Master Thesis

The effects of different designs of longitudinal training dams on countering bed degradation for different discharge scenarios in the River Waal

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Preface

This thesis is the final product of my master's degree in Civil Engineering and Management at the University of Twente. During my graduation period, I studied the morphological effects that longitudinal training dams have on the river Waal for different discharge scenarios.

This project was executed at Royal HaskoningDHV with the support of Rijkswaterstaat. I want to thank Wiebe de Jong from Royal HaskoningDHV for the daily supervision and support. His extensive knowledge of the Dutch river system made me enthusiastic to dive deeper into river modelling and the overall functioning of the Dutch river systems. His feedback and critical questions kept me on track during the process. I enjoyed going to the offices of Royal HaskoningDHV where I felt part of a great team of experts. I want to thank my colleagues that helped me during my graduation process.

Next to this, I want to thank my supervisors from the University of Twente. I want to thank Vasilis Kitsikoudis for the feedback and the valuable meetings. His critical questions and remarks made me make the most of the graduation process. Additionally, I want to thank Denie Augustijn for his valuable feedback and input during the meetings. He made sure the graduation process went smoothly. Both supervisors were valuable sparring partners and at any point in time, I felt like I could reach out to both supervisors with questions.

Additionally, I want to thank Saskia van Vuren from Rijkswaterstaat for providing her knowledge on the Dutch river system and involving me in meetings for the Integral River Management programme. Her critical questions and feedback enhanced the practical relevance of this thesis.

Finally, I want to thank my family and friends who supported me during my graduation process. I am grateful for their support, which has kept me positive and motivated during the process.

I enjoyed the process of graduating despite the small struggles. The process made me enthusiastic about integrated river projects and encourages me to continue working on these engineering projects. A lot of uncertainties remain in the approach to handling bed degradation in the Dutch Rhine system. I hope this thesis will be of use to others and that it will help to find the approach to handle bed degradation in the Dutch Rhine system.

I hope you enjoy your reading.

Cas Pfeijffer

August 2023

Abstract

The ongoing bed degradation in the river Waal, resulting from human interventions in the Dutch Rhine system, affects several functions in the river system. The bed degradation leads to problems regarding navigation depth, flood safety, the stability of infrastructure, nature and water supply. The Integrated River Management (IRM) programme was initiated in 2020 to anticipate climate change and its possible consequences by making the Dutch river system future-proof. The IRM programme aims to stabilise the bed level of the Dutch Rhine branches. Longitudinal training dams (LTDs) are a proposed measure for the IRM programme to achieve the desired stabilisation of the bed. Previous research demonstrated that LTDs are a promising measure in countering bed degradation. A pilot on LTDs at Tiel shows that LTDs counter bed degradation in the short-term, more time is required to measure the long-term effects. Previous studies also looked at the effects of extending the LTDs in the Midden-Waal and to the Boven-Waal, however, these studies did no assess different designs of LTDs or the influence of climate change, which was the objective of this study.

This research makes use of a 2D-modelling approach using the DVR model. This model is based on the computational core of Delft3D-4 and can simulate long-term large-scale morphological changes. The difference in bed level is assessed over 20 years of morphological development for different designs of LTDs to identify possible improvements regarding the design of LTDs. Next to this, different climate change projections are translated into discharge scenarios to assess the effectiveness of LTDs to cope with climate change.

The results of the model show that bed degradation in the Boven-Waal is reduced with the introduction of new LTDs in both the Boven-Waal and Midden-Waal. However, the introduction of these new LTDs results in erosion in the main channel of the Midden-Waal and Beneden-Waal. On the other hand, LTDs reduce water levels at high discharges and increase the discharge towards the Pannerdensch Kanaal during low discharges, which is desired. The LTD designs are assessed on reducing erosion, sufficient navigation depths, lowering water levels during high discharges and increasing discharge towards the Pannerdensch Kanaal during low discharges. Out of the assessed designs of LTDs, it is concluded that widening the riparian channel performs best based on the assessed criteria. LTDs in combination with climate change will counter bed degradation in the Boven-Waal over 20 years. However, bed degradation in the Midden-Waal accelerates as a result of climate change in both cases, with and without new LTDs. Without the new LTDs, sedimentation in the Beneden-Waal is reduced as a result of climate change. The bed of the Beneden-Waal degrades as a result of LTDs and climate change slightly accelerates this degradation.

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1 Introduction

Rivers in the Dutch river system are heavily modified to meet the needs of navigation and to control the course of the river. The Dutch Rhine system is straightened and narrowed by implementing groynes (Le et al., 2020). The canalisation process started in 1871 and changed the Dutch Rhine branches to their current state (Klemann, 2015). The heavy modifications to improve navigation and control the course of the river also have had unforeseen side effects leading to long-term bed degradation. The canalisation led to an increase in flow velocity in the river, higher flow velocities increase sediment transport which results in erosion.

1.1 Background on bed degradation in the Dutch Rhine branches

Bed degradation affects several functions in the river system. First, navigation is affected since the riverbed does not degrade uniformly over the whole length of the river, which may add to the non-uniformity of the riverbed morphology. This leads to problems, especially during low discharges when some parts of the river system have insufficient navigation depth. Fixation of the riverbed aggravates this problem. The riverbed is degrading which in turn leads to lower water levels over the river length, but the fixed layer remains at the same level leading to small water depths over the layer. Next to this, entering harbour facilities, sluices, and canals is made more difficult since these structures do not descend (Sloff et al., 2023). The fixed layers can be seen as bumps in the river system, the layer also leads to erosion pits downstream of the fixed layer (Arcadis, 2022). The transition from a fixed layer to a sandy bed is a hydrodynamic trigger for local scour. Sediment transport over the fixed layer is lower than the sediment transport capacity, this is caused by the supply of sediment being low at a fixed layer in comparison to a sandy bed. This results in erosion at the transition from the fixed layer to the sandy bed. This causes the sandy bed to be lower than the fixed layer, which enhances turbulence and leads to the formation of an erosion pit. The sudden transition from the fixed layer to the erosion pit leads to a drop in water level above the fixed layer (Arcadis, 2022). The decrease in water depth above the fixed layer can pose a threat to ships due to the squat effect. The squat effect is caused by the formation of a low-pressure area underneath a ship when it navigates over a shallow area, increasing the immersion of the ship and thus increasing the possibility for ships to hit the bed. As a result, ships are not able to carry their full load or are not able to navigate at all during low discharges.

Second, structures are also affected by bed degradation. The increased erosion leads to the exposure of the foundation of the structure, compromising its stability. The same holds for infrastructure located underneath the riverbed. Cables and pipelines can become exposed to the river flow and this can lead to damage or destruction (Barneveld, 2022). Third, bed degradation affects the discharge distribution between the Waal and the Pannerdensch Kanaal. The Pannerdensch Kanaal needs sufficient discharge to ensure sufficient navigation depth in the IJssel and sufficient water storage in, for example, the IJsselmeer that ensures a reliable freshwater supply in dry periods (Klijn et al., 2022). Lastly, Barneveld (2022) mentions that the ecology and water supply are also affected by bed degradation. The degraded bed leads to lower water levels which in turn leads to a declining groundwater level. The lower groundwater level also leads to desiccation of the landscape, affecting vegetation and animals (Huysmans, 2021). Next to this, since the water level of the river is lower, floodplains are inundated less frequently adding to the desiccation of the landscape.

The measures implemented in the Dutch Rhine system in the last two centuries have led to the current issues regarding bed degradation. Straightening the river and fixating the position of the river increased erosion by increasing flow velocities (Klijn et al., 2022). Straightening and fixating the river course has been done by introducing groynes (Sloff et al., 2023). In the 70s, mainly in the Waal large quantities of sediment were extracted, resulting in further degradation of the riverbed. Next to this, actions performed in Germany have also influenced the erosion in the Dutch Rhine system (Sloff et al., 2023). Coal mining in the Ruhrgebiet has led to local collapsing mines resulting in holes in the riverbed that capture sediment. The coal mining also led to overall subsidence of the Ruhrgebiet, reducing the slope of tributaries of the Rhine, which results in lower flow velocities and thus less sediment supply from these tributaries. In the tributaries water is also extracted for drinking water purposes, leading to an even lower capacity of the tributaries to transport sediment towards the Rhine. In the Niederrhein in Germany, coarse sediment is dumped on the bed to reduce erosion. The coarse sediment blocks the finer sediment from being put into motion, thus reducing the sediment supply towards the Dutch Rhine branches (Sloff et al., 2023).

