sedimentation can occur due to backwater effects.

Compared to the reference case, erosion is present downstream of the side channels, which is in accordance with the theoretical behaviour of side channels (Ribberink, 2011; Huthoff, 2020). Erosion is also present at the upstream end of the side channels, but less pronounced. In an equilibrium situation, no erosion downstreamof side channels and slight sedimentation upstream of side channels is expected, which is also indicated by Figure 2.3. Therefore, it can be concluded that the Waal River has not reached its equilibrium. This is also visible in Figure 5.2, which shows the behaviour of the deepest side channels (that becomes active once discharge at Lobith exceeds 1000 m^3/s) over time.

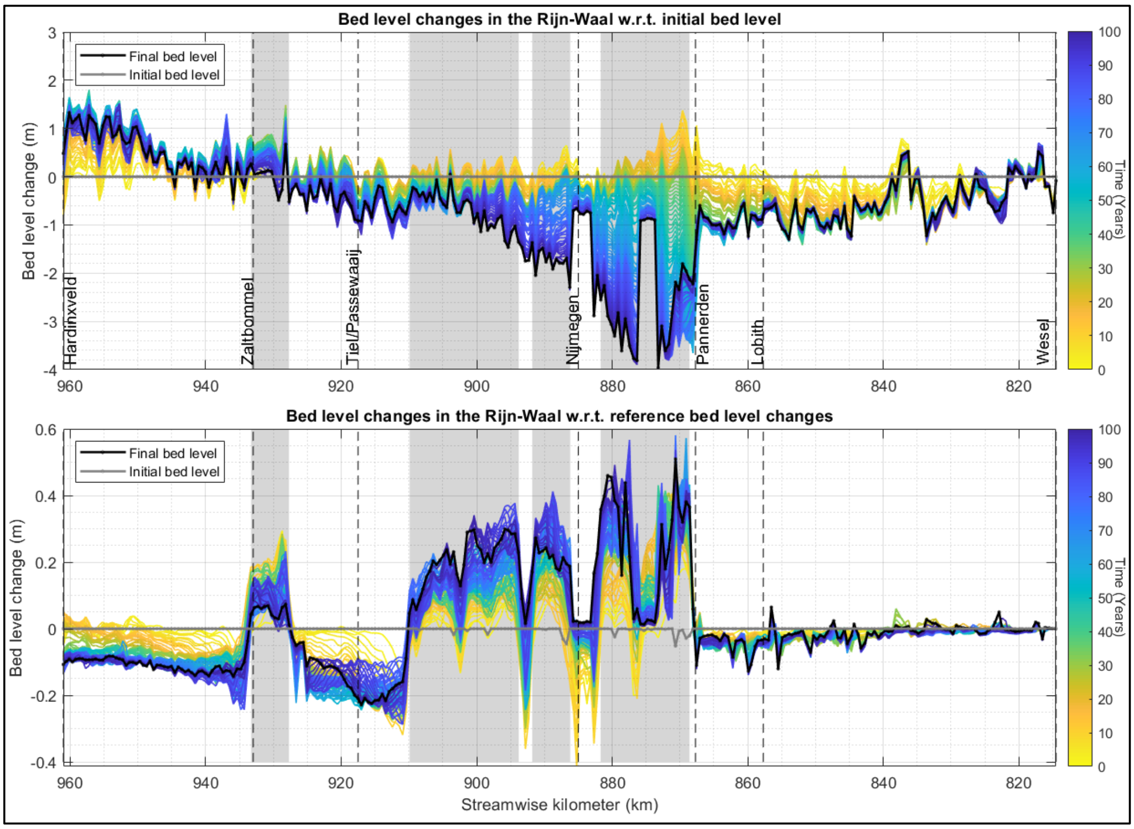

Figure 5.2: Top: Main channel averaged bed level development over time for a case where 4 side channels (starting to flow at 1000 m^3/s at Lobith) have been implemented in the Waal River. Bottom: Main channel bed level change w.r.t. the reference bed level change over time. Side channels are indicated by grey bands.

We see that the initial sedimentation of downstream channels is countered by erosion downstream of upstream side channels. This is clearly visible near the most downstream side channel (rkm 928 – 933), where the initial sedimentation of 0.20-0.30 m turns into a net effect of a mere 0.05 m. Erosion downstream of side channels does not always have to be negative for river management. If in the reference case (unwanted) sedimentation would occur, the erosion as a result of side channel implementation could help to reduce necessary dredging volumes. Likewise, initial sedimentation can (temporally) hamper navigability of the Waal river during low discharge stages, especially in combination with a significant inter-annual variability of the bed level.

Around the fixed layers near Nijmegen and Erlecom, initial erosion is slowly converted to a neutral state. It is expected that this happens due to the fixed layers at these locations. Without side channels, erosion at the fixed layers would be lower, resulting in a net negative effect due to side channel implementation. However, once fixed layers are reached the model does not allow additional degradation. Eventually, the reference case will degrade until the fixed layer as well, at which points there are not differences between the situations with and without side channels.

Next to effects in the Rhine and Waal Rivers, the implementation of side channels in the Waal River also has effects on other distributaries of the Rhine River, especially on the Pannerdensch Kanaal. Due to alterations of the flow conditions in the Waal River, backwater effects travel beyond the bifurcation point upstream to the Rhine and from there also affect the flow conditions in the Pannerdensch Kanaal. Following the morphological loop (Figure 2.1), it is expected that changes in sediment transport and bottom geometry happen if sufficient differences in flow conditions compared to the reference case exist. Figure 6.5 shows the final effects of side channels in the Waal River on the distributaries of the Rhine River.

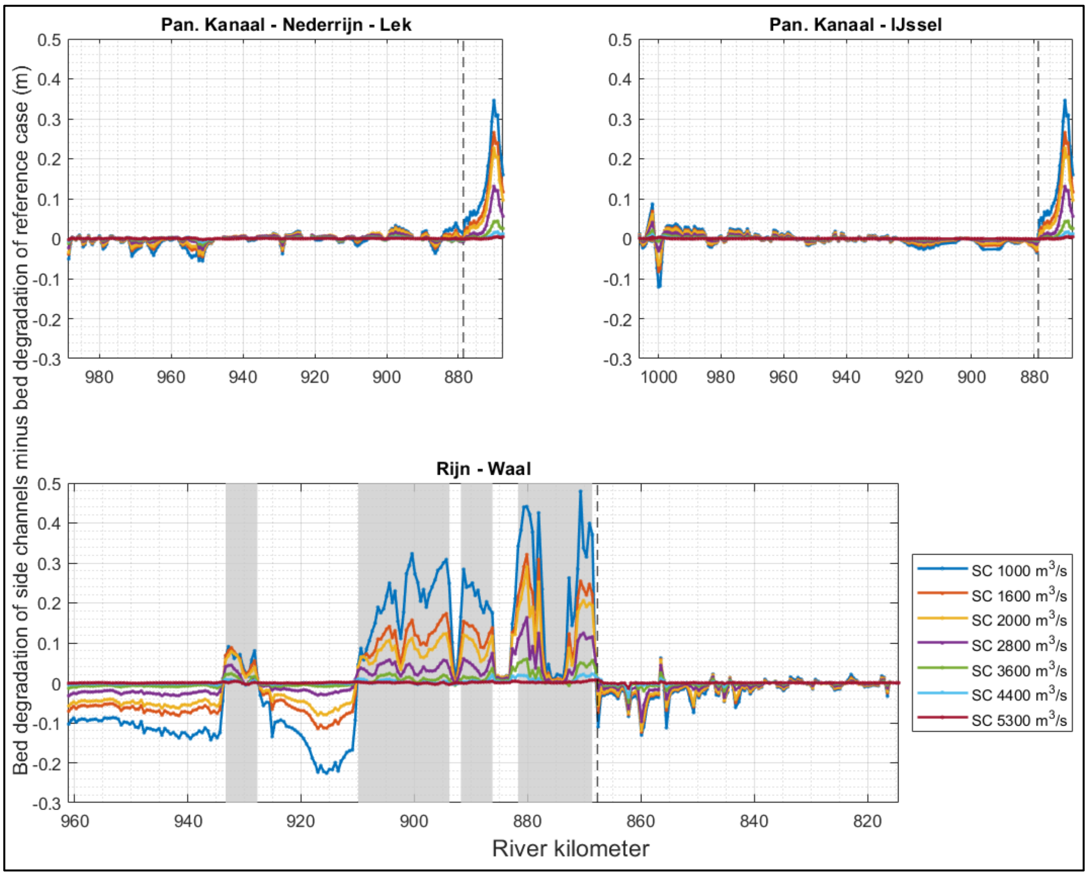

Figure 5.3: Net effects of side channels in the Waal River on main channel bed degradation in the distributaries of the Rhine River compared to reference bed level change. Side channels are indicated by grey bands. Colors indicate the starting discharge for side channels to flow (m^3/s at Lobith). Results are averaged over the final three years of the simulation.

From Figure 5.3 it becomes clear that implementation of side channels in the Waal River indeed leads to a large reduction of bed degradation in the Pannerdensch Kanaal as well. Even so, the relative contribution of side channels in the Waal River to the bed degradation in the Pannerdensch Kanaal is also around 10 - 15%. However, side channels in the Waal River have no significant effects on the main channel averaged bed degradation of the Nederrijn, Lek and IJssel Rivers. The sudden peak and trough in the downstream section of the IJssel River (rkm 1000) is possibly a consequence of the imposed downstream water level boundary. Nevertheless, it is quite far away of the area of interest.

Appendix C shows similar results as Figure 5.3, but then for the cases where side channels have been implemented in the Pannerdensch Kanaal (Figure C.3) or IJssel River (Figure C.4). For the Pannerdensch Kanaal, a reduction of bed degradation of 0.55 m compared to the reference degradation is observed, followed by varying erosion of up to 0.20 m up to river kilometer 922. In addition, erosion of up to 0.40 m is observed in the Nederrijn River until the weir of Driel (rkm 891).

Effects in the Waal River and Rhine River as a consequence of implementation of side channels in the Pannerdensch Kanaal are negligible. Implementation of side channels in the Pannerdensch Kanaal lead to a reduction of bed degradation in the Pannerdensch Kanaal of 20-25%. However, downstream erosion towards the IJssel River is unwanted due to the currently already problematic bed degradation rates of the upper reach of the IJssel River. In addition, downstream erosion towards the Nederrijn river is also unwanted, given the importance of the weir at Driel, which could experience stability problems as a consequence of enhanced bed degradation (Zuijderwijk et al., 2020).

Side channels in the IJssel River show very local effects, which decrease in magnitude for downstream reaches. Sedimentation compared to the reference case is between 0.05 - 0.20 meter, which is quite small. Between side channels local erosion pits ranging between 0.10 - 0.25m are observed. Upstream of the IJssel River, in the Pannerdensch Kanaal, erosion of 0.10m is observed. It is noted that side channels in the IJssel that start flowing at 1600 m^3/s or 2000 m^3/s at Lobith have the same magnitude of effects. A closer inspection of the cross-sectional profiles indicates that the IJssel River has a very narrow main channel and very high situated and wide floodplains, which could explain this partly.

For all cases no significant changes in grain size shifts are observed compared to the reference case. Minor changes are observed in the sediment transport profile, which are given in Figure 5.4. Here, a positive sediment transport gradient is visible upstream of the side channels, which confirms the slight erosion. At the locations of side channels themselves, a negative sediment transport gradient is observed compared to the reference case, resulting in sedimentation. However, the scale of these differences is one order of magnitude smaller than the total sediment transport over the simulation, which confirms the range of effect that side channels in a single branch have on mitigating main channel bed degradation.

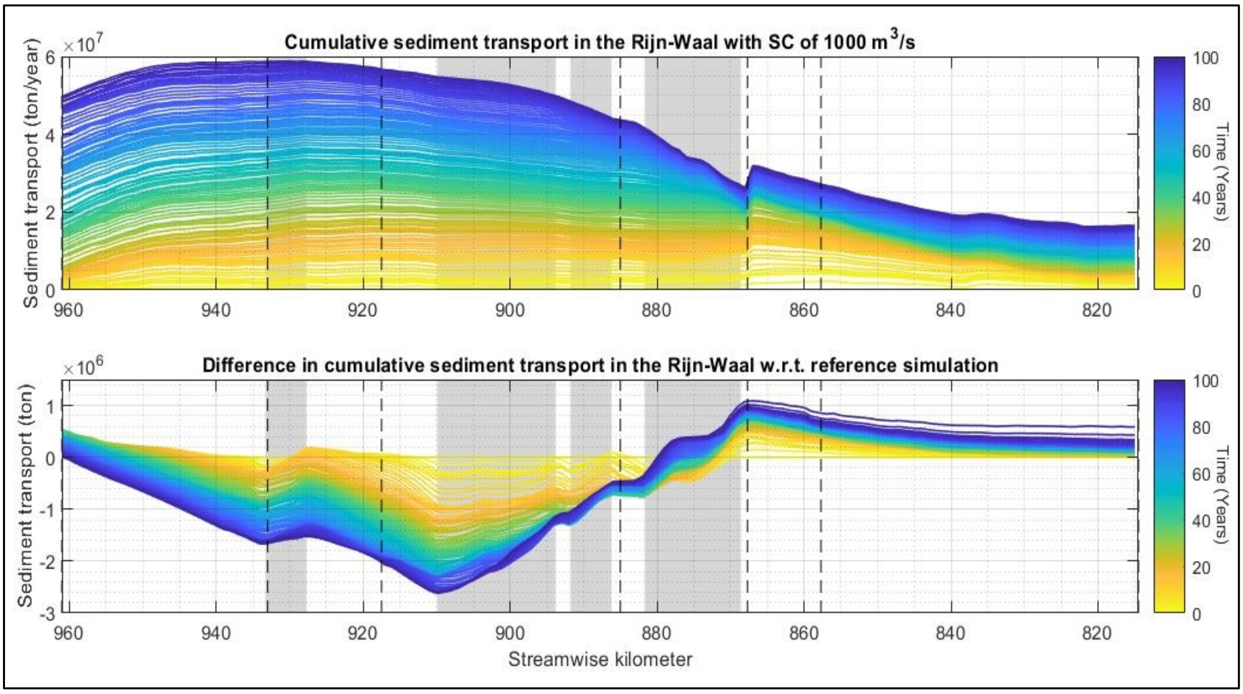

Figure 5.4: Effect of channels in the Waal River on sediment transport in the Rhine and Waal Rivers over time. Top: Cumulative sediment transport in the Rhine and Waal Rivers. Bottom: Differences in sediment transport between a case with side channels and the reference case. Side channels are indicated by grey bands.

Paarlberg & Van Lente (2021) used the same model to simulate similar interventions, but along much shorter stretches of river. In addition, their schematization procedure and thus final side channel geometry was different. Nevertheless, they found comparable magnitudes of effects as presented in this research, but with much more spatial fluctuations as a result of the shorter interventions. Generally, it can be stated that the implementation of side channels along the Waal River leads to a reduction of bed degradation of around 10-15% in both the Waal and the Pannerdensch Kanaal, given the used schematization and simulation period of 100 years. Downstream side channels do contribute slightly less towards the mitigation of bed degradation, but for downstream reaches also less degradation is noted in the reference case. Side channels in the Pannerdensch Kanaal contribute between 20-25% to the autonomous bed degradation, but have no significant effects on bed degradation in the Waal River. On the contrary, side channels in the Pannerdensch Kanaal enhance bed degradation in both the upper reaches of the IJssel and Nederrijn Rivers, which is unwanted. Side channels in the IJssel River have predominantly local effects, which vary between +20 to -25 cm compared to the autonomous reference case. After 100 years, the river system is not yet in equilibrium, since for all side channels downstream erosion is observed. For all cases, it is observed that side channels that become active above 2800 m^3/s at Lobith do very little (on average less than 0.05 m) to mitigate bed degradation.

5.2. Morphological effects of side channels in multiple distributaries of the Rhine River

Results for a combination of side channels in several distributaries are given in Figure 5.5. Here, a similar patterns as for the individual cases is observed, but with different magnitudes. A combination between side channels in both the Waal River and in the Pannerdensch Kanaal has a positive effect in mitigating bed degradation rates in the Pannerdensch Kanaal and Waal River.

Whereas a single side channel in the Pannerdensch Kanaal was able to reduce bed degradation by 0.55m, a combination with side channels in the Waal is able to reduce bed degradation rates up to 0.84m, which increases the total effectiveness up to 30-35%. In addition, no increase in magnitude in downstream degradation for the IJssel and Nederrijn Rivers is observed compared to cases with single side channels. For the Waal River, the reduction of bed degradation compared to the reference case increases from 0.48 to 0.54 m. For the downstream side channels in the Waal River, the effectiveness increases by less than 0.05 m, which is very limited. Upstream of the side channels, degradation in the Rhine River increases slightly by less than 0.05 m as well. Like in the individual cases, no significant changes in grain sizes were present.

It is debatable whether all side channels in the Waal River are necessary to achieve this effect. It is likely that only the most upstream side channel is responsible for the enhancements of the effect compared to individual side channels, since backwater from the most upstream side channel are the largest.

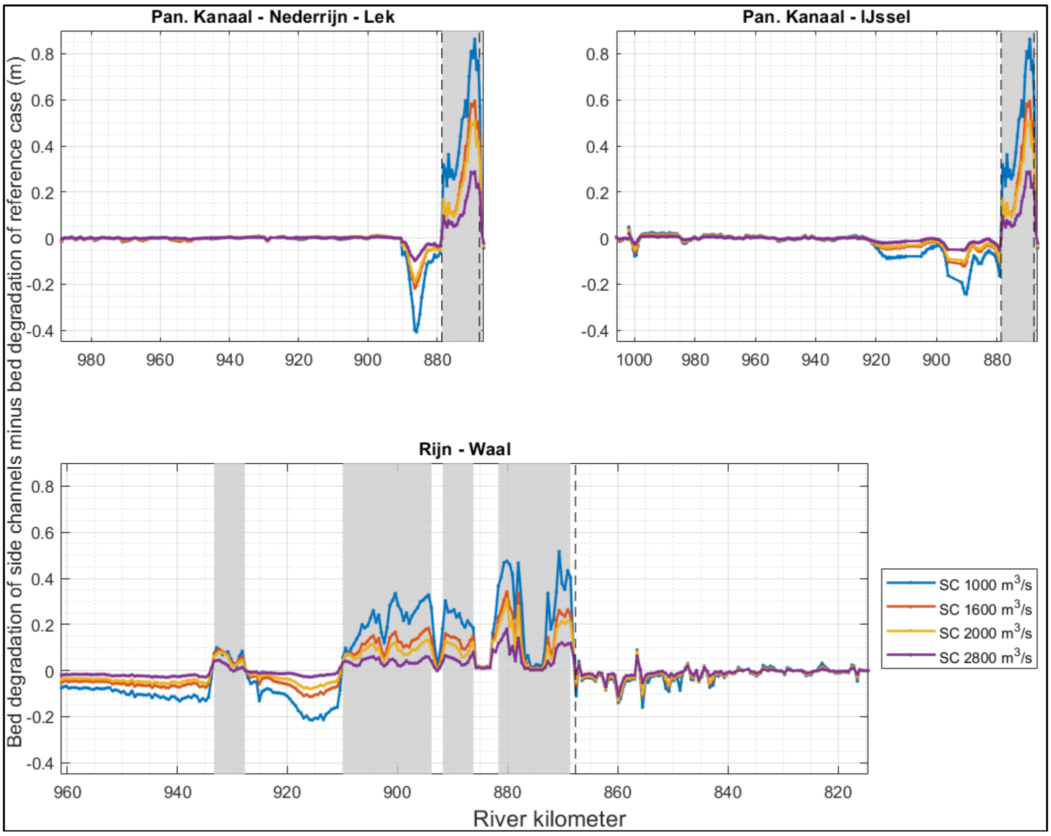

Figure 5.5: Net effects of side channels in the Waal River and Pannerdensch Kanaal on main channel bed degradation in the distributaries of the Rhine River compared to reference bed level change. Side channels are indicated by grey bands. Colors indicate the starting discharge for side channels to flow (m^3/s at Lobith). Results are averaged over the final three years of the simulation.

6. Discussion

River systems have a dynamic and stochastic nature and the underlying processes are not completely understood (Van Vuren, 2005). Therefore, capturing the river processes into a model per definition differs from the real world representation. The modelling of river morphology involves numerous uncertainties. Knowledge and the effects of uncertainties on the model results is essential for a meaningful interpretation of the computed river bed (Van der Klis, 2003). Especially with complex models that incorporate real-life complexity, such as variations in geometry and flow resistance as well as incorporation of multiple branches, bifurcations and hydraulic structures, a complex propagation of input uncertainties through the system is to be expected (Van Vuren, 2005). There are many ways of classifying and assessing uncertainties in river (morphodynamics) modelling as well as many factors influencing uncertainty in river modelling (e.g. Van der Klis, 2003; Loucks et al., 2005; Van Vuren, 2005; Warmink & Booij, 2015; Berends, 2019).

This chapter treats major discussion points followed from the results, data and methodology. The chapter provides an overview of strong and weak points of the research, which is broken down in three pillars: model, data and methodology.

6.1. Discussion of model choices and features

The model was able to simulate 100 year of morphological development of the lower reach of the German Rhine, the Dutch Rhine and its distributaries. More importantly, results seem to follow the current bed level trends by Ylla Arbós (2019) until at least 2050. However, there are some sidenotes to be made.

When conducting preliminary long-term morphological simulations, it was found the model became unstable, similarly to Paarlberg & Van Lente (2021) experienced. Hence, there was a need of artificially implementing a morphodynamic statement that prohibited bed level changes around weirs, as provided by Chavarrias et al. (2020). The implementation of such a condition in reality can be seen as a continuous dredging and dumping cycle that prevents any sedimentation or erosion. Furthermore, modelling of actual 'fixed layers, such as near Erlecom (rkm 873-876), Nijmegen (rkm 882-885) and St. Andries (rkm 925-928) do show morphodynamic changes, including erosion. In reality, only a part of the outer bend at these locations has been fixated to limit morphodynamic changes, but according to Chavarrias et al. (2020) it was not possible to replicate this situation in the model. However, since erosion at the fixed layer exceeds values of up to 0.80 meters after 100 years it can be said that these layers are not functioning as intended. It would be interesting to see how the results will hold compared to a simulation where the fixed layers are also prohibited to simulate erosion. An example to achieve such a simulation is to use a likewise morphological statement as implemented around the weirs. Like Welsch (2021) and Paarlberg & Van Lente (2021), strong morphological changes are observed in the first 2 - 5 years of the simulation. Welsch (2021) notes that this is likely due to excessive transport of fine sediment, which is something that is supported by the rapid change and decrease of D_{50} during the first five years of the simulation. But also later in the simulation (e.g. after 60 years) bed level changes sometimes exceed more than 0.10-0.20 m compared to the previous year, which is not really captured throughout the year. To counter this, it is advised to store model output more frequently or take a look at longer temporal averages.

Next, an question about the validity of the nodal point for long-term simulations can be asked. The nodal point relation stems from Wang et al. (1995) and has been calibrated by Chavarrias et al. (2020) to mimic current annual sediment transport rates as described by Frings et al. (2019). However, for long-term morphological simulations the changes in bathymetry are large enough to change the behaviour of the system. An example of this can be seen at the bifurcation that splits the

Dutch Rhine River into the Pannerdensch Kanaal and the Waal River at rkm 868. Initially, the Pannerdensch Kanaal has a bed level that is much lower than the Waal River, leading to skewed sediment transport rates into the Pannerdensch Kanaal. The results have shown that the sediment transported into the Pannerdensch Kanaal is much coarser than the sediment transported to the Waal. However, as the bed level of the Waal shows higher degradation rates than the bed level of the Pannerdensch Kanaal, the distribution of discharge becomes skewed, but the partitioning of sediments stays as it initially is due to the initial calibration of the nodal point relations. Frings and Kleinhans (2008) note that bend sorting upstream of bifurcations leads to sediment supply limitation, particularly for the branch in the outer bend. Because the variations in sediment transport are complex and poorly correlated with the flow discharge, prediction of the sediment partitioning with existing relationships for one-dimensional models is problematic.

A similar question can be asked about the downstream water level boundaries. Due to the high sedimentation near the downstream reaches (especially of the Waal), which are in the order of 2 m, the Qh-relation becomes inaccurate. Flow velocities will increase when the bed level goes up, but water levels stay the same. This results in higher sediment transport capacity and therefore either overestimation of downstream sedimentation or underestimation of downstream erosion than is currently modelled. In reality, dredging activities in the lower reach of the Waal River will maintain a minimum depth for shipping. To include these activities, the downstream boundary could be fixed in a similar way as the upstream boundary or the weirs. An example could be to fix the position of the bed level at the downstream boundaries, but keep the sediment composition dynamic. Since the equilibrium bed slope of the rivers does not change, it is expected that fixing the downstream bed level will lead to higher degradation rates upstream.

Lastly, the model does not include physical 2D effects. An example of this is the ‘bend effect’, which results in lateral sorting of sediment. Currently, only main channel average bed levels are taken into account. However, relative differences in degradation or sedimentation in the main channel can differ quite substantively. When the main channel width is sufficiently small, even a relatively low degradation over the average main channel can have very skewed local results, which restricts navigability of the river more than anticipated. This is particularly the case for the upper section of the IJssel River, which already suffers from a narrow main channel (Zuijderwijk et al., 2020). In addition, the bend effect is especially important at bifurcations or side channel intakes (Van Denderen, 2018), as they have great implications for the partitioning of sediments between the two (main and side) branches and therefore for their future development. Chavarrias et al. (2020) noted that for later versions of the model this ‘bend effect’ has been solved. However, these versions were unavailable at the time of this thesis project. It is advised to conduct a new reference run using a newer version of the model and compare the results to the reference scenario from this research to quantify the effects that such a ‘bend effect’ has over a longer timescale. Another option would be to use a 2D model of the Dutch Rhine and its distributaries to re-run the reference scenario and compare the results.

6.2. Discussion of used data

Two major remarks can be made about the used data for this research. Firstly, the imposed boundary conditions. The climate is changing, and so are the hydrological conditions of the upstream and downstream boundaries. A prime example of this is sea level rise, which has a current rate of 3 mm/year and is likely to increase. Over the 100 year period, this is expected to be at least 30 centimeters of water level increase. Combined with the expected degradation of the Midden-Waal, tidal influence will extend much farther upstream than in the current situation (up until Passewaaij, rkm 917). Due to climate change, the discharge regime of the Rhine River is expected to change as well, with likely higher discharges during winters and lower discharges during summer (Havinga, 2020). Since sediment transport is nonlinearly correlated to flow velocity (and thus to discharge), it is expected that degradational patterns will change, leading to shorter bursts of large amount of sediment transport followed by longer periods of stability and bed growth. This has large effects for the construction of side channels, as they are designed to accommodate flow for a certain amount of time per year. If discharge regimes change, so do the exceedance frequencies as well as the aggradation behaviour of side channels themselves (Van Denderen, 2019). Paarlberg & Van Lente (2021) conducted a similar study with the same model using a different upstream hydrograph, that consisted of observed discharge at Lobith from 1916-2016. The results of their reference run did not show significant differences from the results of the reference run in this study, which included an overlapping part of the discharge time series and replicated it four times. However, this does not guarantee that future discharge changes will not affect the model output.

Secondly, the initial grain size distribution of Sloff (2006) has been used as initial condition. This distribution is already over 15 years old. Given the high transport rates of some of the finer sediments (of 1 - 2 km/year), it is estimated that simulated results will occur much earlier. In addition, the model uses several underlayers without knowledge of substrate data. It is assumed that the substrate of underlayers is identical to the top layer, which is not always the case. Since the system is dominated by the sediment composition at the upstream node for long-term simulations, accurate description of the sediment that is fed into the system of the Rhine River and its distributaries is crucial. It is debatable whether the initial distribution of Sloff (2006) is still usable, given recent nourishments in Germany and the progression of sediment through the system.

6.3. Discussion of followed methodology

The main discussion point of the followed methodology is the position and schematization of the side channels. Side channels must be of sufficient size to have any meaningful impact. Paarlberg & Van Lente (2021) note that their interventions are in the order of 1 - 2 km (3 - 5 cross-sections), which is much shorter than the chains of side channels implemented in this study (10 - 20 kilometers). However, Paarlberg & Van Lente (2021) did include all side channels in the middle reach of the Waal River, starting downstream of Nijmegen. Like in Paarlberg & Van Lente, this study also observed that the largest effects on bed level change are observed just after the intervention has started and that effects fluctuate spatially and temporally. This raises the question whether a chain of a many very short interventions would generate the same results as a few very large side channels. Based on work done by Oldenhof (2021) and Van Denderen (2019), side channels should ideally have a minimum length. This is also stressed by Chavarrias (2020), as the model is unsuited to predict morphodynamic changes at a spatial scale that is smaller than the grid size (approximately 500 m).

To add to this, side channels currently have been parametrized by flow depth based on discharge. The width of side channels has been set at 25%, which was rather arbitrary. It would be interesting to see how wider side channels (i.e. 30%, 35% or 40%) stack up to the cases that we have presented. Based on theory, we would expect to see a higher reduction in bed degradation compared to the reference case. However, wider side channels probably mean that at some locations it is not possible to implement side channels. In addition, implementation of wider (and larger) side channels poses additional challenges regarding land use, soil volume balance, ecological value and costs.

In this study, all human interference in the Rhine River is ignored for the coming 100 years, which is quite a bold assumption given that the current state of the Rhine River and its distributaries is not the state that river managers want. Therefore, future interventions are likely to happen.

Lastly, the way of schematizing side channels has an impact on the results as well. Currently, side channels have been schematized as an extension of the main channel by 25% and excavated up to a certain water level. However, change of roughness values has been ignored, which leads to a more conservative estimate in bed degradation reduction than would actually be the case in the field, as side channels can convey less discharge and therefore more discharge remains in the main channel, leading to a lower reduction of flow velocities and sediment transport. Another parameter that is neglected is the sediment balance in a side channel. Side channels in the model do not aggrade or degrade and have no sediment sources or sinks. A dredging module could be imposed to create more realistic dynamics, but due to simplicity and time constraints this option is not investigated.

Side channels could also have been schematized differently, by for example making side channels lateral in- and outflows. Lateral in- and outflows are included in the model by default. The entrance of a side channel can be schematized as a time series of a lateral discharge abstraction. Similarly, the exit of a side channel can be schematized as a time series of a lateral discharge inflow. The advantage of such a schematization is that the discharge actually leaves the system without extraction of bed material load. The disadvantage is that creating the abstraction and inflow time series is very labor intensive and these time series only remain valid shortly after the simulation starts. After morphological changes in the main channel occur, the discharge distribution between main channel and side channel becomes skewed, and so does the extraction towards the side channel.

7. Conclusions and recommendations

7.1. Conclusions

This research made use of a newly developed 1D model to investigate the potential of side channels to mitigate main channel bed erosion along the Dutch Rhine River and its distributaries. The model was able to simulate a 100 year period without instabilities with plausible results. In order to determine the effectiveness of side channels a reference scenario was set up to determine the autonomous development of the bed of the Dutch Rhine River and its distributaries for the coming 100 years. In addition, several scenarios where investigated where side channels have been implemented in one or more distributaries of the Rhine River. These side channels became active at different discharge stages near Lobith, depending on the scenario. Overall, the following answers are formulated for the research questions:

1. **How does the main channel bed of the Dutch Rhine River and its distributaries develop over the coming 100 years under autonomous conditions?**

Based on autonomous conditions that remain as they currently are, the simulation of autonomous bed development shows various degrees of degradation and sedimentation for the Rhine River and its distributaries. Degradation in the upper reach of the Waal River reaches values op 3.5 - 4.0m, whereas the Pannerdensch Kanaal reaches values op 1.0 - 2.6 m. As a result, discharge partitioning will be skewed towards the Waal River. The middle and lower reach of the Waal River are characterized by slope decrease, leading to incision between Nijmegen (rkm 885) and Passewaaij (rkm 917) and sedimentation between Zatlbommel (rkm 933) and Hardinxveld (rkm 962). The Nederrijn, Lek and IJssel Rivers show predominantly local morphological effects that vary between 0.5 m erosion and 1.0 m sedimentation over the simulation period, with the exception of the upper IJssel river and a few minor locations. The distributaries of the Rhine River are not in equilibrium after 100 years and show high values of inter-annual change in bed level of up to 0.4 m. The values that followed from this simulation are in line with projections from Ylla Arbós (2019) and simulations by Welsch (2021) and Paarlberg & Van Lente (2021). For longer timescales (more than 50 years), the system gets dominated by the composition of the upstream node, which happens to contain relatively coarse sediments. There is a significant increase in D50 and decrease between the D_{90}/D_{10} ratio for the majority of distributaries.

2. **How does the main channel bed of the Dutch Rhine River and its distributaries develop over the coming 100 years for different cases where side channels are implemented along one of the distributaries?**

Generally, it can be concluded that the implementation of side channels along the Waal River leads to a reduction of bed degradation of around 10-15% in both the Waal and the Pannerdensch Kanaal for a period of 100 years, given that side channels equal 25% of the adjacent main channel width. Side channels that are located further downstream contribute slightly less towards the mitigation of bed degradation, but for downstream reaches also less degradation is note, which keeps the total reduction of bed degradation around 10-15%. Side channels in the Pannerdensch Kanaal contribute between 20-25% to the autonomous bed degradation, but have no significant effects on bed degradation in the Waal River. On the contrary, side channels in the Pannerdensch Kanaal slightly enhance bed degradation in both the upper reaches of the IJssel and Nederrijn Rivers, which is unwanted. Side channels in the IJssel River have predominantly local effects, which vary between +20 to -25 cm compared to the autonomous reference case. After 100 years, side channels have not yet reached their equilibrium configuration, since for all side channels downstream erosion is observed. For all cases, it is observed that side channels that become active above 2800 m^3/s at Lobith do very little (on average less than 0.05 m) to mitigate bed degradation.

3. **How does the main channel bed of the Dutch Rhine River and its distributaries develop over the coming 100 years for different cases where side channels are implemented along several distributaries?**

A combination with side channels in the Waal River and in the Pannerdensch Kanaal is able to reduce bed degradation by 30-35%. In addition, no increase in magnitude in downstream degradation for the IJssel and Nederrijn Rivers is observed compared to cases with single side channels. For the upper reach of the Waal River, the reduction of bed degradation compared to individual cases increases slightly, by 0.06 m. For lower reaches of the Waal River, the effects become insignificant. The effects are stronger felt by locations that lie close to the bifurcation points.

These conclusions lead to the following conclusion for the main research question.

> ***"To what extent can implementation of side channels reduce the autonomous long-term large-scale main channel bed degradation in the Dutch Rhine River and its distributaries?"***

Side channels with a width that equals 25% of the adjacent main channel width are able to reduce bed degradation rates. The effectiveness is influenced by side channel size and side channel location. In general, side channels that become active above 2800 m^3/s at Lobith (i.e. less than 20% of the year) do very little to reduce bed degradation. However, side channels that become active at 1000 m^3/s at Lobith (almost 100% of the year) are able to reduce bed degradation by 10-15% for the Waal River and 20-25% for the Pannerdensch Kanaal. A combination of side channels in both the Waal River as the Pannerdensch Kanaal is even able to reduce bed degradation rates in the Pannerdensch Kanaal by 30-35%, which is a considerable benefit regarding long-term dredging volumes and in line with Barneveld et al. (2019). Nevertheless, additional soft measures (such as sediment nourishments) will continue to be necessary to mitigate bed degradation rates.

Since after 100 years the Dutch Rhine and its distributaries have not reached their equilibrium bed level, it is unadvisable to design interventions based on their equilibrium configuration. The long adaptation time of the main channel bed should be taken into account in the design of interventions to not overestimate the benefits. Degradation is observed up- and downstream of the locations where side channels are implemented. By choosing strategically located areas, i.e. upstream of fixed layers or upstream of locations where currently sedimentation is present, the local bed level dynamics can be used in combination with side channel implementation to minimize dredging costs.