The bed degradation as a result of choices made in the past has led to the problems that are currently encountered in the Dutch Rhine system, however, the problems are expected to worsen over time since bed degradation is expected to continue (Zuijderwijk et al., 2020). Spatial variations are observed in the period of 2000-2020 by remarking differences in the morphological development between the branches, confirming the non-uniform degradation of the riverbed. Next to this, temporal variations are also observed in the period of 2000-2020 by observing bed degradation in waves over time (Sloff, 2019). The riverbed not rising or declining steadily but in waves means that at the same location, both erosion and sedimentation can occur over time with the fluctuation amplitude for bed level also varying per location (Sloff, 2019).

Based on measured historical trends in bed degradation, Sloff (2019) conducted a numerical study in which a prognosis of the bed degradation for the period 2020-2050 for parts of the Dutch Rhine branches was made. The prognosis is based on multibeam measurements of morphological changes in the Dutch Rhine branches from around the year 2000 onwards and comparisons with the prognoses of bed degradation by Ten Brinke (2019) for the IRM programme and by Ylla Arbós et al. (2019) for the research programme Rivers2Morrow. The prognosis by Sloff (2019) is in line with the observed developments of the last 20 years, however, several corrections are made to comply with expected morphological effects resulting from recently implemented measures such as river widening. If no new measures would be implemented from now on, the bed level in the Boven-Rijn will show no big differences till 2050. However, in the Bovenwaal, Middenwaal, Pannerdensch Kanaal, Nederrijn, and Boven-IJssel there is an expected erosion of 1.9, 0.6, 1, 0.1, and 0.3 cm/year till 2050, respectively (Sloff, 2019). The differences in erosion show the spatial variations in the different Dutch Rhine branches. The change in bed level in the different Dutch Rhine branches can be seen in Figure 1.

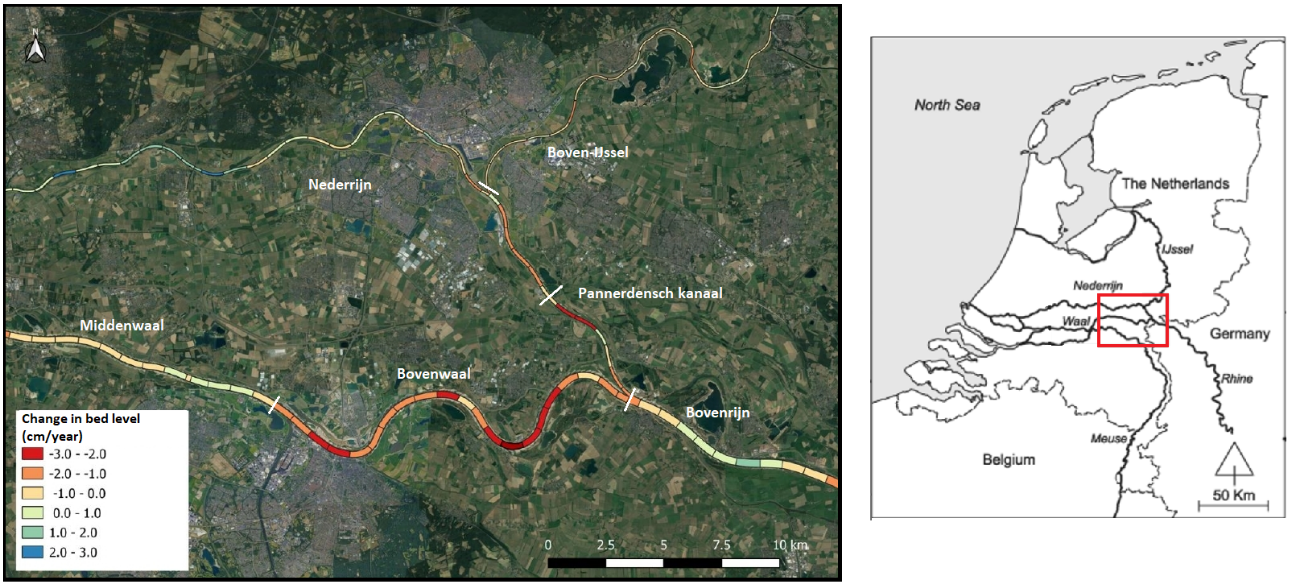

Figure 1: Change in bed level in the Dutch Rhine branches (adapted from Sloff, 2019).

The spatial variations in bed degradation also cause changes in discharge distributions at the Pannerdense Kop, at which the Rhine bifurcates into the Waal and the Pannerdensch Kanaal. The Waal erodes faster than the Pannerdensch Kanaal, causing more skewness in the discharge distribution (Sloff, 2019). The skewness causes an increase of water flowing towards the Waal and reduces the amount of water flowing towards the Pannerdensch Kanaal. During low discharges a relatively larger portion of water flows towards the Waal than during high discharges, resulting in even lower water depths in the Pannerdensch Kanaal and the IJssel. In 1990, during low discharges around 22% of the discharge at Lobith flowed towards the Pannerdensch Kanaal (Klijn et al., 2022). In 2018 the amount of water of the Boven-Rijn flowing towards the Pannerdensch Kanaal decreased to 19%. While during high discharges, around 31% of the water flows towards the Pannerdensch Kanaal. The lower water depths in the Pannerdensch Kanaal and the IJssel cause problems for navigation and nature in floodplains. The more the skewness is, the more the skewness in distribution keeps increasing (Klijn et al., 2022). This comes from the fact that larger discharges lead to more erosion, which in turn leads to more bed degradation which thus leads to even more skewness in discharge distribution. The change in discharge distribution affects flood safety in the areas around the rivers. Current flood safety standards are based on standard high discharge distributions at bifurcation points in the Dutch Rhine branches. However, when a larger portion of the water flows through the Waal, the distributions on which the flood safety standards are based are no longer correct. Next to this, climate change leads to weather events being more erratic and more extreme (Koninklijk Nederlands Meteorologisch Instituut [KNMI], 2012). The combination of the non-uniform bed degradation in the Dutch Rhine branches leading to different discharge distributions and climate change poses a threat to flood safety.

1.2 River programmes and measures

The extreme discharges in 1993 and 1995 in the Netherlands were the motive for Rijkswaterstaat (RWS) to initiate the Room for the River (RvdR) programme (Ministerie van Verkeer en Waterstaat, 2000). This programme was launched to counter the floods of major rivers in the Netherlands. Within this programme, measures were taken to give the river more space and let nature safely regulate the river. The RvdR programme mainly focused on flood safety, however, this was the first programme that indicated the ongoing bed degradation in the Dutch rivers. The following measures were taken within the RvdR programme: flood channels, lowering of groynes, longitudinal training dams (LTDs), obstacle removal, depoldering, lowering of floodplains, lowering of the summer bed, water storage, strengthening dikes and relocating dikes (Ministerie van Verkeer en Waterstaat, 2022). After the RvdR programme was officially completed in 2019, the programme Integrated River Management (IRM) was initiated in 2020 to help make policy choices regarding the preparation of the Dutch river system for climate change and aims to find a new balance between functions and values of the river system for future generations. Within the IRM programme, regional authorities and the government work together on the basis of a joint vision of a safe, navigable, vital and attractive Meuse and Rhine area that is prepared for the future and sustainably managed (Klijn et al., 2022).

The task of the IRM programme is to anticipate climate change and its possible consequences by revising the current management and design of the river areas by making the Dutch river system future-proof. The IRM programme will be wrapped up in 2050 and during this programme policy choices will be made for the riverbed level, sediment management, and high water discharges (Klijn et al., 2022). The policy choices will be stated in the Programme for Environmental Law (POW), which is expected to become effective at the start of 2024. Currently, the IRM programme is working on setting policy choices in this POW. It is still unsure which policy choices will be incorporated in the POW, however, the policy choices will be set up in a manner to counter bed degradation. The aim of the IRM programme is to stabilise the bed level of the Dutch Rhine branches and if possible achieve the bed level of an earlier year. As a consequence of climate change, the river areas will experience more frequent higher high discharges and longer low discharges (Klijn et al., 2022). The river areas can be prepared for this on the one hand by increasing the discharge capacity of the rivers during wet periods and on the other hand by water retention during dry periods. The IRM programme explores a multitude of measures to achieve these aims. The IRM programme explores the measures of the RvdR project further and also considers new additional measures such as nourishments.

LTDs were a promising measure in the RvdR programme to counter bed degradation and increase flood safety and are explored further in the IRM programme. Countering bed degradation is the aim of the IRM programme and LTDs counter bed degradation by widening the river during high discharges while maintaining water depths during low discharges (Eerden, 2022). LTDs redesign the summer bed of a river by replacing the groyne field in the inner bend of the river with an LTD, this creates a two-channel river system at the location of the LTD. The river is divided into a main channel and a riparian channel. A pilot on LTDs is performed near Tiel, where three LTDs were constructed of quarry stone in 2015 (Eerden, 2022). Measurements at the pilot location show a reduction in flow velocity, reducing erosion at the location of the LTDs. If the LTDs are extended from 11 km to a reach of 40 to 60 km, it is expected that LTDs are twice as effective in the reduction of the water level during high discharges (Eerden, 2022). Since this pilot showed good results that are in line with the expected results, a follow-up model study performed by Sloff et al. (2023) explored the possibilities and effects of additional LTDs along the whole Boven-Waal and Midden-Waal. Figure 2 shows the locations of LTDs in the study of Sloff et al. (2023).