7.2. Recommendations

Based on the findings in this research, it is recommend to enhance the credibility of the model for long-term simulations, by assessing the sensitivity of the model to (morphological) boundary conditions. A comparison of the findings from this research to findings of Paarlberg and Van Lente (2021) indicates that that hydrodynamic conditions have limited effect on the final morphological outcome. However, hydrographs used in this study and in Paarlberg & Van Lente (2021) are not that different. It is recommended to include use the model for evaluation of a climate change scenario to gain better insights in the behaviour of the system under more extreme conditions. In addition, Chavarrias et al. (2020) note that some of the main morphological parameters (i.e. active layer thickness and nodal point relation) have major impact on the results. In addition, the upstream sediment composition has a major influence on the on the coarsening of sediment in the Rhine and Waal Rivers. Consequently, the upstream node dominates the degradation and aggradation process. It is recommended to update the initial sediment composition from Sloff (2006) with recent field measurements about location and content of the bed sediment and substrate.

Second, it is recommended to vary the width of side channels. Side channel width has been fixed at 25% of the main channel width in this research, which has a major impact on the results. Wider side channels will be better at mitigating ongoing bed degradation locally, but are likely to also have stronger effects up- and downstream of their location of implementation. By evaluating several scenarios with variable side channel width, a better estimate can be given about the potence of side channels in reducing bed degradation rates. Side channels alone will not be enough to totally mitigate or even reverse the ongoing bed degradation. Additional soft measures (such as sediment nourishments) will be necessary. It is recommended to investigate to what extent a combination between side channels and coarse and fine sediment nourishments can strengthen each other to mitigate bed degradation.

Lastly, it is recommended to model the bifurcation area in a 2D model. The current nodal-point relation is calibrated based on initial conditions and it may not be suited to fully capture the morphological processes on a long timescale. By evaluating the bifurcation area in a 2D grid, the initial nodal point relation can be updated based e.g. bed level, transverse slope, sediment composition and local hydrodynamics. Downstream distributaries can be coupled in a 1D model to the 2D output, thereby keeping the upstream sediment composition and downstream sediment partitioning variable depending on local conditions.

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Appendices

Appendix A: Theoretical background and methodology

A.1: Inclusion of river morphodynamics formulas in the used model

1D Momentum equation

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

1D Continuity equation

$$\frac{\partial h}{\partial t} + \frac{\partial uh}{\partial x} = 0 \tag{A.2}$$

With:

- u the width-averaged flow velocity [m/s];
- g the gravitational acceleration [m/s^2];
- h the water depth [m];
- z_b the width-averaged bed level [m+NAP];
- C the Chèzy coefficient [m$^{1/2}$/s].

Sediment transport relation for gravel fractions (Meyer-Peter & Müller)

$$q_{bk}^* = \alpha * 8 * (\theta_k - \xi_k\theta_c)^{3/2} \tag{A.3a}$$

where:

$$\xi_k = \begin{cases} 0.843\left(\frac{d_k}{D_m}\right)^{-1}, & for\,\frac{d_k}{D_m} \leq 0.4 \\ \left(\frac{\log_{10}(19)}{\log_{10}\left(19\frac{d_k}{D_m}\right)}\right)^2, & for\,\frac{d_k}{D_m} > 0.4 \end{cases} \tag{A.3b}$$

Sediment transport relation for sand fractions (Engelund & Hansen)

$$q_{bk}^* = \alpha\frac{0.05}{C_f}(\theta_k)^{\frac{5}{2}} \tag{A.4a}$$

where:

$$q_{bk}^* = \frac{q_{bk}}{F_{ak}\sqrt{g\Delta d_k^3}}, \qquad C_f = \frac{n^2 g}{R_h^{1/3}}, \qquad \theta_k = \frac{\tau_b}{\rho g \Delta d_k}, \qquad \tau_b = \rho g R_h S_f, \quad S_f = \frac{C_f u^2}{g R_h} \tag{A.4b}$$

With:

- q_{bk}^* is the nondimensional sediment transport rate [-];
- α is a sediment transport calibration parameter [-];
- θ_k is the Shields stress on sediment size fraction *k*;
- ξ_k is the hiding and exposure relation by Ashida and Michiue (1971) [-];
- θ_c is the critical bed Shields number (0.025) [-];
- d_k is the characteristic grain size of sediment fraction *k* [m];
- D_m is the arithmetic mean grain size [m];
- α is a sediment transport calibration parameter [-] (Chavarrias et al., 2020), see Table A.1;
- C_f is non-dimensional friction coefficient [-];
- q_{bk} is the width-averaged sediment transport rate [m^2/s];
- F_{ak} is the sediment volume of fraction *k* in the active layer [m^3];
- Δ is the submerged specific density (1.65) [-];
- g is the gravitational acceleration (9.81) [m/s^2];
- n is the Manning friction coefficient [s/m$^{1/3}$];
- R_h is the hydraulic radius [m];

- τ_b is the bed shear stress [N/m^2];
- ρ is the density of water [kg/m^3];
- S_f is the friction slope [-];
- u is the width-averaged velocity [m/s].

Table A.1: Calibration parameters of the sediment transport relations (Chavarrias et al., 2020).

Branch	**α Sand fractions [-]**	**α Gravel fractions [-]**
German Rhine River Dutch Rhine River	0.47	0.60
Waal River	0.18	0.32
Pannerdensch Kanaal	0.22	0.12
Nederrijn – Lek Rivers	0.10	0.10
IJssel River	0.10	0.10

Channel development (Exner)

$$(1-\varepsilon_0)\frac{\partial z_b}{\partial t}+\frac{\partial q_{bk}}{\partial u}\frac{\partial u}{\partial x}=0 \tag{A.5}$$

With:

- ε_0 is the sediment porosity (0.4) [-];
- z_b is the width-averaged bed level [m+NAP];
- q_{bk} is the width-averaged sediment transport [m^2/s];
- u is the width-averaged flow velocity [m/s].

Nodal-point relation

$$\frac{Q_{bk1}}{Q_{bk2}}=\beta_k\frac{Q_1}{Q_2} \tag{A.6}$$

With:

- Q_{bkj} is the sediment transport rate of size fraction k on the outgoing branch j [m^3/s];
- Q_j is the water discharge on the outgoing branch j [m^3/s];
- β_k is a calibration parameter [-] (Chavarrias et al., 2020), see Table A.2.

Table A.2: Calibration parameters of the nodal-point relations (Chavarrias et al., 2020).

Bifurcation Distributary 1 Distributary 2	**β Sand fractions [-]**	**β Gravel fractions [-]**
Pannerdensche Kop Waal Pannerdensch Kanaal	1.79	1.79
IJsselkop Nederrijn IJssel	1.35	0.99

A.2: Boundary conditions of upstream and tidal boundaries

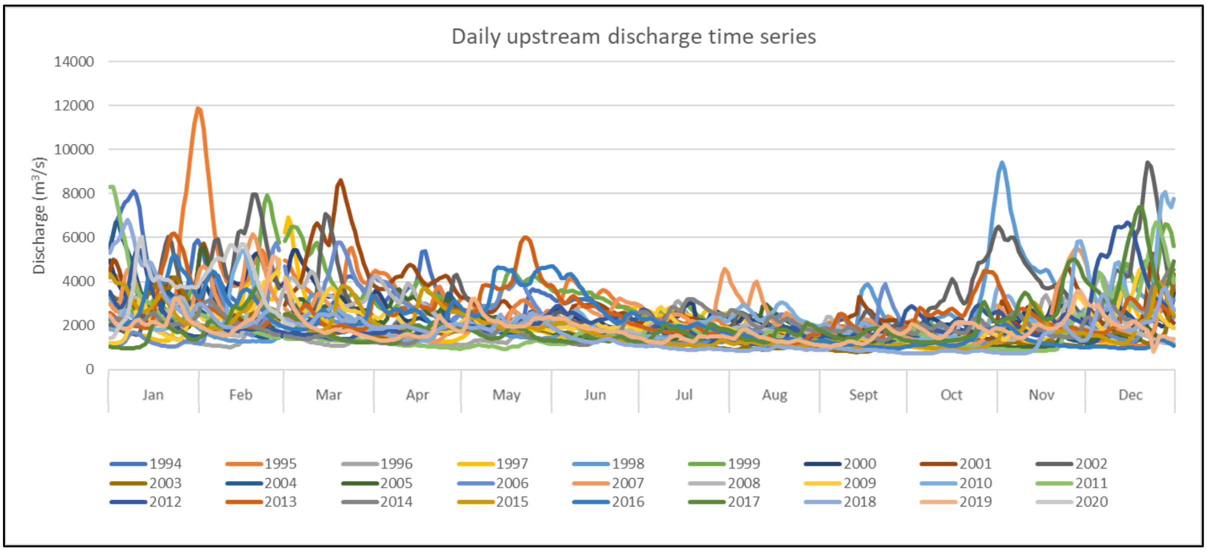

Figure A.1: Daily discharge values from the observed time series at Lobith used as upstream boundary condition. Adapted from Chavarrias et al. (2020).

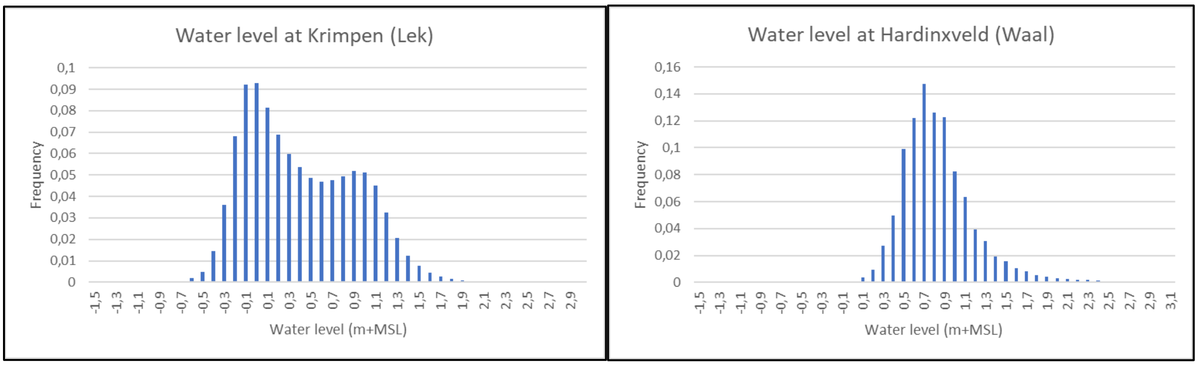

Figure A.2: Exceedance frequencies of water levels at the tidal downstream boundaries. Adapted from Chavarrias et al. (2020).

A.3: Distinction of river reaches of the Rhine River and its distributaries.

Table A.3: Distinction between river reaches of the Rhine and its distributaries used in the model as well as projected current bed level change rates of the reaches.

River	Segment	rkm start	rkm end	Length (km)	Average bed level change between 2000-2018 (cm/year)
Rhine River	German Rhine River	814,5	857,7	43,2	*No data*
	Dutch Rhine River	857,7	867,1	9,4	- 0.5
Waal River	Upper Waal River	867,1	887	19,9	-1.9
	Middle Waal River (1)	887	917,5	30,5	-0.5
	Middle Waal River (2)	917,5	933	15,5	+0.5
	Lower Waal River	933	961	28	+0.5
Pannerdensch Kanaal	Pannerdensch Kanaal	867,1	878,6	11,5	-1.1

Nederrijn-Lek Rivers	Upper Nederijn River	878,6	891,5	12,9	+1.0
	Middle Nederrijn River	891,5	922,3	30,8	+0.6
	Lower Nederrijn River	922,3	946,9	24,6	+0.6
	Lek River	946,9	988,6	41,7	+0.3
IJssel River	Upper IJssel River	878,6	911,5	32,9	-1.5
	Middle IJssel River	911,5	970	58,5	-0.3
	Lower IJssel River	970	1001,4	31,4	+0.5
	Keteldiep	1001,4	1006	4,6	*No data*
	Kattendiep	1001,4	1004,4	3	*No data*

Appendix B: Autonomous bed development of the Rhine River and its distributaries

B.1: Verification run using stationary upstream discharge of Q=2250 m^3/s

Simulated main channel averaged bed level development

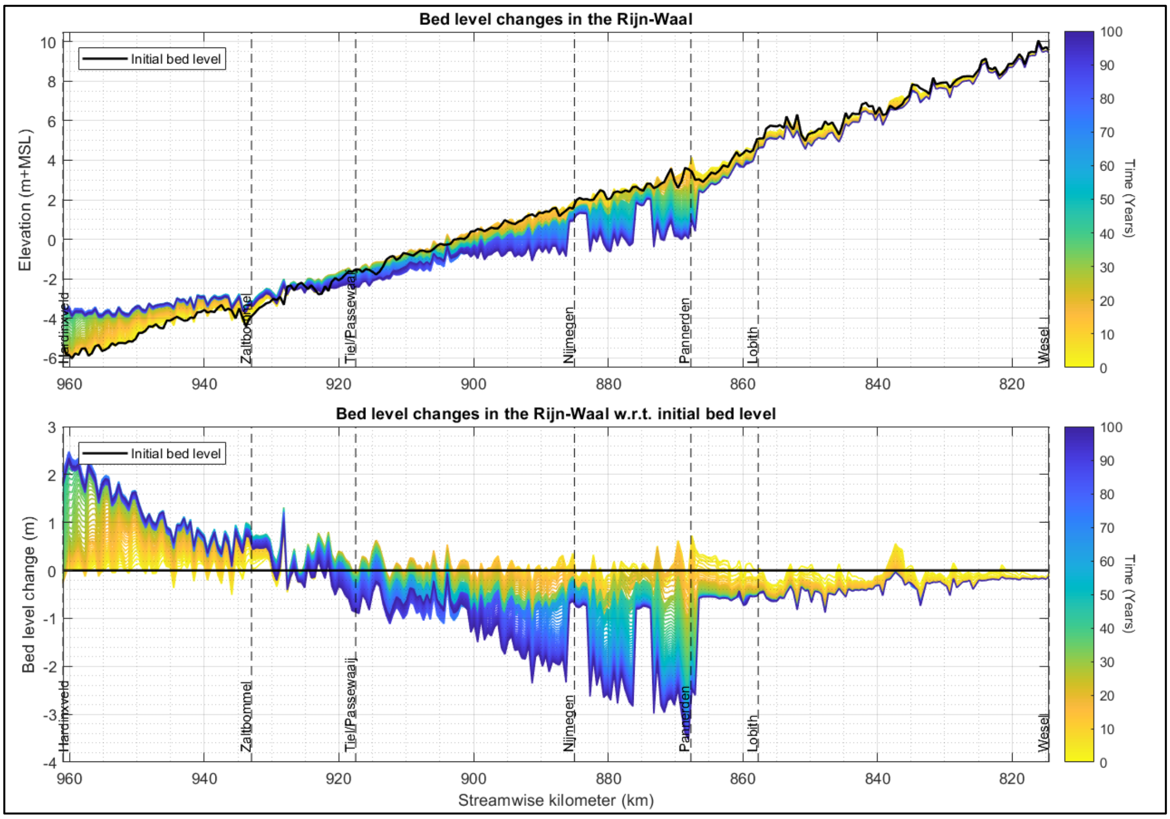

Figure B.1: Simulated bed level changes in the Rhine and Waal Rivers for a 100 year period using a stationary discharge of Q=2250 m^3/s. Top: Position of the bed level over time. Bottom: Change of bed level w.r.t. the initial bed level position.

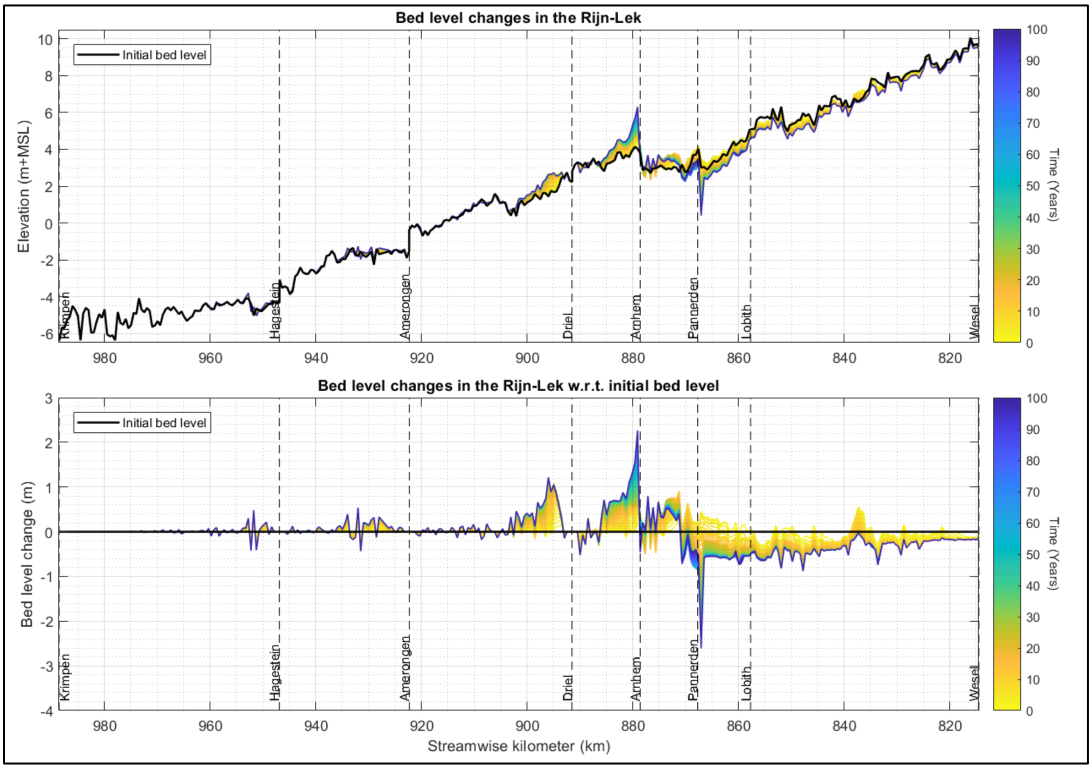

Figure B.2: Simulated bed level changes in the Rhine, Pannerdensch Kanaal, Nederrijn and Lek Rivers for a 100 year period using a stationary discharge of Q=2250 m³/s. Top: Position of the bed level over time. Bottom: Change of bed level w.r.t. the initial bed level position.