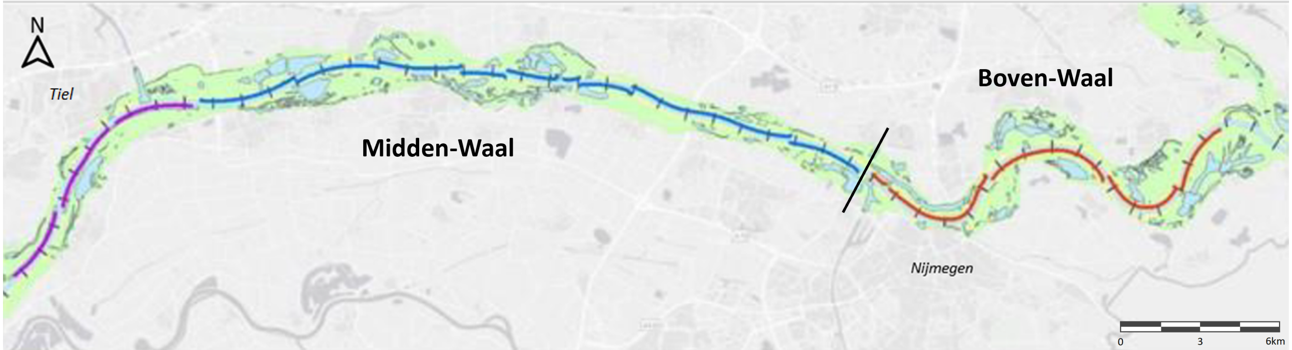

Figure 2: Implemented LTDs in the model of Sloff et al. (2023), in red unrealized LTDs in the Boven-Waal, in blue unrealized LTDs in the Midden-Waal and in purple the existing LTDs near Tiel in the Midden-Waal (adapted from Sloff et al., 2023).

An additional benefit of an LTD is that the riparian channel is a good habitat for macro-invertebrates and stream-loving fishes. The population and biodiversity of fishes increase as a result of LTDs (Collas et al., 2018). Next to this, the riparian channel is a suitable habitat for aquatic plants. The construction of LTDs increases the ecological value of the summer bed significantly (Eerden, 2022). The main cause of this is that ships do not navigate through the riparian channel (Eerden, 2022). Measurements of the abiotic conditions demonstrate significantly higher stability in flow and significantly lower water level in the riparian channels in comparison to groyne fields (Collas et al., 2018).

1.3 Problem statement

LTDs are a promising measure to counter bed degradation, however, LTDs are a new measure of which there is little knowledge. The pilot performed near Tiel offers perspective in the sense that LTDs reduce bed degradation locally (Eerden, 2022). A net accumulation of sediment was observed in the pilot area in the 5 years after the construction (Czapiga et al., 2022). However, measurements and observations over a longer period are needed to conclude the long-term morphological effects of LTDs. The pilot showed that improvements could be done to the design of the LTDs, during the pilot the LTDs were adapted since the LTDs drained too much water from the main channel of the river (De Ruijsscher et al., 2020a). Van Linge et al. (2017) used a 1D hydrodynamic model to show the sensitivity of the inlet height, opening heights and the width of the riparian channel related to the main channel width on the discharge distribution between the main channel and riparian channel. Van Linge et al. (2017) has shown that adjusting the inlet height has the most influence on the discharge distribution between the main channel and riparian channel. However, a 2D hydrodynamical and morphological modelling study can provide more insight into the effects of different designs of LTDs since a 2D morphological model can capture transverse variability in flow and bed level. Zuijderwijk and De Jong (2019) optimised the LTDs that are implemented near Tiel by performing 2D hydrodynamic simulations of different LTD configurations in Delft3D that were assessed based on flow velocities and water levels during different discharges. Only hydrodynamic simulations were performed and the morphological component was excluded, but the simulated flow velocities were assessed and qualitative estimates of morphological effects were made. The design of the existing LTDs near Tiel is optimised for that location. A 2D-modelling study that includes the morphological effects of different LTD designs can provide more insight into the best possible LTD design. Sloff et al. (2023) conducted a study in which the effect of 12 new LTDs over a reach of 40 km in the Boven-Waal and Midden-Waal was analysed for 20 years of morphological changes on countering bed degradation in the Rhine branches via the Delft3D-4 DVR model. The results show increased erosion in the Midden-Waal as a result of the LTDs, however, climate change was not taken into account. In Chapter 3, the result of the study by Sloff et al. (2023) is discussed in detail.

It is not known whether different configurations of LTDs can reduce bed degradation along all parts of the Rhine branches. Next to this, there is also a lack of knowledge on the effects of LTDs for different climate scenarios. The aforementioned studies about LTDs do not consider changing discharge regimes as a result of climate change making the long-term morphological effects even more uncertain. The effects of different designs of LTDs in the Boven-Waal and Midden-Waal to counter bed degradation in the entire Waal are uncertain and require further research. This research aims to fill in this knowledge gap by studying the effects of different designs of LTDs in the Waal and assessing the performance of LTDs for various climate scenarios.

1.4 Research questions

This research aims to quantify the effects of new LTDs in the Waal. This is done by simulating different configurations of LTDs with different discharge time series corresponding to different climate change scenarios and assessing the effect on the bed level. The LTD configurations are altered based on the configuration used in the study of Sloff et al. (2023). The simulations are performed using a 2D numerical model. The aim is to maintain sufficient water depth for navigation during low discharges and to minimize water levels for flood safety during high discharges. Based on the results of the simulations, expectations on the morphodynamic evolution in the Waal can be given for the upcoming 20 years. Next to this, the morphodynamic evolution in the Waal is also assessed for different climate projections that are translated in different discharge regimes for the Rhine. To address the quantification of the effects of LTDs the main research question is defined.

What are the effects of different designs of longitudinal training dams on countering bed degradation for different discharge scenarios in the river Waal?

With the following sub-questions:

1. How do different designs of longitudinal training dams in the Boven-Waal and Midden-Waal affect bed degradation in the river Waal using a standard hydrograph?

2. What is the effect of the best performing longitudinal training dam design in the river Waal on the morphodynamic evolution for different discharge scenarios based on climate projections?

1.5 Study area

The ongoing bed degradation affects the whole river system in the Netherlands. However, this research focuses on the effect of different designs of LTDs in the Waal. The Waal itself has sufficient width for the LTDs to be implemented contrary to, for example, the IJssel which is too narrow to implement LTDs (Arcadis, 2022). Next to this, the largest erosion in the Dutch Rhine branches is measured in the Waal (Sloff, 2019). Since bed degradation is the most fierce in the Waal and the Waal has sufficient space for LTDs, the Waal is chosen as the study area of this research. In Figure 3, the course of the Waal as part of the Dutch river system is shown. The fixed layer at Nijmegen and the existing LTDs near Tiel are indicated in the figure. At the Pannerdense Kop, the Rhine bifurcates into the Pannerdensch Kanaal and the Waal. The Waal merges with the Afgedamde Maas near Gorinchem to become the Boven-Merwede.