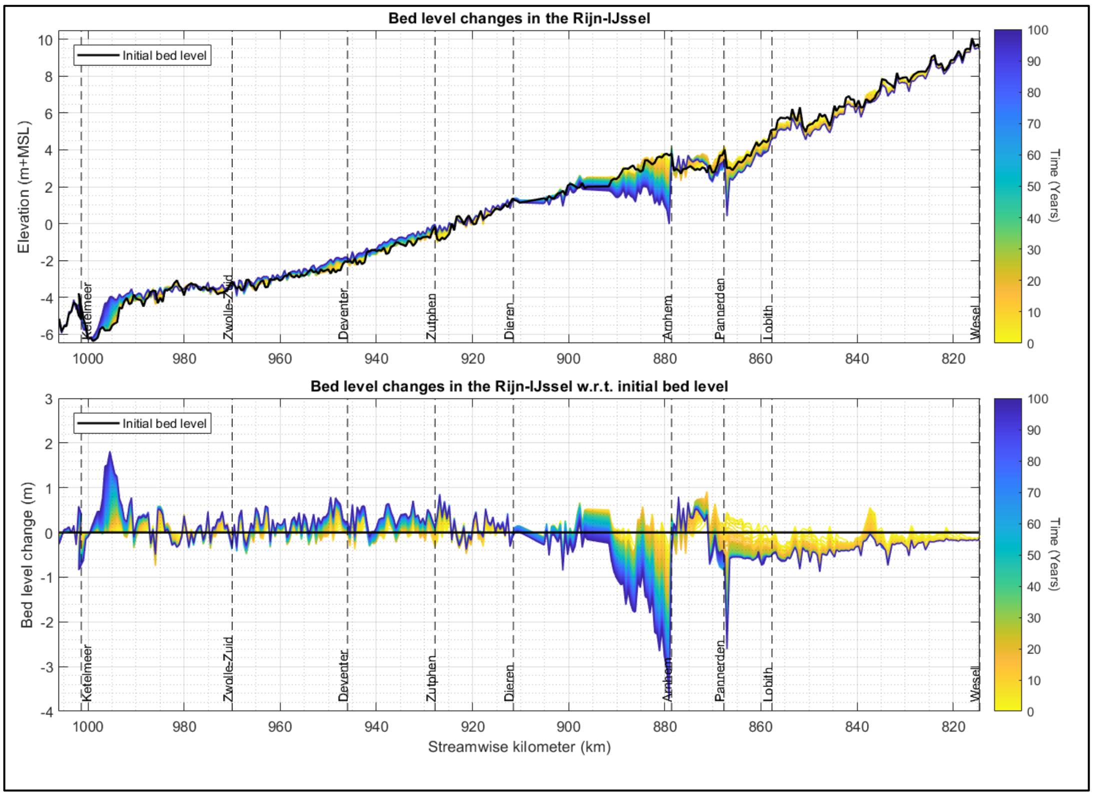

Figure B.3: Simulated bed level changes in the Rhine, Pannerdensch Kanaal and IJssel Rivers for a 100 year period using a stationary discharge of Q=2250 m³/s. Top: Position of the bed level over time. Bottom: Change of bed level w.r.t. the initial bed level position.

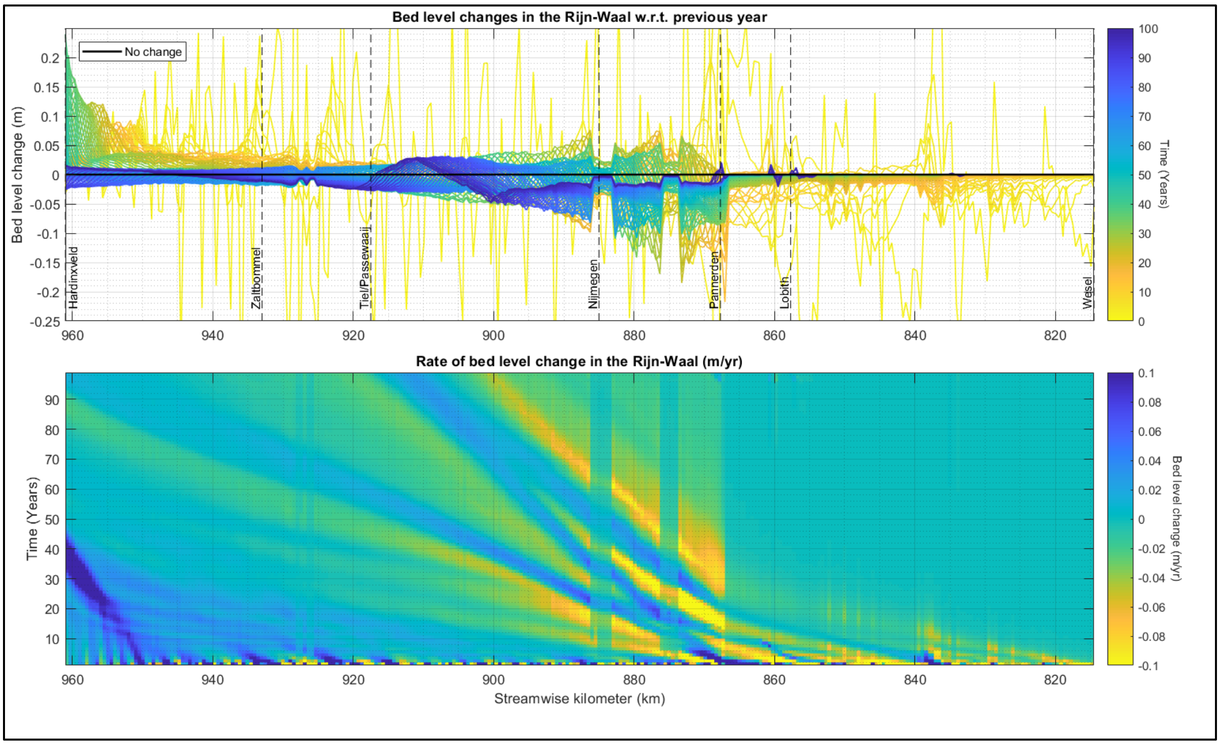

Figure B.4: Simulated rate of bed level changes w.r.t. previous year in the Rhine and Waal Rivers for a 100 year period using a stationary discharge of Q=2250 m^3/s. Top: Rate of bed level change in space using time as color scale. Bottom: Surface plot of the migration of bed level changes over time using magnitude as color scale. Graphs are capped off and do not show the extreme initial bed level changes to their full extent.

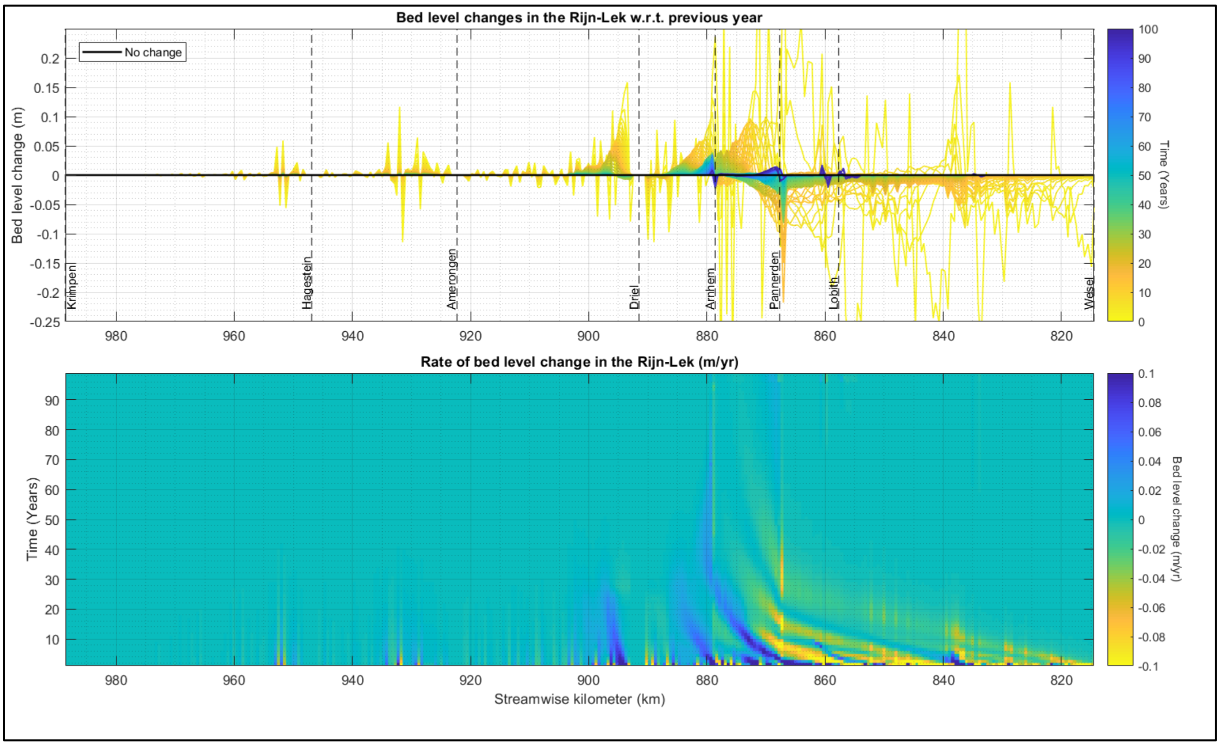

Figure B.5: Simulated rate of bed level changes w.r.t. previous year in the Rhine River, Pannerdensch Kanaal, Nederrijn and Lek Rivers for a 100 year period using a stationary discharge of Q=2250 m^3/s. Top: Rate of bed level change in space using time as color scale. Bottom: Surface plot of the migration of bed level changes over time using magnitude as color scale. Graphs are capped off and do not show the extreme initial bed level changes to their full extent.

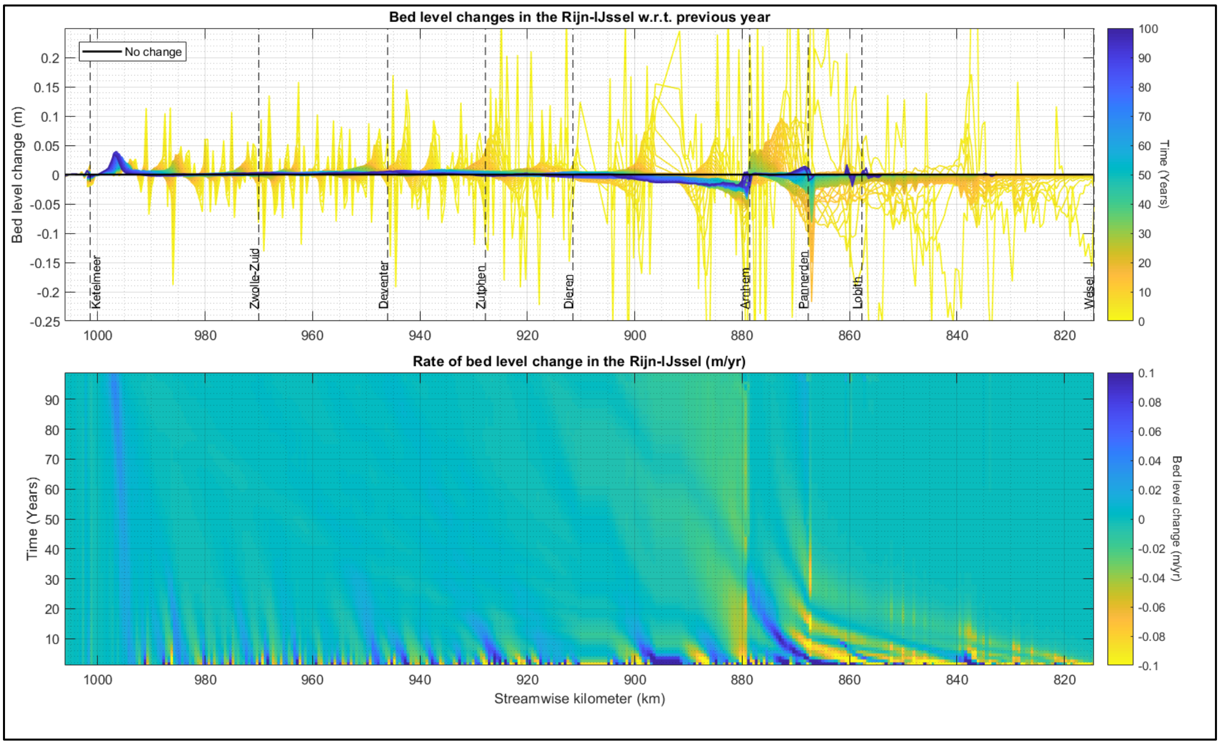

Figure B.6: Simulated rate of bed level changes w.r.t. previous year in the Rhine River, Pannerdensch Kanaal and IJssel River for a 100 year period using a stationary discharge of Q=2250 m³/s. Top: Rate of bed level change in space using time as color scale. Bottom: Surface plot of the migration of bed level changes over time using magnitude as color scale. Graphs are capped off and do not show the extreme initial bed level changes to their full extent.

Simulated grain size changes

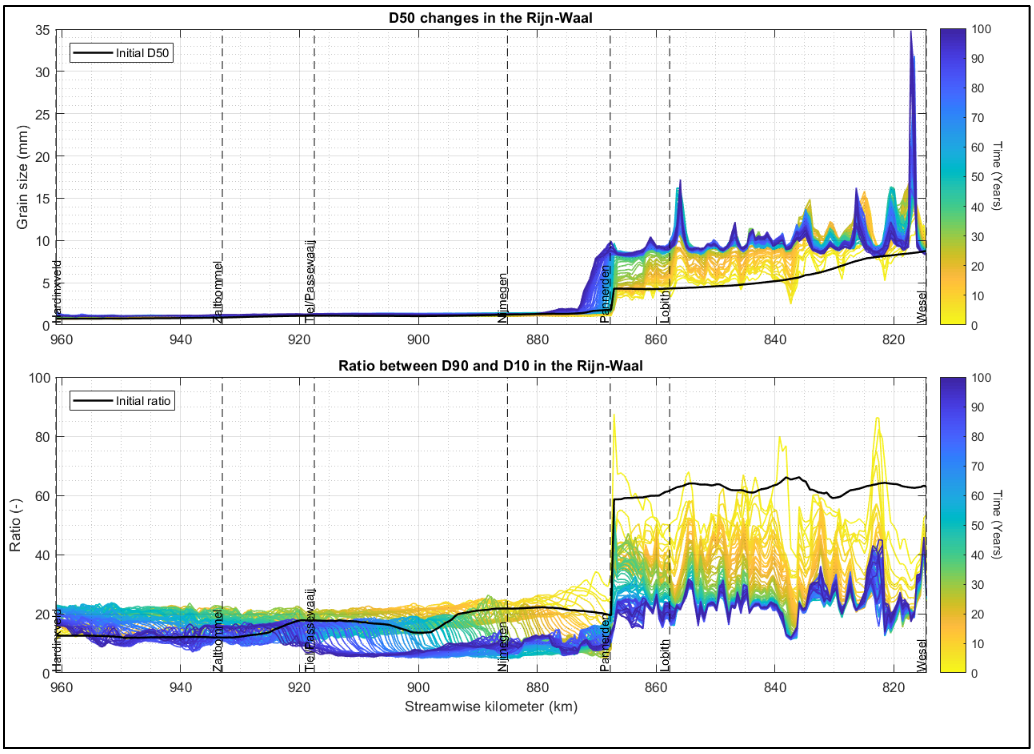

Figure B.7: Simulated grain size changes in the Rhine and Waal Rivers for a 100 year period using a using a stationary discharge of Q=2250 m³/s. Top: Changes in D50 along the rivers using over time. Bottom: Change of the D90/D10-ratio along the rivers over time.

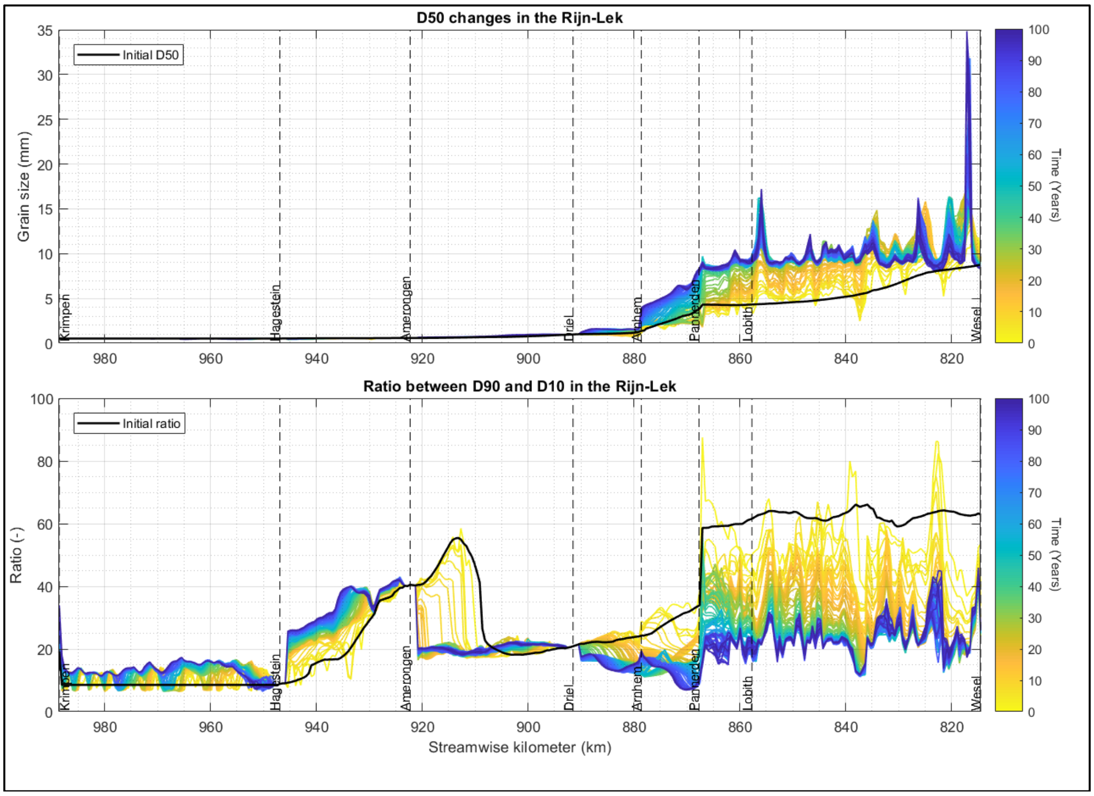

Figure B.8: Simulated grain size changes in the Rhine River, Pannerdensch Kanaal, Nederrijn and Lek Rivers for a 100 year period using a using a stationary discharge of Q=2250 m³/s. Top: Changes in D50 along the rivers using over time. Bottom: Change of the D90/D10-ratio along the rivers over time.

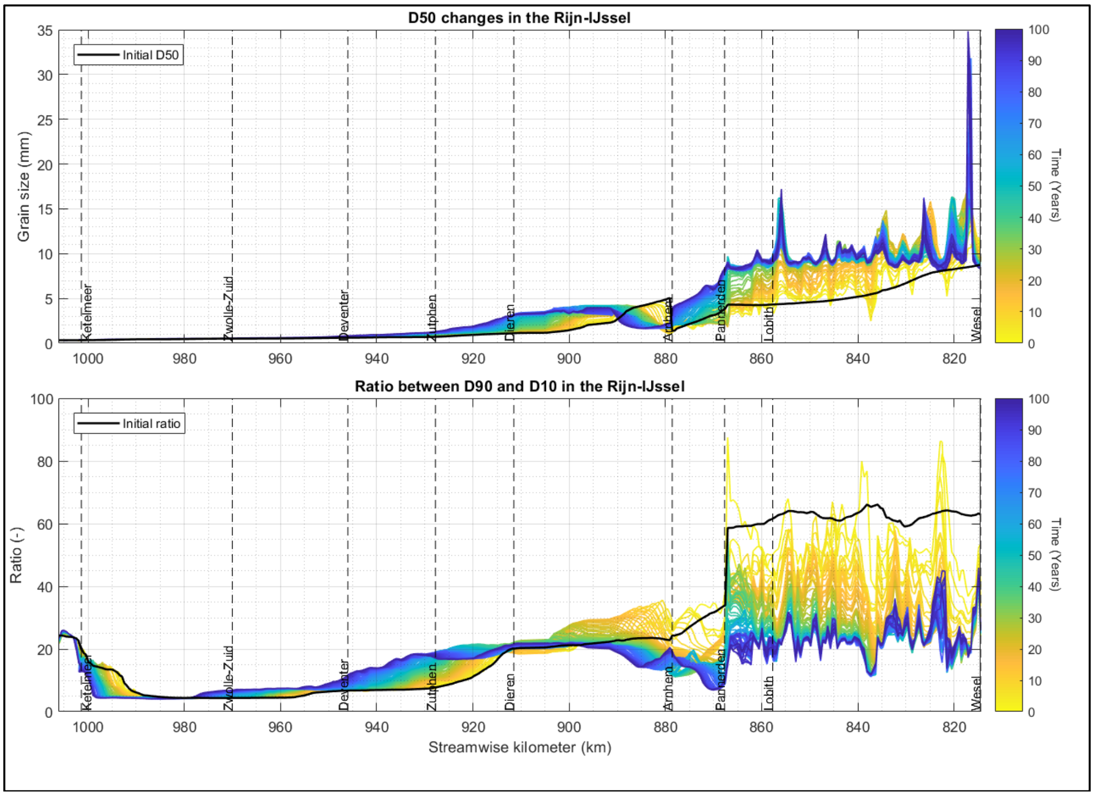

Figure B.9: Simulated grain size changes in the Rhine River, Pannerdensch Kanaal and IJssel River for a 100 year period using a using a stationary discharge of Q=2250 m³/s. Top: Changes in D50 along the rivers using over time. Bottom: Change of the D90/D10-ratio along the rivers over time.

Simulated sediment transport

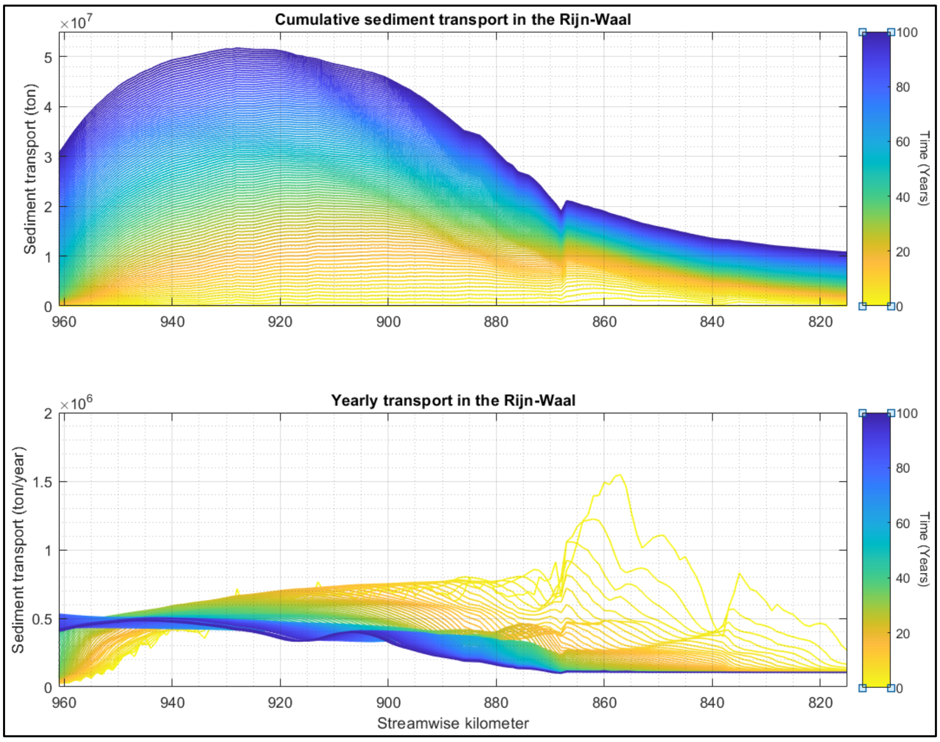

Figure B.10: Simulated grain size changes in the Rhine and Waal Rivers for a 100 year period using a stationary discharge time series of Q= 2250 m^3/s. Top: Cumulative sediment transport along the rivers over time. Bottom: Yearly sediment transport along the rivers over time.

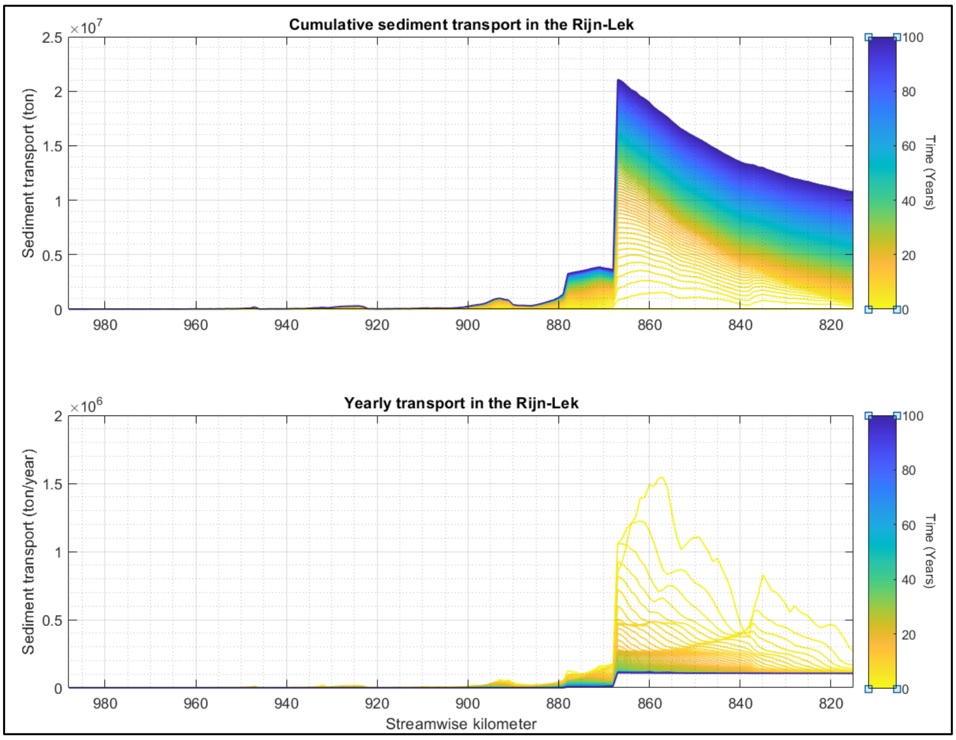

Figure B.11: Simulated grain size changes in the Rhine River, Pannerdensch Kanaal, Nederrijn and Lek Rivers for a 100 year period using a stationary discharge time series of Q= 2250 m^3/s. Top: Cumulative sediment transport along the rivers over time. Bottom: Yearly sediment transport along the rivers over time.

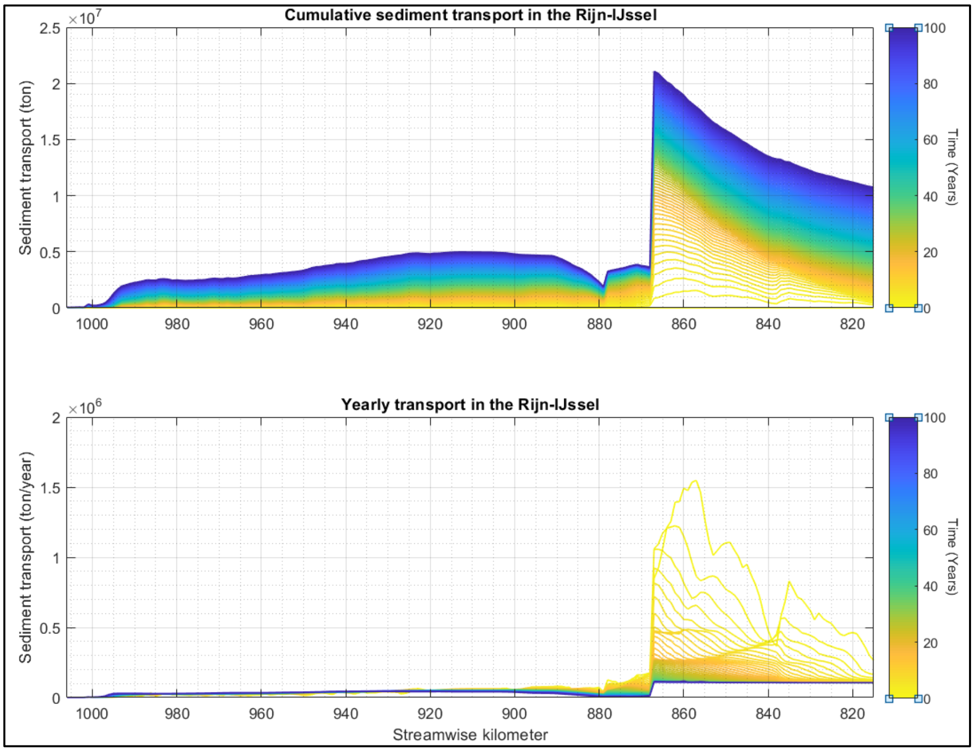

Figure B.12: Simulated grain size changes in the Rhine River, Pannerdensch Kanaal and IJssel River for a 100 year period using a stationary discharge time series of Q= 2250 m^3/s. Top: Cumulative sediment transport along the rivers over time. Bottom: Yearly sediment transport along the rivers over time.

B.2: Reference run using observed upstream discharge time series

Simulated main channel averaged bed level development

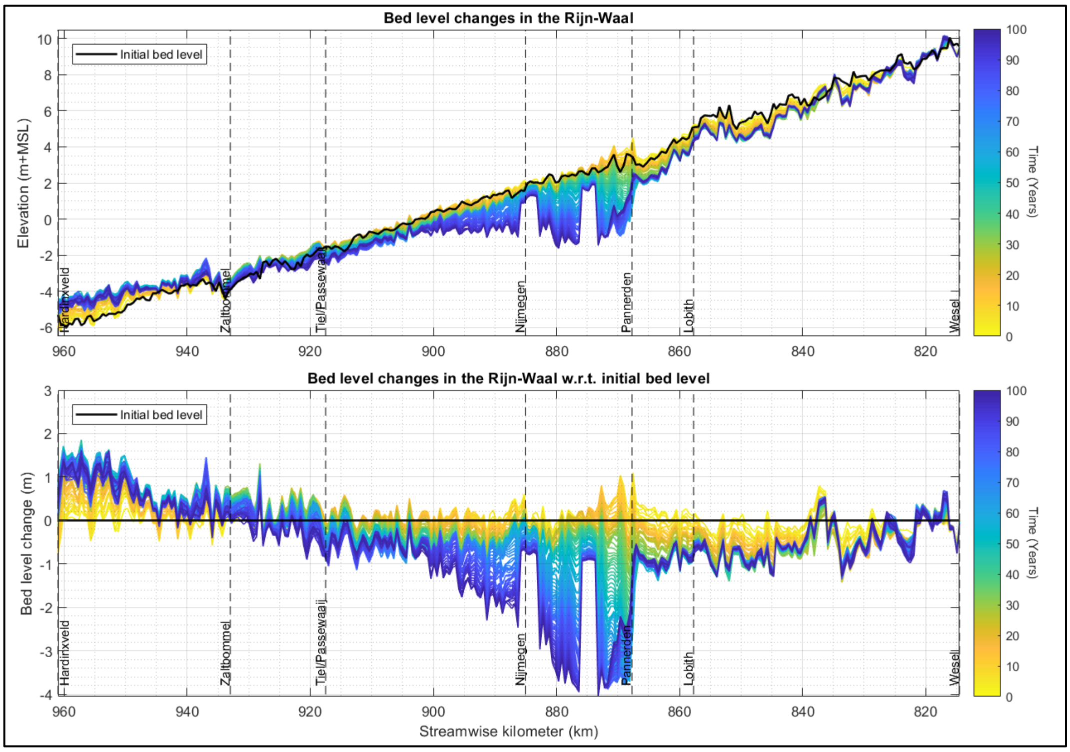

Figure B.13: Simulated bed level changes in the Rhine and Waal Rivers for a 100 year period using a historical discharge time series. Top: Position of the bed level over time. Bottom: Change of bed level w.r.t. the initial bed level position.

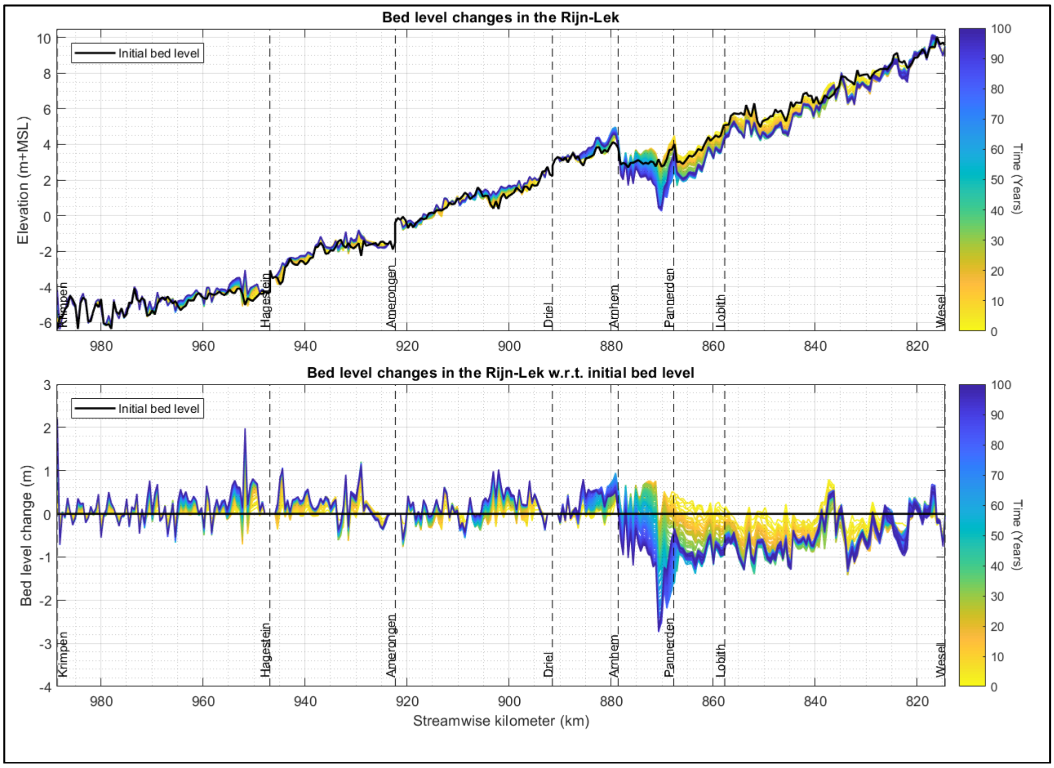

Figure B.14: Simulated bed level changes in the Rhine River, Pannerdensch Kanaal, Nederrijn and Lek Rivers for a 100 year period using a historical discharge time series. Top: Position of the bed level over time. Bottom: Change of bed level w.r.t. the initial bed level position.