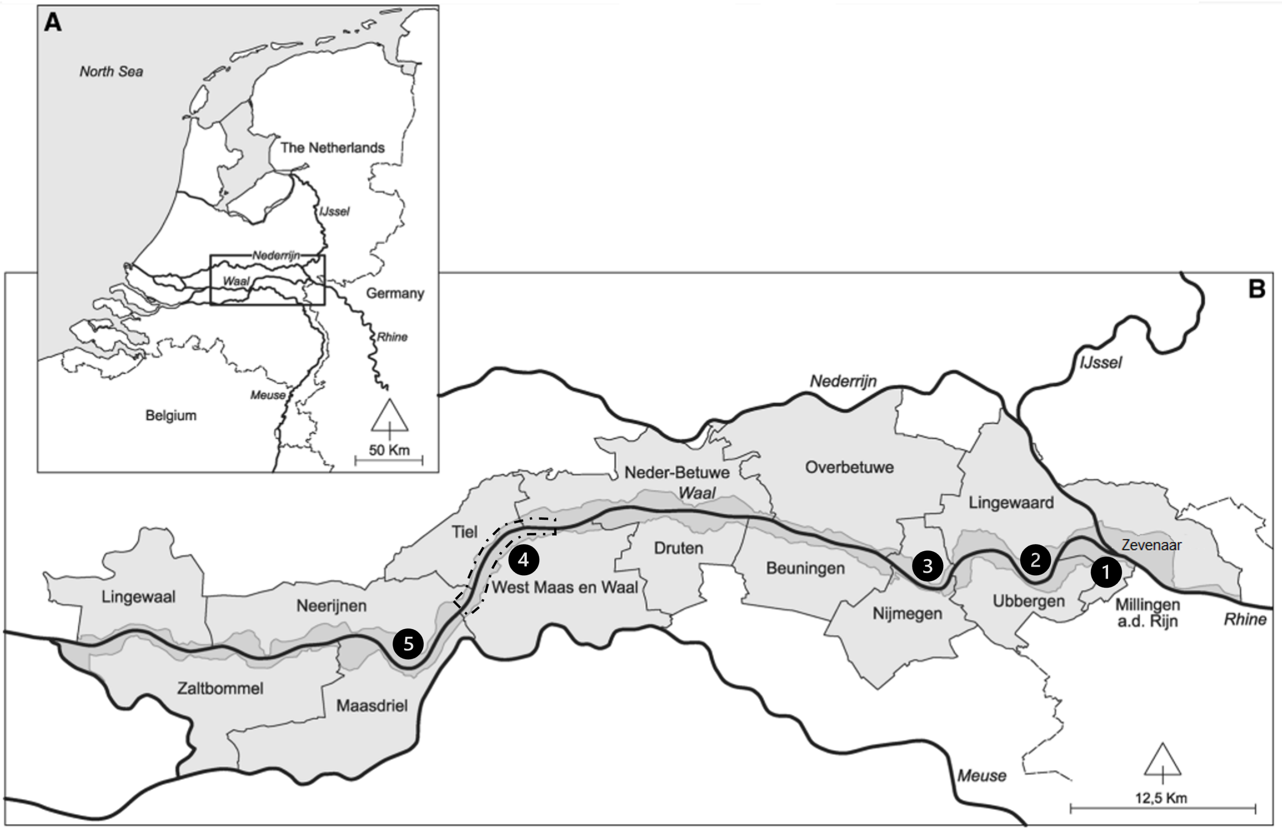

Figure 3: Study area: (A) location of study area in The Netherlands (B) floodplain areas of the Waal (dark grey); and locations of municipalities near the Waal (light grey); Pannerdense Kop (1), bed groynes at Erlecom (2), fixed layer at Nijmegen (3), the existing LTDs near Tiel (4) and the fixed layer at St. Andries (5) (adapted from Fliervoet et al., 2013).

Figure 4, shows the Rhine kilometres (rkm) in the Waal. The rkm is used to refer to locations in the Waal in this report. Figure 4 shows the beginning of the Boven-Waal (rkm 868), Midden-Waal (rkm 891.6) and Beneden-Waal (rkm 923.6) and also the end of the Waal (rkm 951.7). Figure 4 shows the fixed layers at Nijmegen (rkm 883-885) and St. Andries (rkm 925-928) and the bed groynes at Erlecom (873-876) which influence the morphological development in the Waal since the layers do not degrade and affect the morphological changes upstream and downstream of these layers. Next to this, the existing LTDs near Tiel are located at rkm 912-922.

Figure 4: Rkm along the Waal with the fixed layers and bed groynes denoted in red and domain transitions denoted with the thick black lines (adapted from Esri Nederland & Sweco Nederland, 2019).

1.6 Report outline

Chapter 2 provides a relevant theoretical background to this study, this theoretical background gives an understanding of the current knowledge of LTDs and how the LTDs work. The methodology of this study is described in Chapter 4, comprising an explanation of the modelling approach, a description of the simulations and the discharge scenarios. The results of the different LTD design simulations are presented in Chapter 5. The results of the effects of LTDs under the influence of climate change are presented in Chapter 6. Next, Chapter 7 provides a discussion on the reliability of the results and used method and discusses the potential of LTDs to counter bed degradation in the Waal. Chapter 8 provides the main conclusions and recommendations of this study.

2 Theoretical background

This chapter provides the relevant theoretical background for this research. A description of the functioning of LTDs is given in Section 2.1. In this section, the results of the pilot performed near Tiel are also discussed and the morphodynamic effects of LTDs are explained. The description and results of the pilot on LTDs near Tiel are discussed in Section 2.2.

2.1 Longitudinal training dams

LTDs redesign the summer bed of a river by splitting the main channel up into two parallel streams. In Figure 5, a top-view schematisation of a river section with an LTD can be seen. LTDs divide the river into a main channel and a riparian channel. A sill is located at the inlet of the riparian channel, the sill height regulates at what water level, water and sediment flows through the riparian channel. The largest portion of discharge flows through the main channel. Water and sediment are also able to enter the riparian channel via several openings in the side of the LTD. The opening in an LTD is small compared to the dam length, the opening allows water and sediment to be exchanged between the main and riparian channel (Van Linge et al., 2017). At an opening, the LTD is generally lower by a meter and more porous, which makes the exchange of water, sediments, and biota possible (Collas et al., 2018). The lateral exchange of water and sediment along the LTD distinguishes it from a side channel. Water and sediment enter the riparian channel at three different elevations, over the sill at the upstream part of the LTD, through inlet openings, and over the crest of the LTD itself (Czapiga et al., 2022). At the outlet of the LTD, the riparian channel and the main channel combine into one channel again. The fraction of total discharge that flows through the main channel decreases when the water level increases (De Ruijsscher et al., 2020a). The higher the flow, the larger the flow area over the sill. The height of the sill determines the discharge distribution over the main and riparian channels. As can be seen in Figure 5, the LTD replaces groynes at one side of the river.

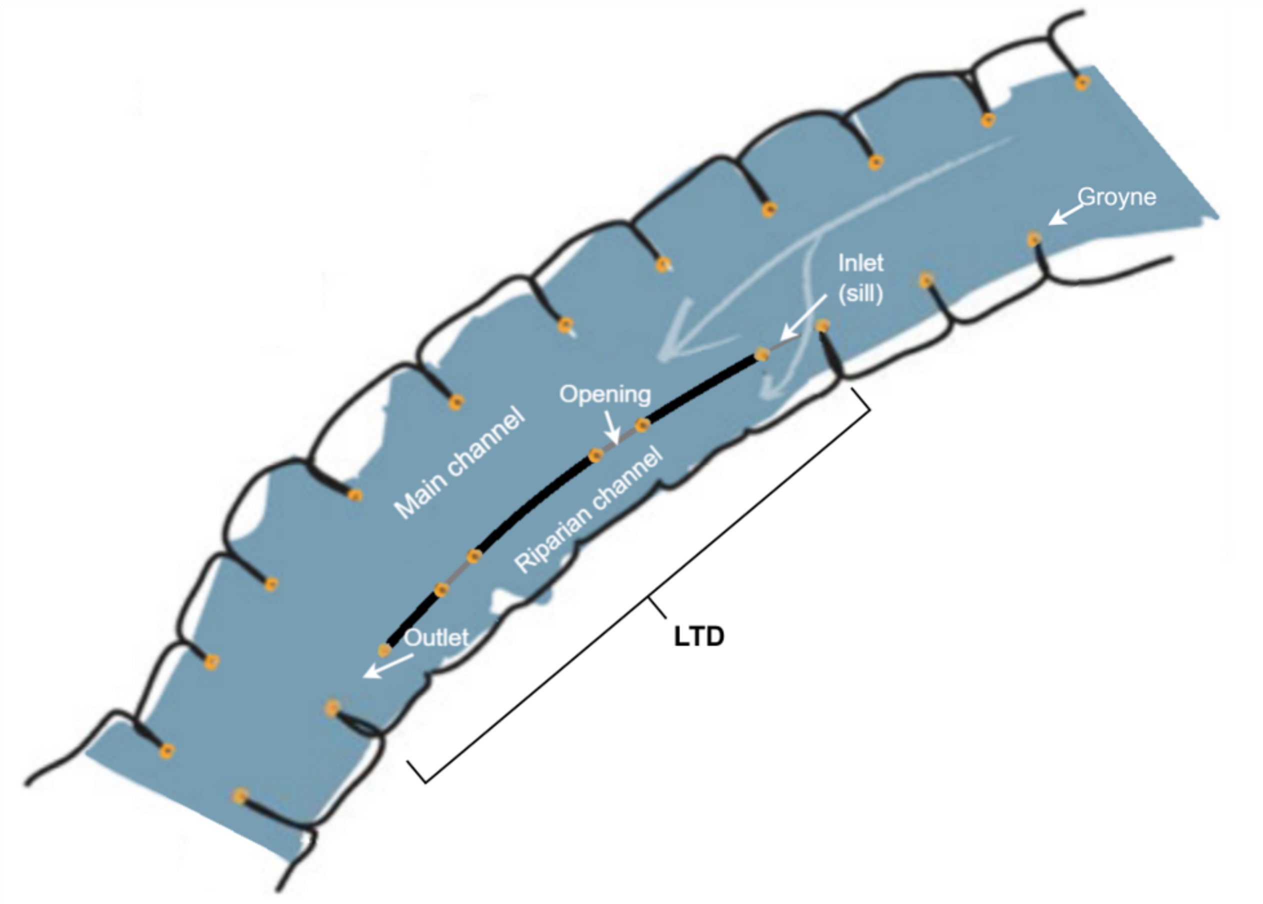

Figure 5: Schematisation LTDs, including openings, inlet (sill) and outlet. The yellow dots denote head beacons to indicate structures in the river (adapted from Collas et al., 2018).

LTDs are placed in the inner bend of the river to avoid the bend apex and crossovers in the river. LTDs that are placed on the curvature crossover or the bend apex tend to cause the closure of one channel due to rapid sedimentation (Czapiga et al., 2022). The bend apex is located on the outer bank of a bend, where the water depth and flow velocity are larger than average. If the LTD is located in this area, large erosion would occur in the outer bend channel where large flow velocities are present and large sedimentation would occur in the inner bend channel where low velocities are present. The crossover is located at the transition from one river bend to another in the middle of the river, if the LTD is located at this position the largest portion of water will flow through the inner bend instead of through the outer bend leading to large sedimentation in the inner bend. In Figure 6, a cross-sectional schematisation of the difference between a river with groynes and a river with LTDs is shown. The figure depicts the river with no measures, with groynes and the groynes at the inner bend replaced by an LTD. In Figure 6, it can be seen that the LTD is located in the inner bend since the bed level is generally deeper in the outer bend than in the inner bend of a river (Ribberink, 2011).

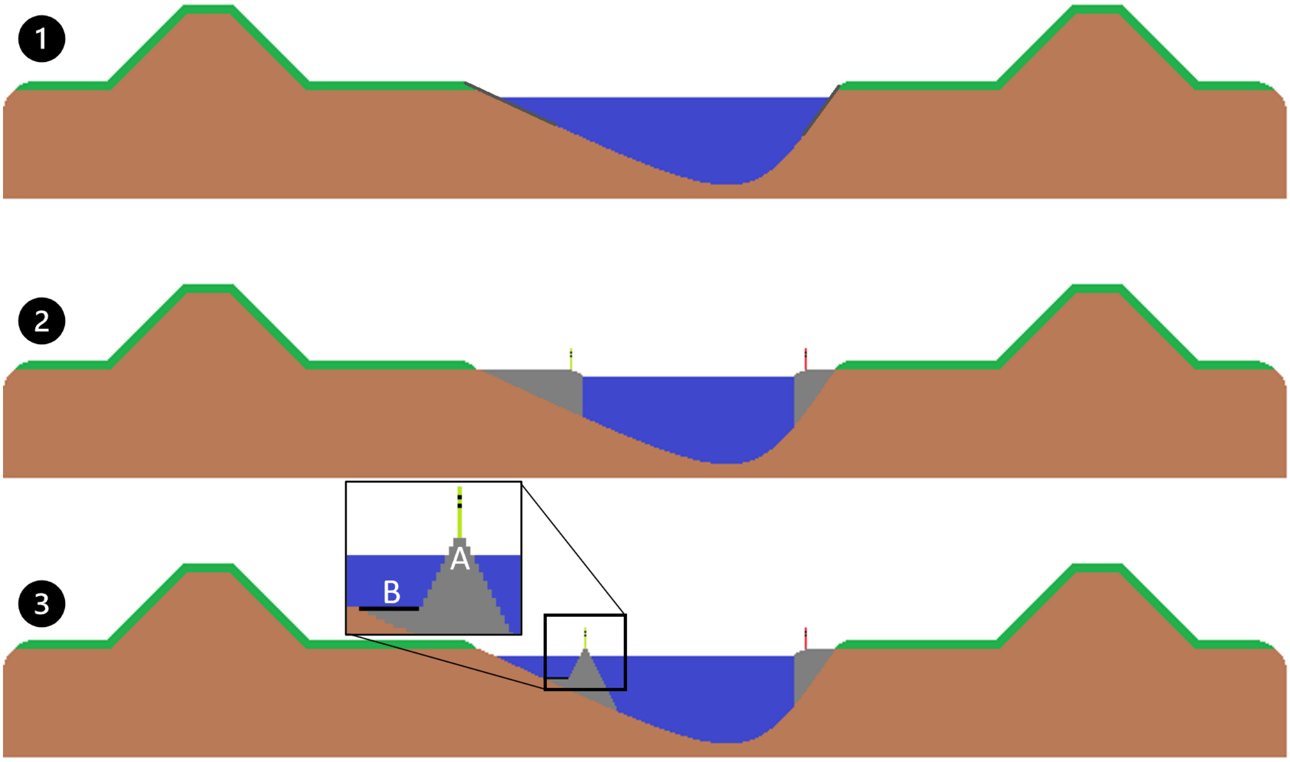

Figure 6: Cross-sectional schematisation of different bed regulation measures in a river: river with bank protection (1), river with groynes on both sides (2), and river with an LTD on the left side and groyne on the right side (3); Crest of the LTD (A), and sill of the LTD (B).

2.1.1 Hydraulic effects LTDs

LTDs replace groynes in the inner bend, enabling water to flow through the space where the groynes and groyne fields used to be, increasing the discharge capacity during high flows (Jammers et al., 2017). In Figure 7, the difference during low and high discharges between the current approach of rivers with groynes and the possible approach with LTDs can be seen. During high discharges, when the riparian channel is active, the river experiences less resistance in comparison to the situation with groynes on both sides of the river. The removal of groynes also leads to a larger flow width during floods (Czapiga et al., 2022). Overall, LTDs cause a lower water level during high discharges. On the other hand, during low flows, the relative water depth increases since the water level is not high enough to flow over the sill into the riparian channel and thus is forced to flow through the main channel. The river width remains the same after the implementation of an LTD. LTDs cause a narrower active main channel of around 20 m in comparison to a river with groynes, which is shown in Figure 6 in cross-sections 2 and 3 (Sloff et al., 2023). During low flows when the riparian channel is not active, the main channel receives as much discharge as before the implementation of the LTDs. This results in an increased water depth because the same discharge is forced through a smaller main channel.