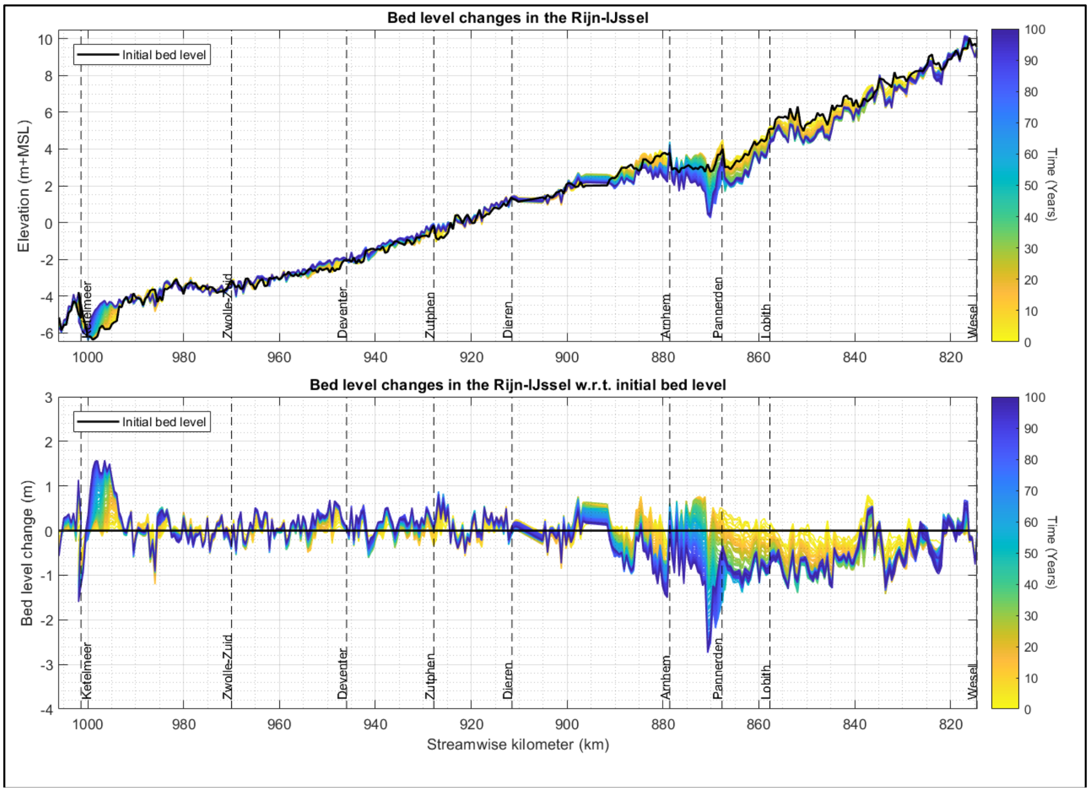

Figure B.15: Simulated bed level changes in the Rhine River, Pannerdensch Kanaal and IJssel River for a 100 year period using a historical discharge time series. Top: Position of the bed level over time. Bottom: Change of bed level w.r.t. the initial bed level position.

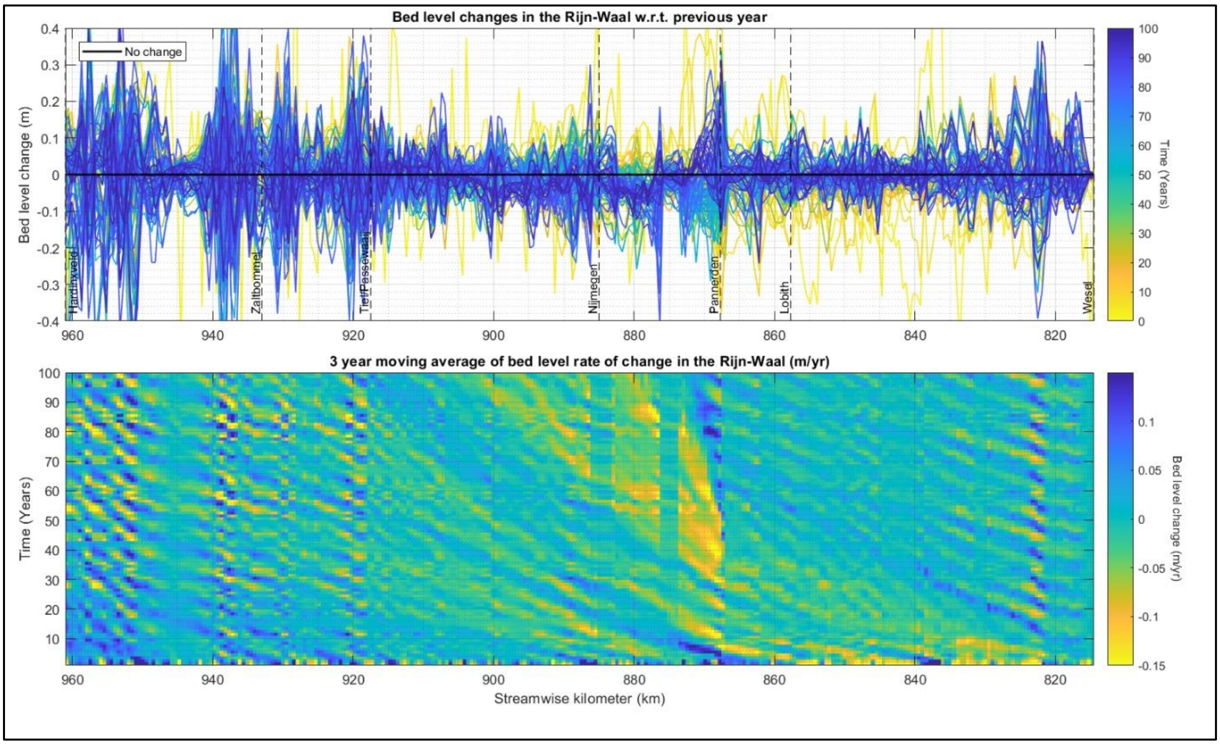

Figure B.16: Simulated rate of bed level changes w.r.t. previous year in the Rhine and Waal Rivers for a 100 year using a historical discharge time series. Top: Rate of bed level change in space using time as color scale. Bottom: Surface plot of the 3-year moving average of the rate of change of the bed over time using magnitude as color scale. Graphs are capped off and do not show the extreme initial bed level changes to their full extent.

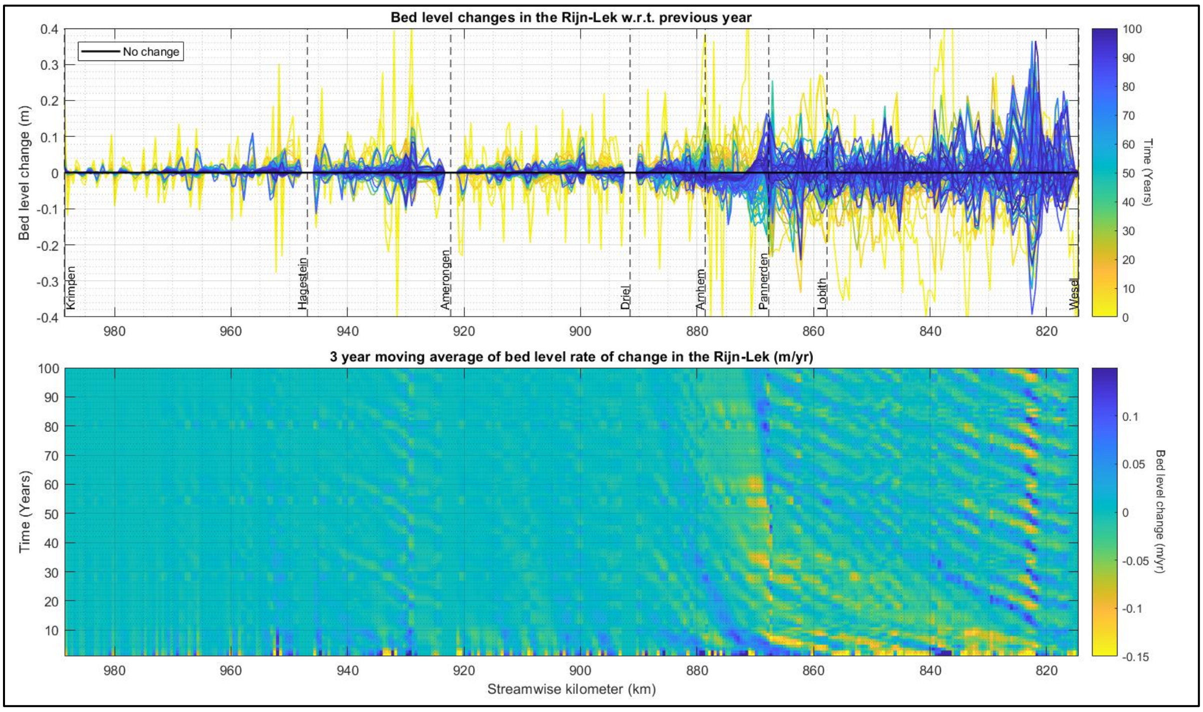

Figure B.17: Simulated rate of bed level changes w.r.t. previous year in the Rhine River, Pannerdensch Kanaal, Nederrijn and Lek Rivers for a 100 year using a historical discharge time series. Top: Rate of bed level change in space using time as color scale. Bottom: Surface plot of the 3-year moving average of the rate of change of the bed over time using magnitude as color scale. Graphs are capped off and do not show the extreme initial bed level changes to their full extent.

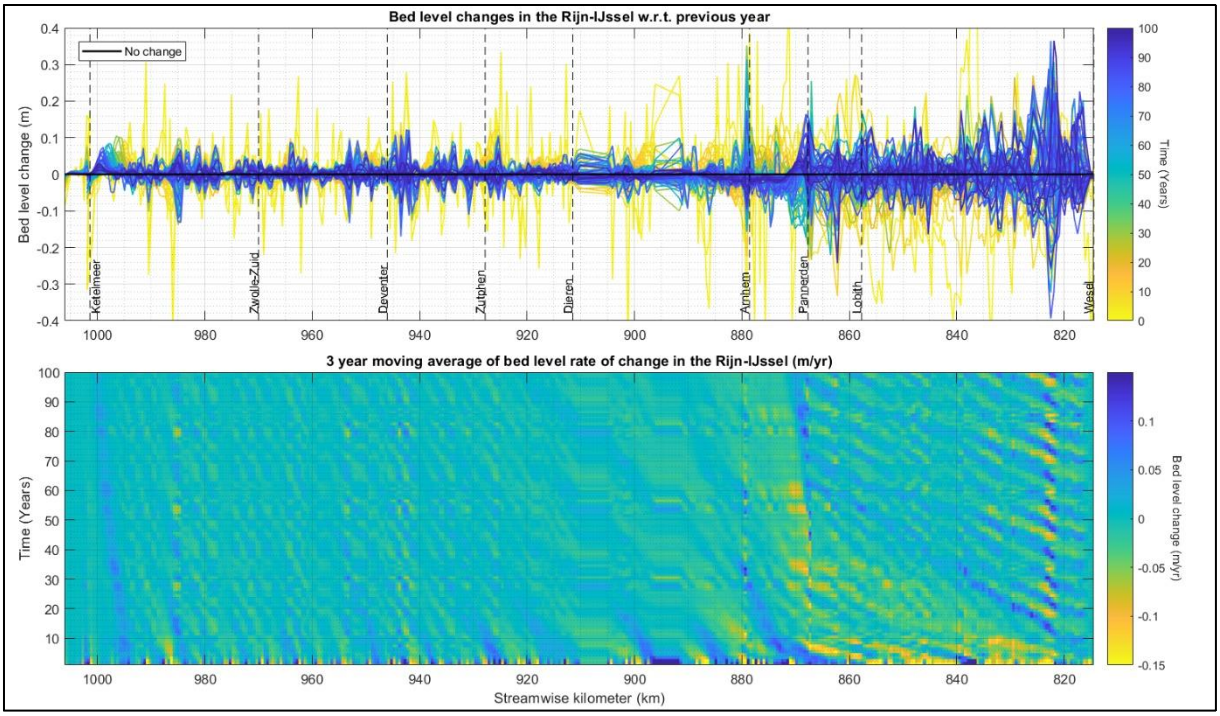

Figure B.18: Simulated rate of bed level changes w.r.t. previous year in the Rhine River, Pannerdensch Kanaal and IJssel River for a 100 year using a historical discharge time series. Top: Rate of bed level change in space using time as color scale. Bottom: Surface plot of the 3-year moving average of the rate of change of the bed over time using magnitude as color scale. Graphs are capped off and do not show the extreme initial bed level changes to their full extent.

Comparison of simulated bed level position to projection of Ylla Arbós et al. (2019)

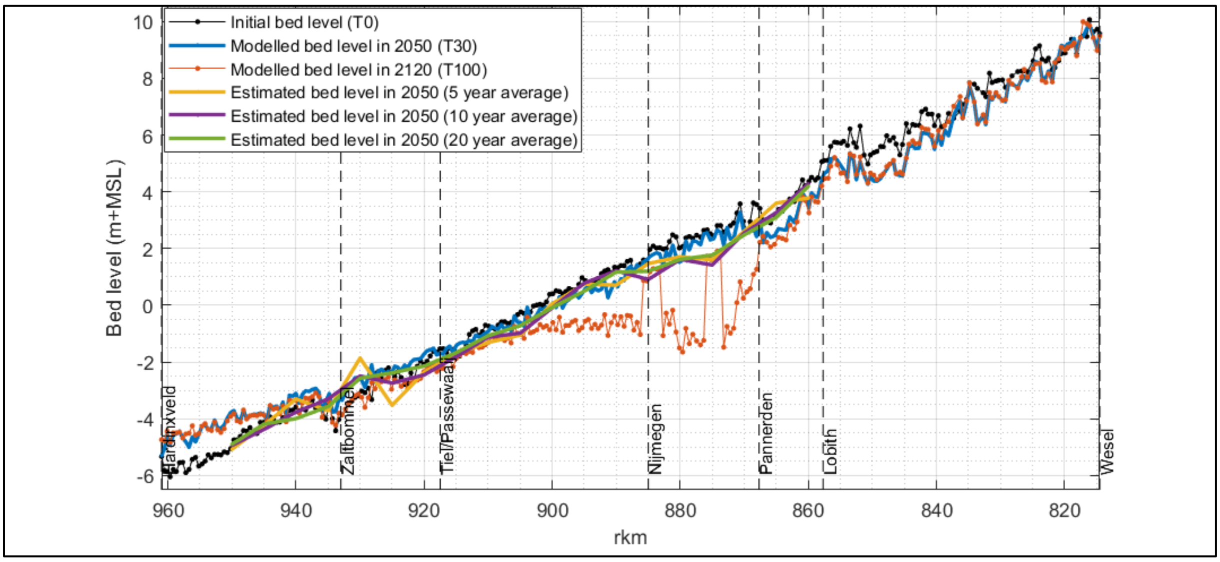

Figure B.19: Comparison of the simulated main channel averaged bed level of the Rhine and Waal Rivers to the expected bed level in 2050 based on historic 5- 10- and 20-year averaged bed degradation rates by Ylla Arbós et al. (2019).

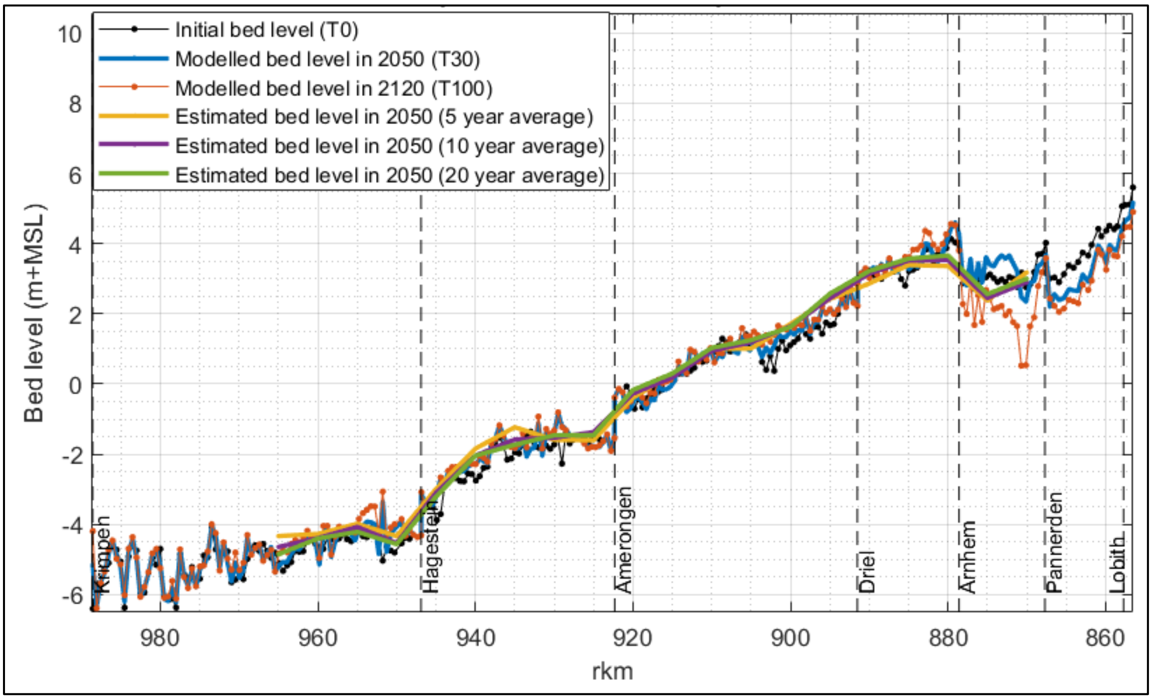

Figure B.20: Comparison of the simulated main channel averaged bed level of the Rhine River, Pannerdensch Kanaal and Nederrijn – Lek Rivers to the expected bed level in 2050 based on historic 5- 10- and 20-year averaged bed degradation rates by Ylla Arbós et al. (2019).