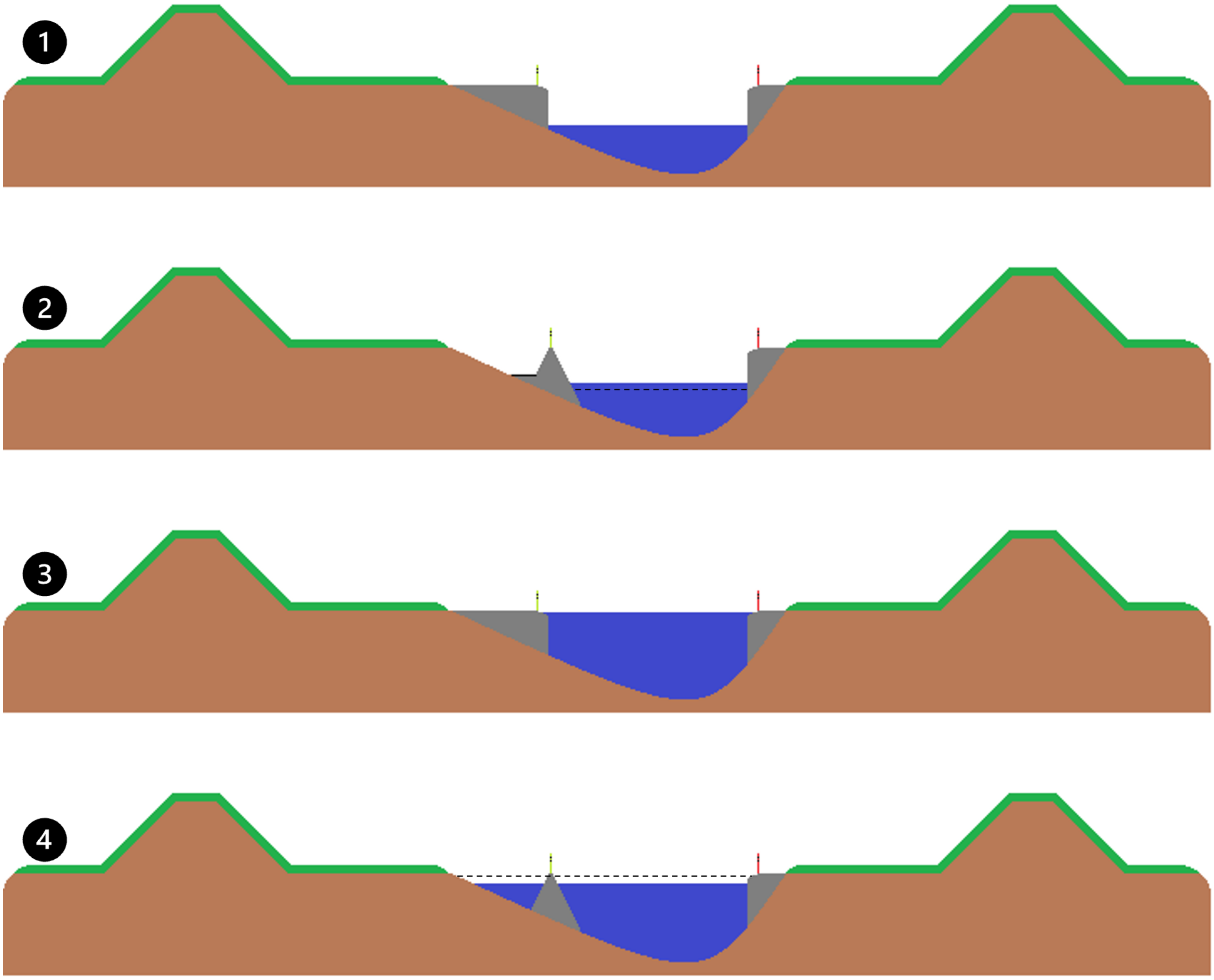

Figure 7: Cross-sectional schematisation of a river with groynes and LTDs for different discharge levels: river controlled by groynes during low discharge (1), river controlled by LTDs and groynes during low discharge (2), river controlled by groynes during bankfull discharge (3), and river controlled by LTDs and groynes during bankfull discharge (4). The dashed lines in the LTD schematisations denote the water levels in the case of the corresponding groyne schematisations.

2.1.2 Morphological effects LTDs

Next to the hydraulic effects of LTDs, there are also morphological effects. LTDs reduce the sediment transport capacity of the river by reducing the discharge in the main channel during high discharges since a portion of the flow is directed towards the riparian channel during sufficient discharges. The reduction in discharge in the main channel leads to an increase in equilibrium slope in the main channel which in turn leads to sedimentation in the main channel (Czapiga et al., 2022).

During high discharge events, localized scour occurs at the downstream end of the LTD where the riparian channel rejoins the main channel, since at these locations the total flow width is abruptly narrowed (Czapiga et al., 2022). Between flood events, dispersion of the accumulated sediment occurs and the scour pits tend to fill up.

Implementing LTDs in a river is seen as a river widening measure. It is seen like this since the river has a larger flow width during high discharges. The river has a larger flow width because water can now flow in the place of the preceding groynes. The river widening is only active during high discharges, thus when the riparian channel is active. High discharges lead to high flow velocities which cause high sediment transport and thus the largest effect on the morphology of a river. The river widening results in reduced flow velocities during high discharges, reducing the sediment transport at the location of the LTDs and inducing sedimentation.

The initial morphological response of LTDs is comparable to the initial morphological response of river widening. Under steady flow conditions, the backwater curves for the initial morphological response are based on the critical water depth h_c (m) and equilibrium water depth h_e (m). The critical water depth is the depth of the flow where energy is at a minimum for a certain unit discharge and the equilibrium water depth is the depth of the flow when the flow becomes uniform for a certain unit discharge (Vermeulen et al., 2018). In Equations (1) and (2) the formulas for the equilibrium water depth h_e and the critical water h_c depth are given. In which Q (m^3/s) is the discharge, B (m) is the width of the river, C (m$^{0.5}$/s) is the Chézy roughness coefficient, g (m/s^2) is the gravitational acceleration and i_b (-) is the bed slope.

$$h_e = (\frac{Q}{BC\sqrt{i_b}})^{2/3} \tag{1}$$

$$h_c = (\frac{Q^2}{B^2 g})^{1/3} \tag{2}$$

In Figure 8 profile A, the backwater effects caused by river widening are shown. Smaller depths result in acceleration of the flow and larger depths result in deceleration of the flow since in both cases the discharge remains the same. These accelerations and decelerations cause spatial variations in the sediment transport capacity. At accelerations, the sediment transport capacity increases and extra sediment of the bed is put into motion, causing erosion. The opposite occurs at decelerations, causing sedimentation. The river widening initially decreases water depths upstream of the LTD, increasing flow velocities and leading to erosion, as can be seen in Figure 8. In which u (m/s) is the flow velocity, q_s (m^2/s) is the sediment discharge, $\frac{\partial q_s}{\partial x}$ is the gradient of sediment transport and $\frac{\partial z}{\partial t}$ is the initial change in bed level. At the transition towards the widened section, the flow velocity abruptly decreases, leading to locally pronounced sedimentation that moves downstream over time. Within the widened section, the flow velocity further decreases, contributing to sedimentation. At the transition from the downstream end of the widened section towards the initial river width, an abrupt increase in flow velocity occurs leading to locally pronounced erosion that moves downstream. Eventually, an equilibrium will be reached, LTDs cause sedimentation when this equilibrium is reached. LTDs lead to a new morphological equilibrium that includes a higher bed level at the location of the measure itself and also an increased bed level upstream. The long-term morphological effects are schematised in Figure 9.

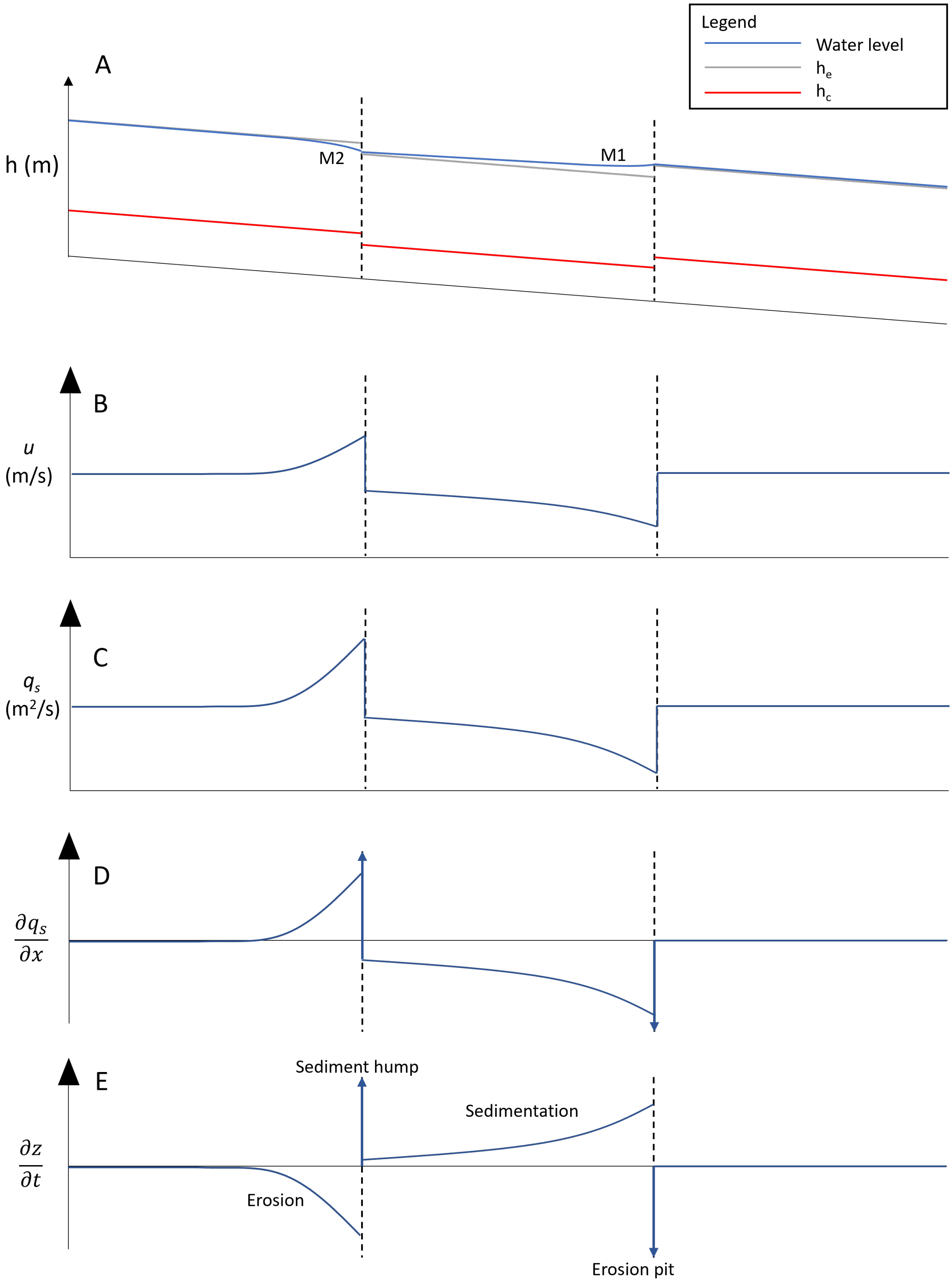

Figure 8: Initial hydraulic response on a river widening, river widening takes place in between the dashed lines. The vertical dimensions of water levels are in the magnitude of meters, while the horizontal dimensions are in kilometers. With the water levels (A), the velocity profile (B), sediment discharge profile (C), initial sedimentation/erosion profile (D) and initial change in bed level (E) resulting from the river widening.

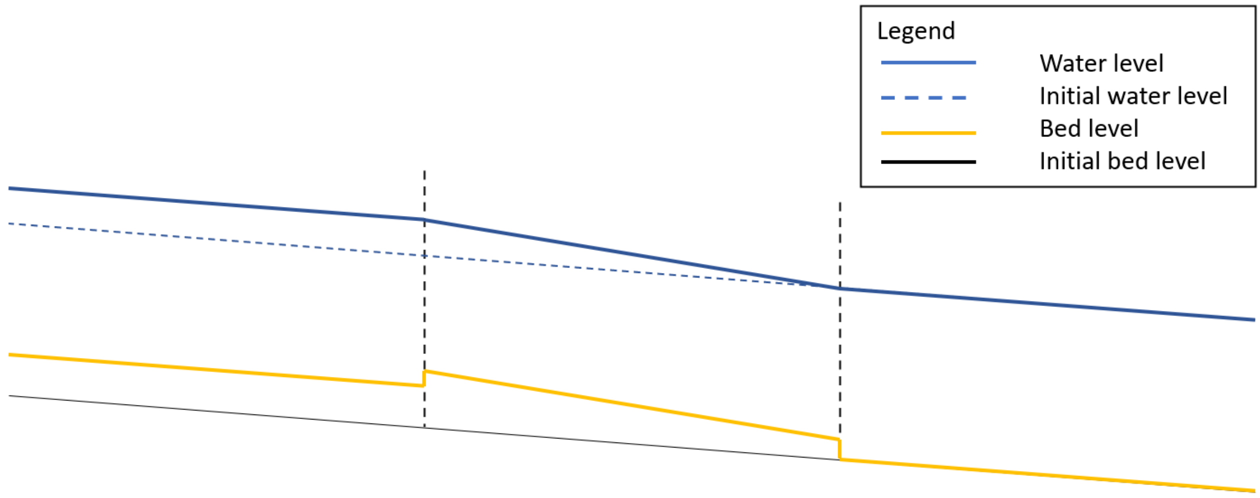

Figure 9: Schematisation of long-term bed and water level response to river widening for steady flow conditions (Lokin, 2022).

2.1.3 Expected effects of LTDs

Summarising Sections 2.1.1 and 2.1.2 results in the expected effects of LTDs in the Waal. During low discharges, it is expected that LTDs result in a larger average water depth than a typical river controlled by groynes since LTDs narrow the main channel on average by 20 m (Sloff et al., 2023). During high discharges, it is expected that LTDs result in a lower water level than a typical river controlled by groynes since the active summer bed is larger. Regarding the morphological effects of LTDs, it is expected that the initial response of the river will be erosion in the main channel. However, in the course of time, sedimentation is expected as a result of the reduced flow velocities caused by the LTDs. The expected effects of LTDs led to a pilot at Tiel and Sint Andries in the Waal (Van Linge et al., 2017).

2.2 Pilot longitudinal training dams

LTDs were finalized in 2015 over a reach of around 10 kilometers (rkm 912-922), 40 kilometers downstream of the Pannerdense Kop (Czapiga et al., 2022). A schematisation of the LTDs near Tiel is shown in Figure 10. The LTDs are constructed at the initial location of the preceding groyne heads (Zuijderwijk & De Jong, 2019). The existing LTDs are designed such that water flows over the sill at a discharge of 400 m^3/s at Lobith. At a discharge of 1800 m^3/s at Lobith the openings in the LTDs become active and water flows over the dam at a discharge of 3000 m^3/s at Lobith (Zuijderwijk & De Jong, 2019). The results of the pilot offer perspective in the sense that it reduces the bed degradation locally (Eerden, 2022). The evolution of the bed is a function of flow velocities. After the construction of the LTDs near Tiel a reduction in flow velocity of 2-20% is measured (ADCP) over a period of 5 years in comparison to the situation before the construction (Eerden, 2022). This reduction in flow velocities leads to an average reduction in sediment transport of approximately 40%. For discharges between 2500 m^3/s and 3500 m^3/s the averaged flow velocity decreased at the end of the first LTD from 1.36 m/s to 1.28 m/s and at the end of the last LTD from 1.2 m/s to 1.04 m/s (Mosselman et al., 2021). The measurements near Tiel showed less erosion and more sedimentation upstream of the LTDs over a period of 5 years. Downstream of the LTD, stabilisation of the riverbed and sedimentation were measured. According to research performed by Czapiga et al. (2022), sediment is deposited near the upstream end of the dam after a flood. The results of the implemented LTDs can not say anything about the long-term morphological effects, however, initial measurements show overall bed deposition at the pilot location instead of the pre-construction trend of erosion during the 5 years after construction of the LTDs (Czapiga et al., 2022; De Ruijsscher et al., 2020a). Previous studies suggested further optimisation of the dams by customizing each LTD based on its location (Deltares & HKV, 2022). In the initial design of the LTDs, too much water was diverted towards the riparian channel resulting in a shortage of available sediment in the main channel, reducing the flow area towards the riparian channel solved this problem (De Ruijsscher et al., 2020a).

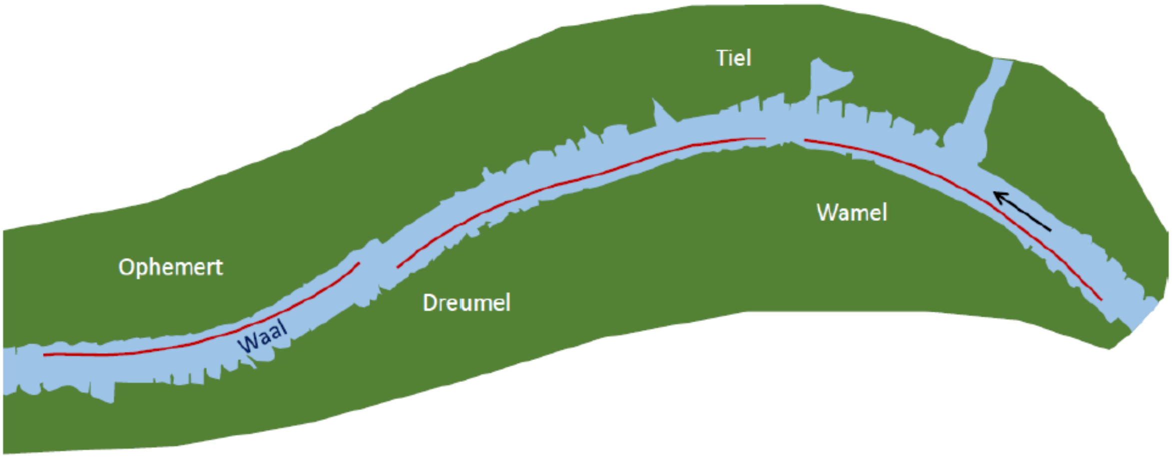

Figure 10: Locations of LTDs near Tiel (rkm 912-922) (Zuijderwijk & De Jong, 2019).

During high discharges, the LTDs reduce high water levels at least as much as the lowering of groynes. Where the river is wide enough, the channel width does not necessarily have to be adjusted to implement LTDs. At a discharge of 6,000 m^3/s at Lobith, there is a maximum reduction of 16 cm in water level with respect to the situation without LTDs, while during an extreme discharge of 18,000 m^3/s, there is a reduction of 10 cm in water level with respect to the case without LTDs (Eerden, 2022). In the current case, the LTDs are in total around 10 km long, however, in the case of a dam length of 40 to 60 km the water level reduction is estimated to be twice as large (Eerden, 2022).