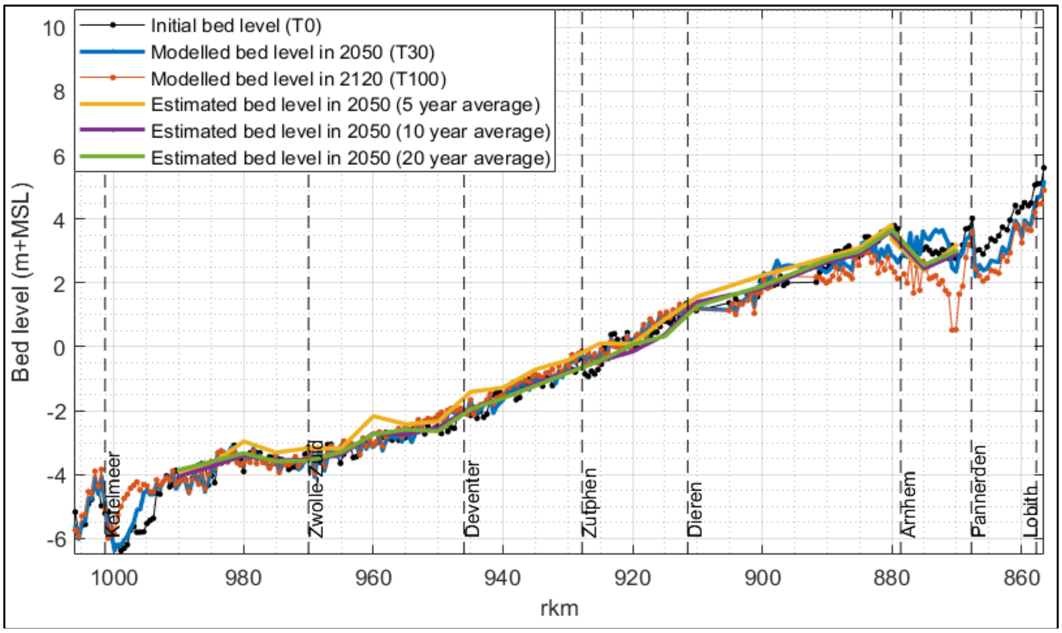

Figure B.21: Comparison of the simulated main channel averaged bed level of the Rhine River, Pannerdensch Kanaal and IJssel River to the expected bed level in 2050 based on historic 5- 10- and 20-year averaged bed degradation rates by Ylla Arbós et al. (2019).

Simulated grain size changes

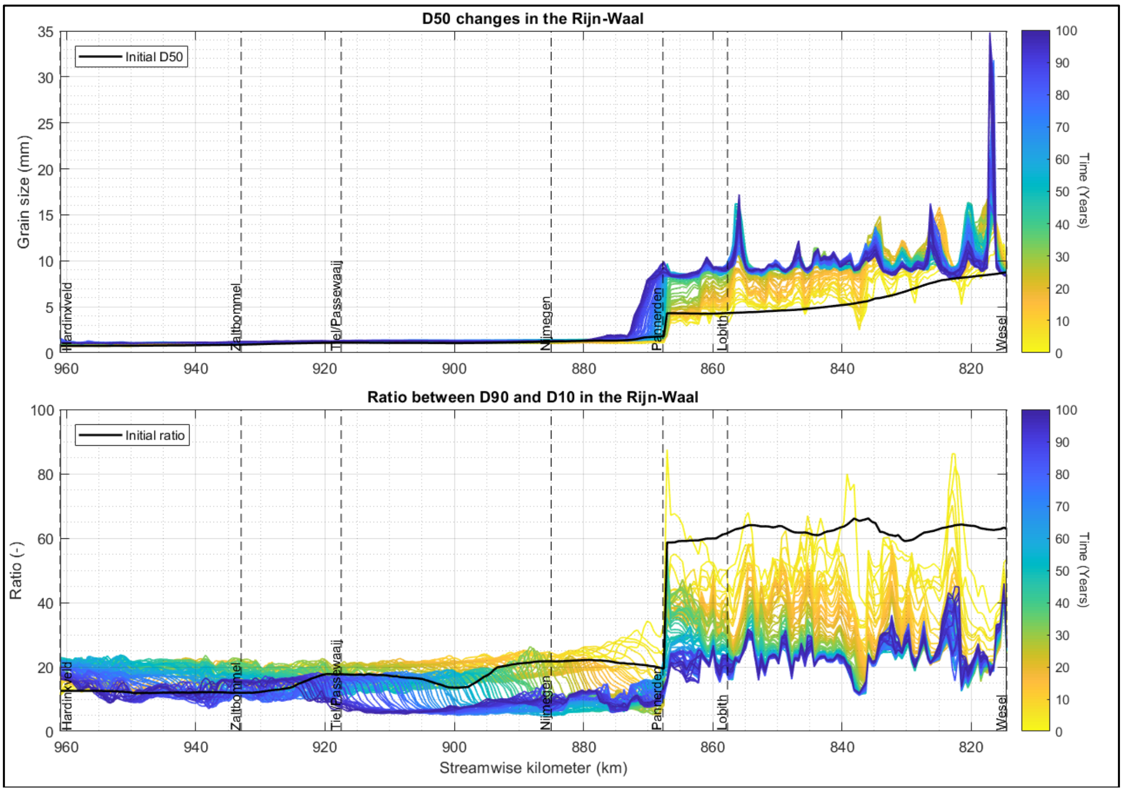

Figure B.22: Simulated grain size changes in the Rhine and Waal Rivers for a 100 year period using a historical discharge time series. Top: Changes in D50 along the rivers using over time. Bottom: Change of the D90/D10-ratio along the rivers over time.

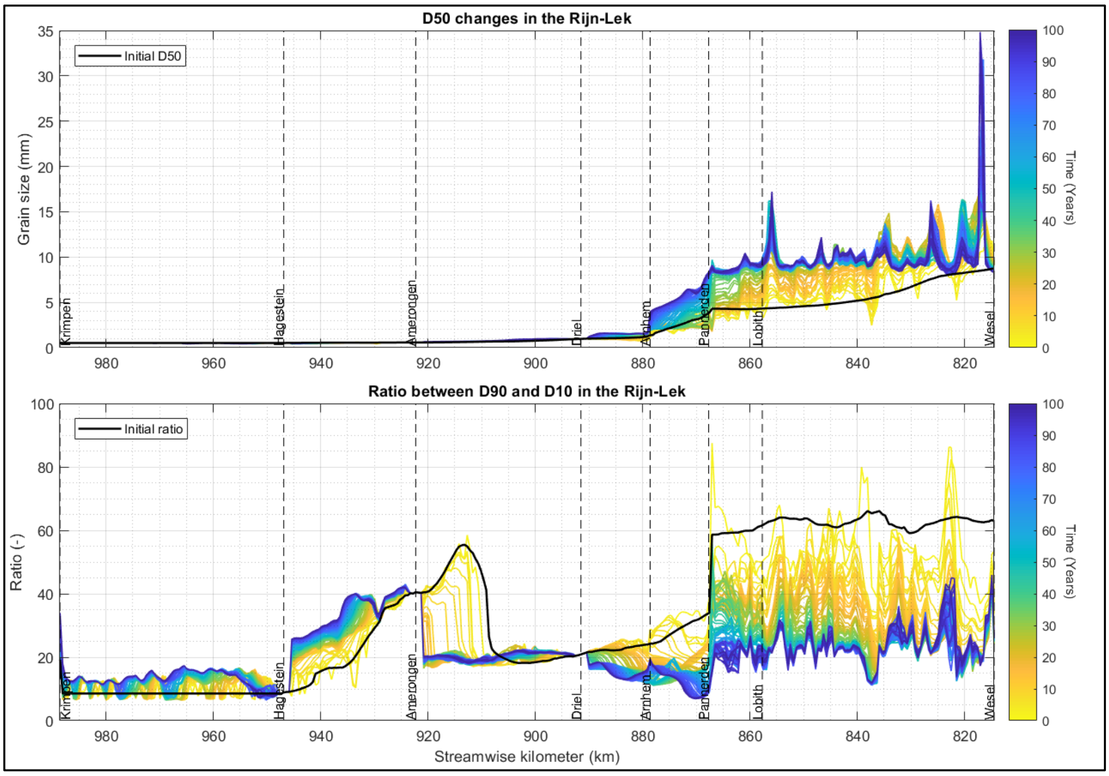

Figure B.23: Simulated grain size changes in the Rijn, Pannerdensch Kanaal, Nederrijn and Lek Rivers for a 100 year period using a historical discharge time series. Top: Changes in D50 along the rivers using over time. Bottom: Change of the D90/D10-ratio along the rivers over time.

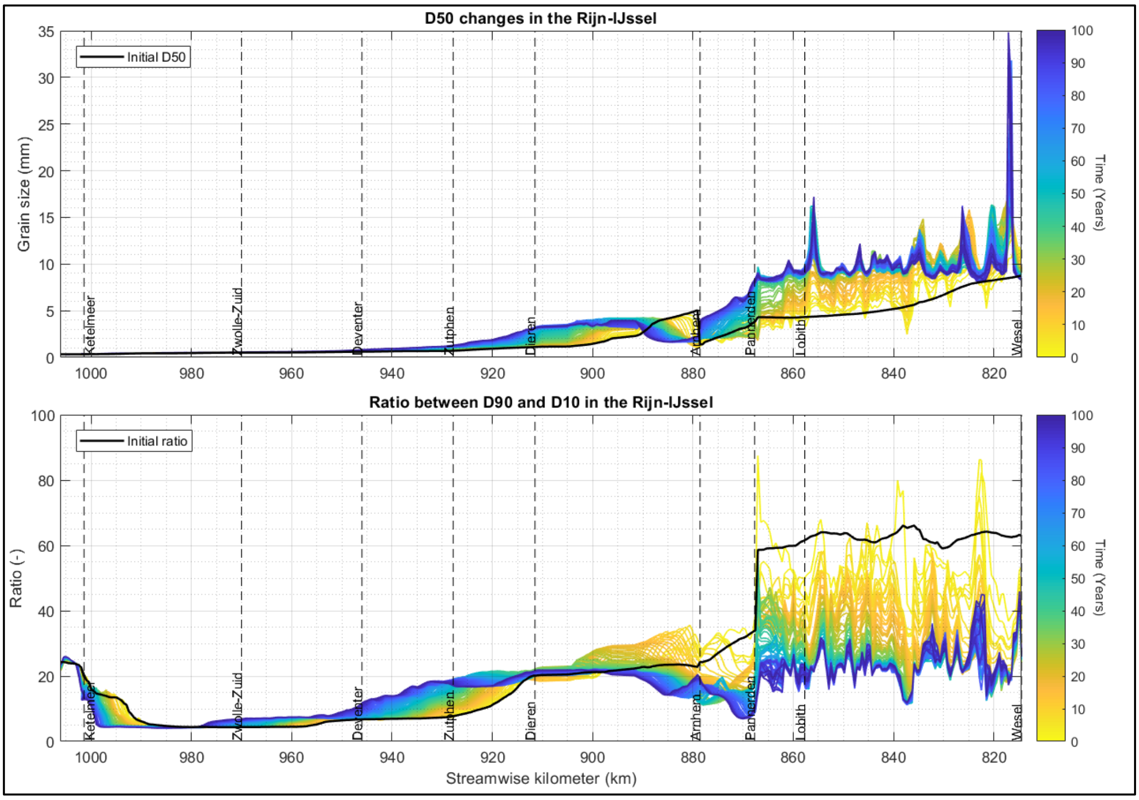

Figure B.24: Simulated grain size changes in the Rijn, Pannerdensch Kanaal and IJssel Rivers for a 100 year period using a historical discharge time series. Top: Changes in D50 along the rivers using over time. Bottom: Change of the D90/D10-ratio along the rivers over time.

Simulated sediment transport

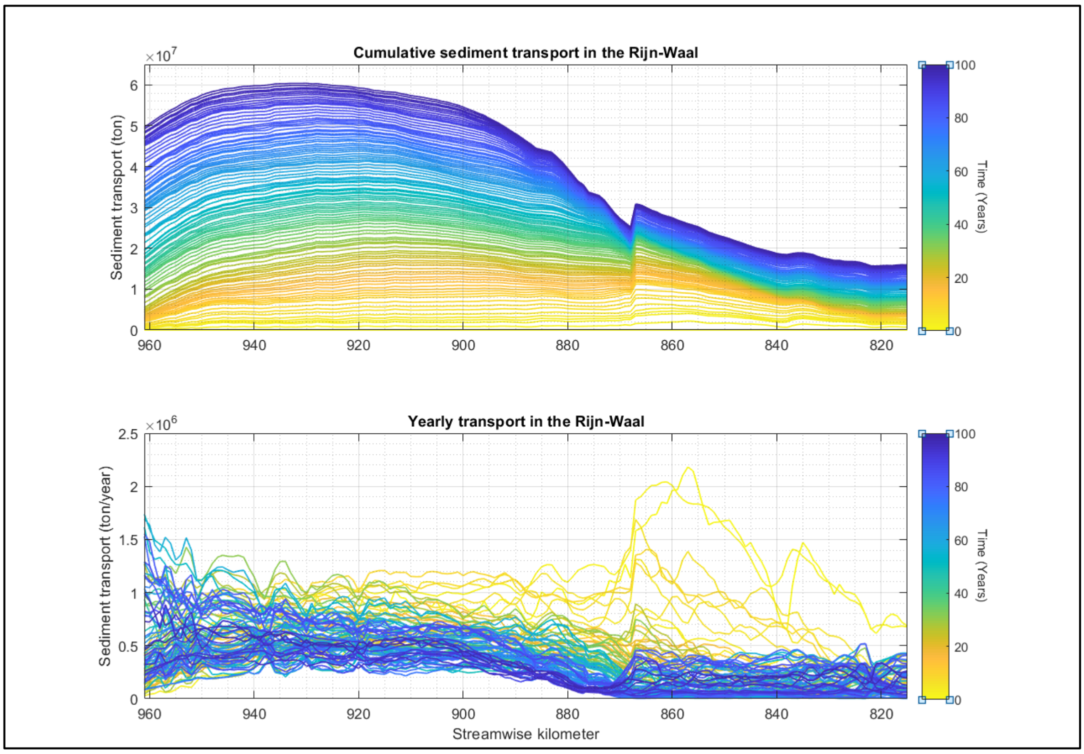

Figure B.25: Simulated sediment transport in the Rhine and Waal Rivers for a 100 year period using a historical discharge time series. Top: Cumulative sediment transport along the rivers over time. Bottom: Yearly sediment transport along the rivers over time.

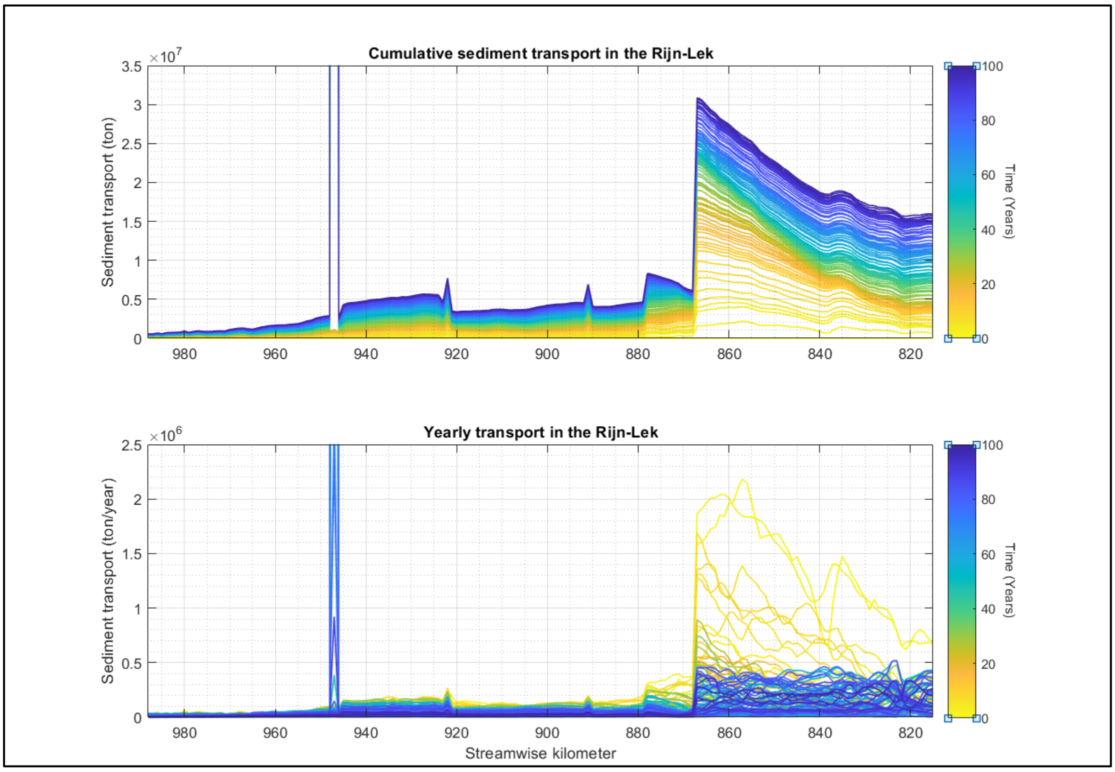

Figure B.26: Simulated sediment transport in the Rhine River Pannerdensch Kanaal and Nederrijn and Lek Rivers for a 100 year period using a historical discharge time series. Top: Cumulative sediment transport along the rivers over time. Bottom: Yearly sediment transport along the rivers over time.

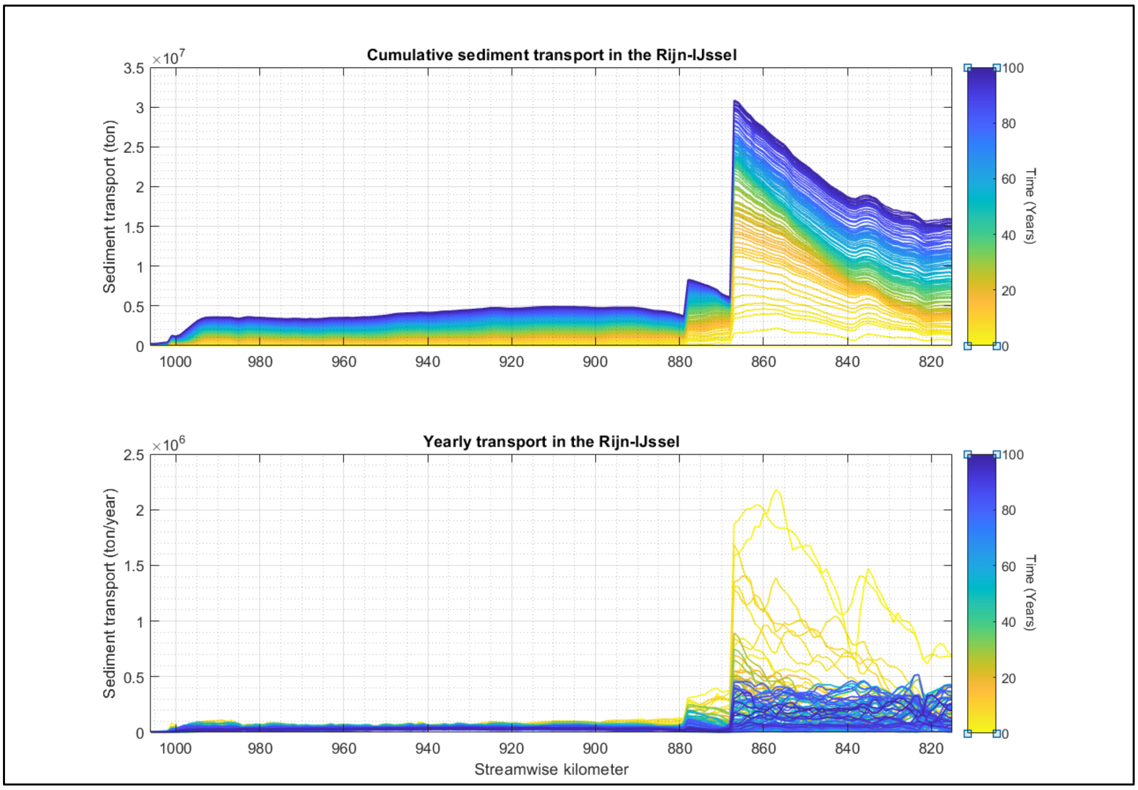

Figure B.27: Simulated sediment transport in the Rhine River, Pannerdensch Kanaal and IJssel River for a 100 year period using a historical discharge time series. Top: Cumulative sediment transport along the rivers over time. Bottom: Yearly sediment transport along the rivers over time.

Appendix C: Bed development of the Rhine River and its distributaries under influence of side channels

Bed development under influence of side channels in the Waal River

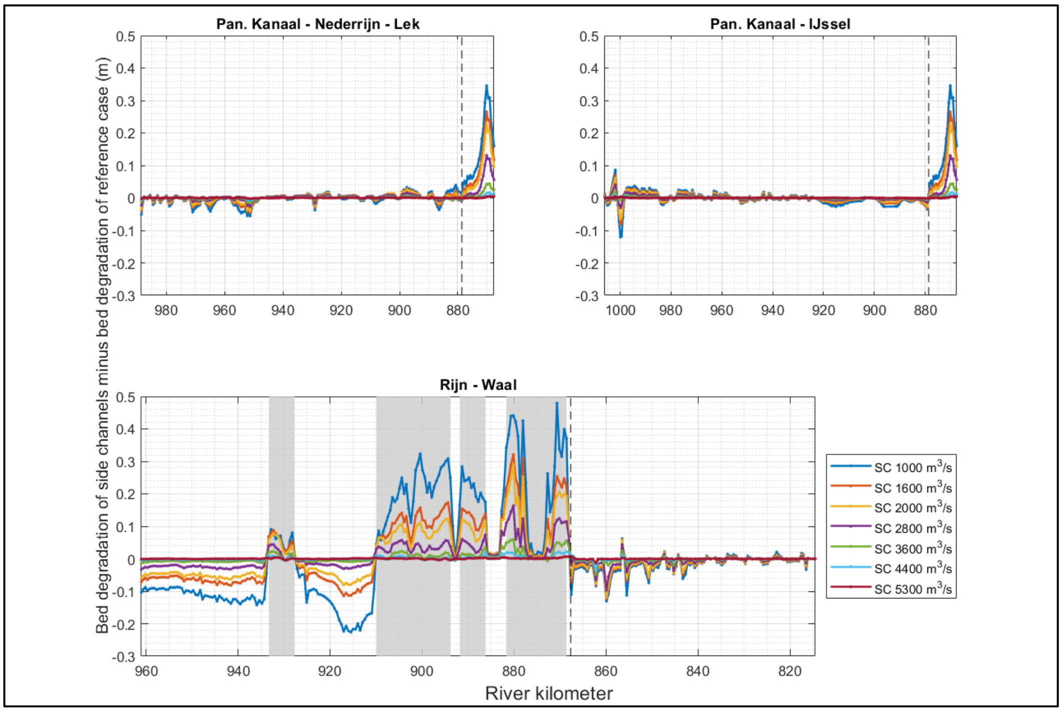

Figure C.1: Three-year averaged effects of side channels in the Waal River on main channel bed degradation in the distributaries of the Rhine River compared to reference bed degradation. Side channels are indicated by grey bands. Colors indicate the starting discharge for side channels to flow (m^3/s at Lobith).

Sediment transport along the Rhine and Waal Rivers under influence of side channels in the Waal River.

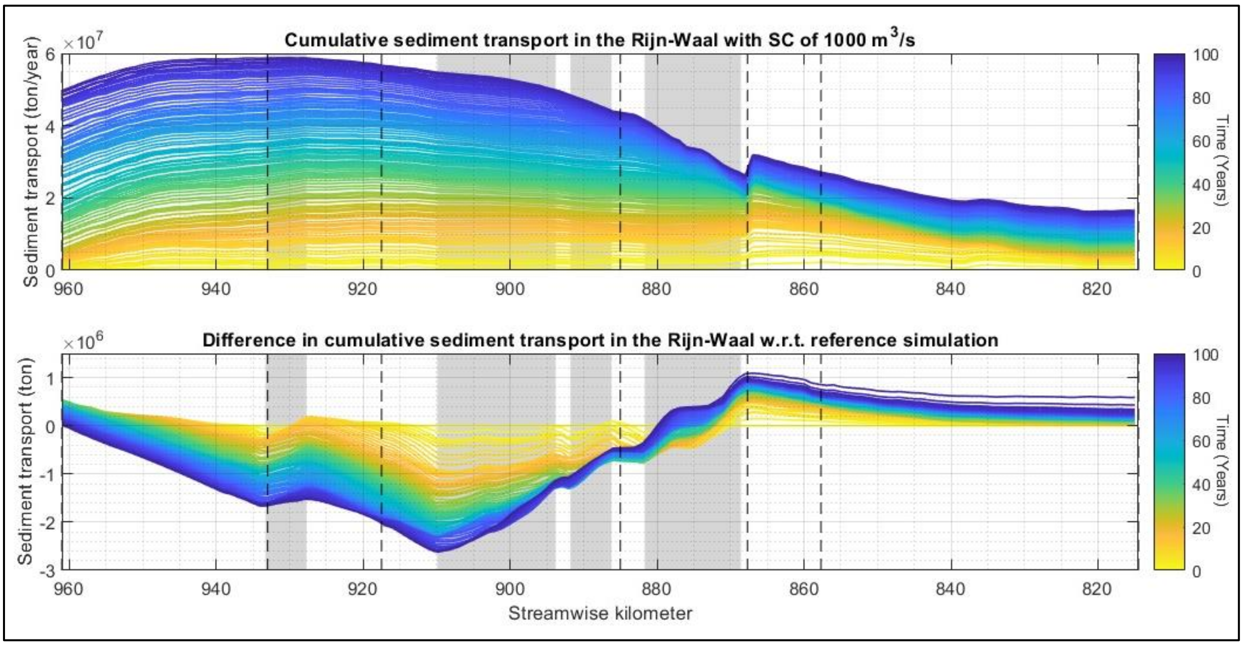

Figure C.2: Effect of channels in the Waal River on sediment transport in the Rhine and Waal Rivers over time. Top: Cumulative sediment transport in the Rhine and Waal Rivers. Bottom: Differences in sediment transport between a case with side channels and the reference case. Side channels are indicated by grey bands.

Bed development under influence of side channels in the Pannerdensch Kanaal

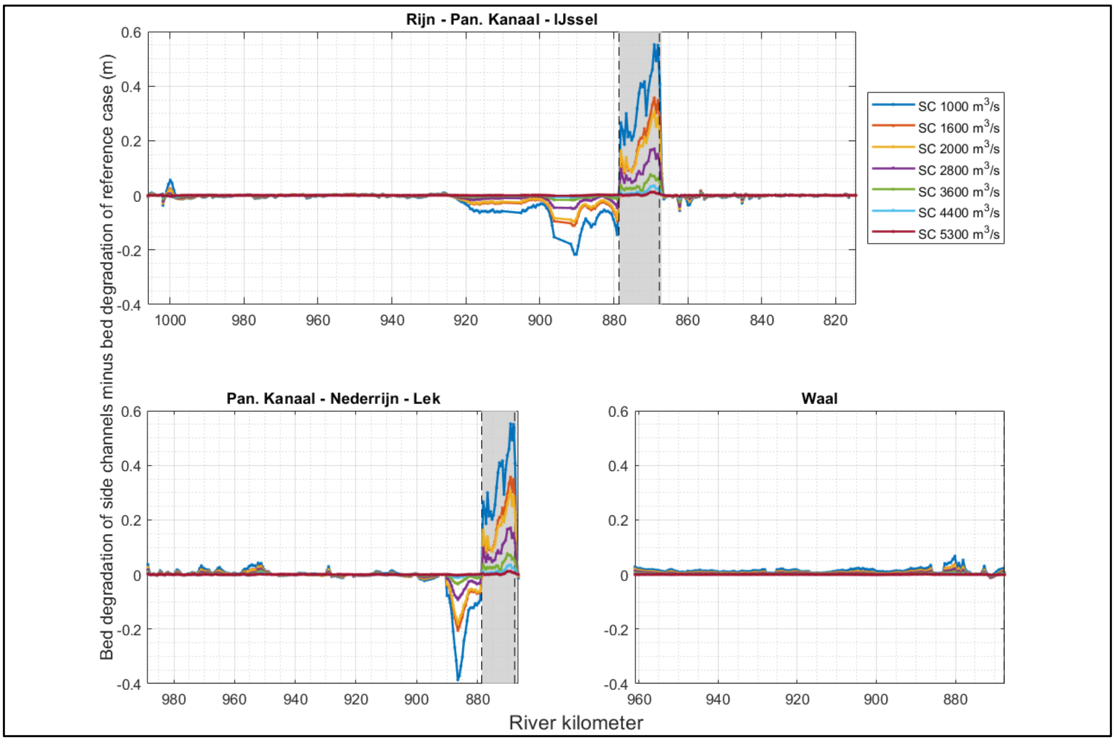

Figure C.3: Three-year averaged effects of side channels in the Pannerdensch Kanaal on main channel bed degradation in the distributaries of the Rhine River compared to reference bed degradation. Side channels are indicated by grey bands. Colors indicate the starting discharge for side channels to flow (m^3/s at Lobith).

Bed development under influence of side channels in the IJssel River

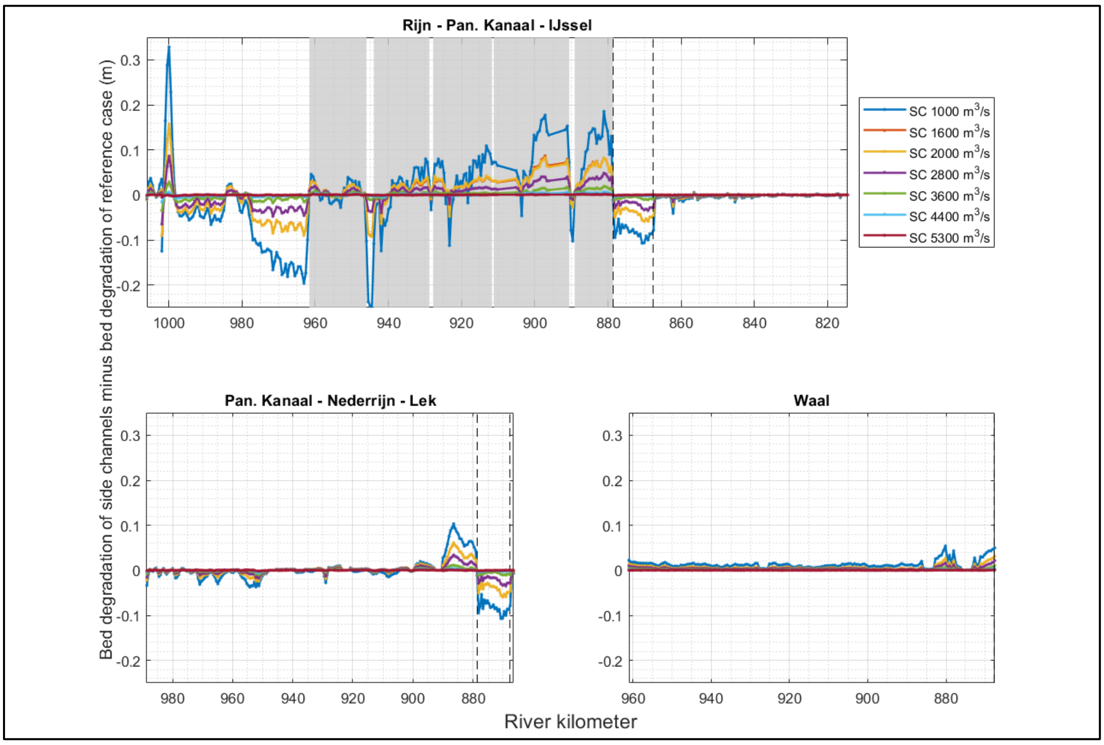

Figure C.4: Three-year averaged effects of side channels in the IJssel River on main channel bed degradation in the distributaries of the Rhine River compared to reference bed degradation. Side channels are indicated by grey bands. Colors indicate the starting discharge for side channels to flow (m^3/s at Lobith).

Bed development under influence of side channels both Pannerdensch Kanaal and Waal River

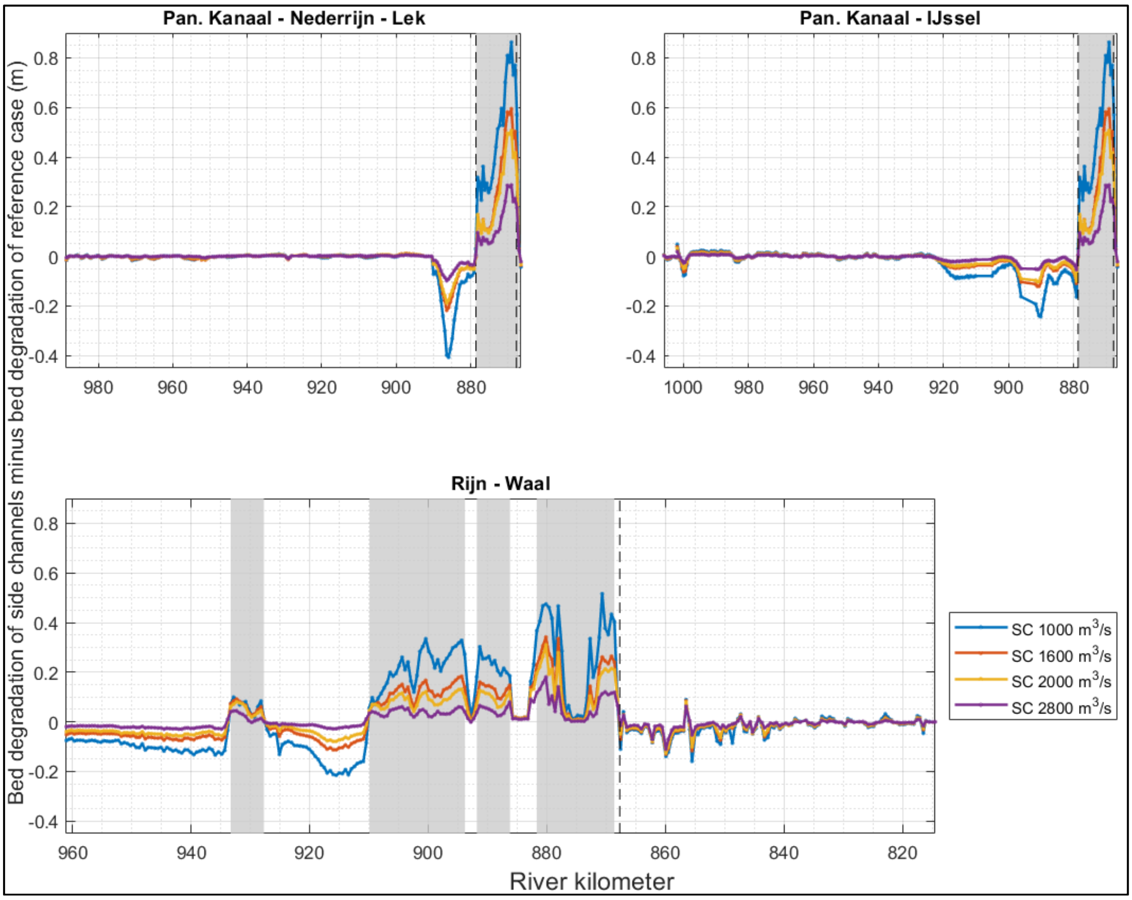

Figure C5: Three-year averaged effects of side channels in the Waal River on main channel bed degradation in the distributaries of the Rhine River compared to reference bed degradation. Side channels are indicated by grey bands. Colors indicate the starting discharge for side channels to flow (m^3/s at Lobith).