3 Existing study on new LTDs in the Waal for the IRM programme

In this chapter, the results of the study of the IRM programme for addressing the riverbed level with new LTDs in the Waal are discussed. The IRM programme aims to make policy decisions regarding the riverbed of the Rhine branches during 2023. This study uses the final configuration, which is discussed in this chapter, of the study by Sloff et al. (2023) as a starting point. In this substantiation, Sloff et al. (2023) and Barneveld et al. (2023) conducted a numerical study together, which is mainly discussed by Sloff et al. (2023), to get insight into the effects of possible measures for the Rhine branches to counter bed degradation and whether it is possible to achieve the following three policy options:

1. Stabilise current bed level, stopping ongoing erosion.
2. Restore the 1980 low discharge distribution at the Pannerdense Kop (1020 m^3/s and 1203 m^3/s). Currently 19% of the Boven-Rijn discharge flows towards the Pannerdensch Kanaal, while in 1980 this was around 22%.
3. Restore the 2010 bed level or an earlier year.

To assess the results of LTDs in the Waal, Sloff et al. (2023) set up a model for the hydrodynamics of the river and a model for the morphological effects.

The hydrodynamic model is set up using a 2-dimensional D-Hydro model (Sloff et al., 2023). The aim of the hydrodynamic model is to compute large-scale hydrodynamic effects to assess changes in discharge distribution at the Pannerdense Kop caused by LTDs and assess water levels during low discharges. The model is computed using stationary boundary conditions, varying discharge distributions at bifurcations and discharges at Lobith of 1,020 (OLA[1]), 2,000, 4,000 and 6,000 m^3/s. To assess the morphological effects in the Dutch Rhine branches, the Delft3D-4 DVR model is used. In Section 4.1, the morphological model is discussed in detail and Table 1 gives an overview of the situations that are mentioned in this chapter.

Table 1: Explanation of situations used in the morphological study of Sloff et al. (2023) that are mentioned in this chapter.

Situation	**Explanation situation**
t_0	Initial situation, existing situation including the LTDs near Tiel
Reference	Situation after 20 years of morphological changes of the existing situation
LD-v5	Situation after 20 years of morphological changes with new LTDs in the Boven-Waal and Midden-Waal

Within the study of Sloff et al. (2023) it became apparent that LTDs are a promising measure to counter bed degradation, thus within their study, different configurations of LTDs were studied in the Waal. In these studies, LTDs were implemented in the Boven-Waal and Midden-Waal and the existing LTDs at Tiel are also present in the model, as shown in Figure 2. After several computations using the Duurzame Vaardiepte Rijndelta (DVR) toolbox, which is explained in Chapter 4, one configuration of new LTDs in the Boven-Waal and Midden-Waal seemed promising and was studied further. The configuration is based on the parametrisation used for the existing LTDs near Tiel, this parametrisation can be found in Table 2 in Section 4.3.1. In the promising configuration (LD-v5), which this study build upon, the LTDs in the Boven-Waal and Midden-Waal had a riparian channel bed level equal to the average summer bed level. This configuration was compared to a reference configuration that only included the existing LTDs at Tiel and no further measures. The configuration was computed using a

[1]OLA: agreed-upon low discharge (In Dutch: Overeengekomen lage rivierstand)

fixed discharge distribution at the Pannerdense Kop (Q_{fixed}) and also a varying discharge distribution at the Pannerdense Kop (Q_{free}). After analyzing the differences in morphological effects between the Q_{fixed} and Q_{free}, it was found that there are little differences in morphological effects and thus the configuration was solely computed using Q_{fixed} (Sloff et al., 2023). Running the model with a fixed discharge distribution is less computationally demanding.

To optimise the LTDs, the riparian channel width was made uniformly along the whole length of the LTD. The new LTDs in the model by Sloff et al. (2023) do not contain side openings, unlike the existing LTDs at Tiel that are also present in the model. However, in the study by Barneveld et al. (2023), it was concluded that the LTDs in the Boven-Waal reduced the effectiveness of the LTDs in the Midden-Waal by trapping sediment in the upper section of the Waal. The supply of sediment decreased towards the Midden-Waal, while the demand remained the same. To reduce erosion in the Midden-Waal, wider riparian channels in the Midden-Waal are suggested to reduce flow velocities during higher discharges further. When the riparian channel is increased in width, more water is diverted towards the riparian channel during higher discharges (Czapiga et al., 2022).

Results of LTDs in the Boven-Waal and Midden-Waal

Figure 11 shows the erosion in the Boven-Waal and Midden-Waal when no measures are performed for 20 years of morphological changes.

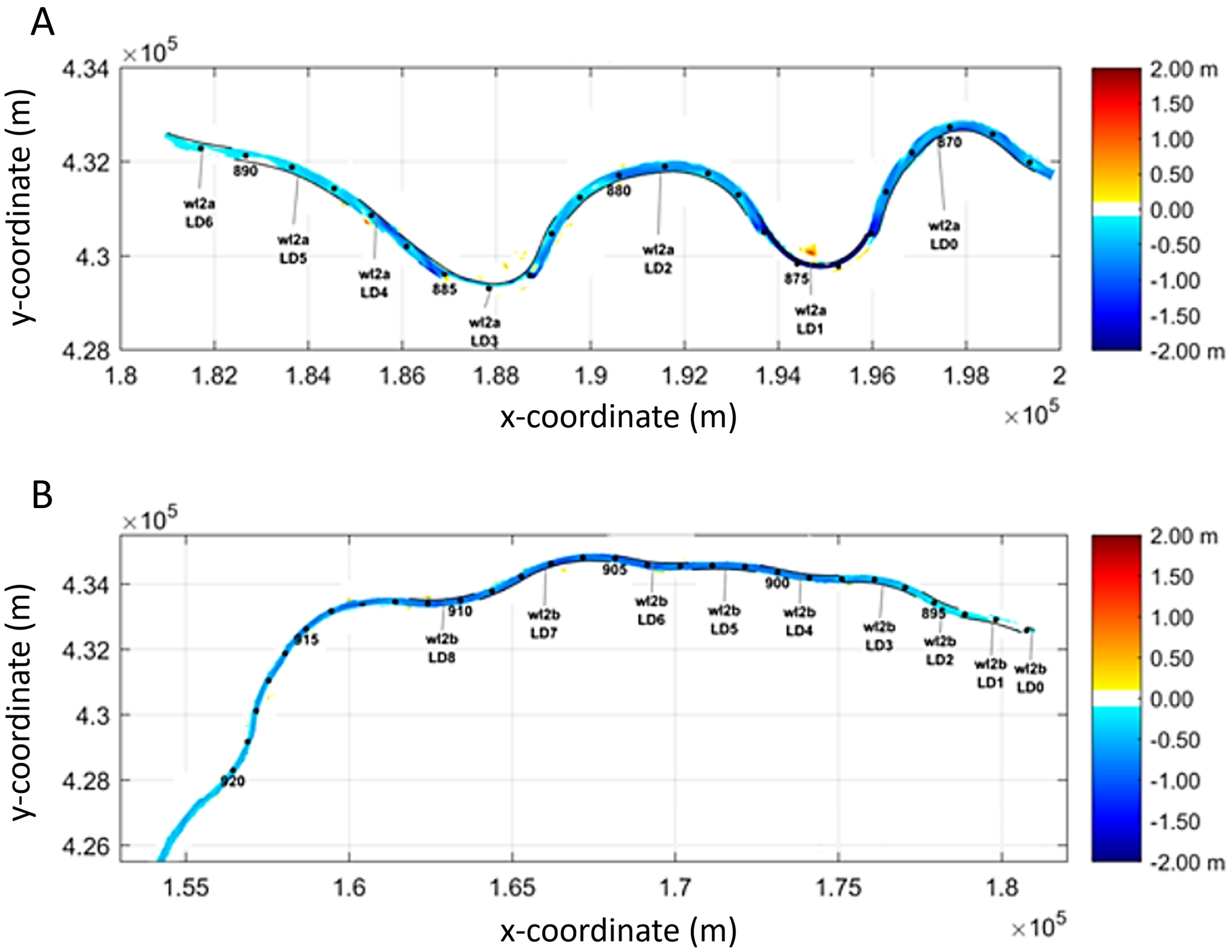

Figure 11: Numerical study by Sloff et al. (2023), changes in bed level after 20 years of morphological development in case of no measures in the Boven-Waal (A) and Midden-Waal (B). The numbers in the figure denote the rkm and the existing LTDs start at rkm 912 and the codes denote the partial model and LTD number per partial model (adapted from Sloff et al., 2023).

The model substantiates the effect of LTDs on the water level. As explained in Section 2.1, the water depth is theoretically expected to increase during low discharges (1020 m^3/s and 1203 m^3/s), and water levels are reduced during high discharges ($\geq$1635 m^3/s), Figure 12 supports this statement. The aforementioned discharges are each fixed discharge levels in the DVR model. In the figure it can be seen that water levels increase during low discharges and water levels decrease during high discharges along the length of the dams. During low discharges, there is a water level increase of 20-30 cm in river sections with LTDs. Next to this, during low discharges, the LTDs significantly increase the discharge towards the Pannerdensch Kanaal by 20 m^3/s (increase of $\sim$10%).

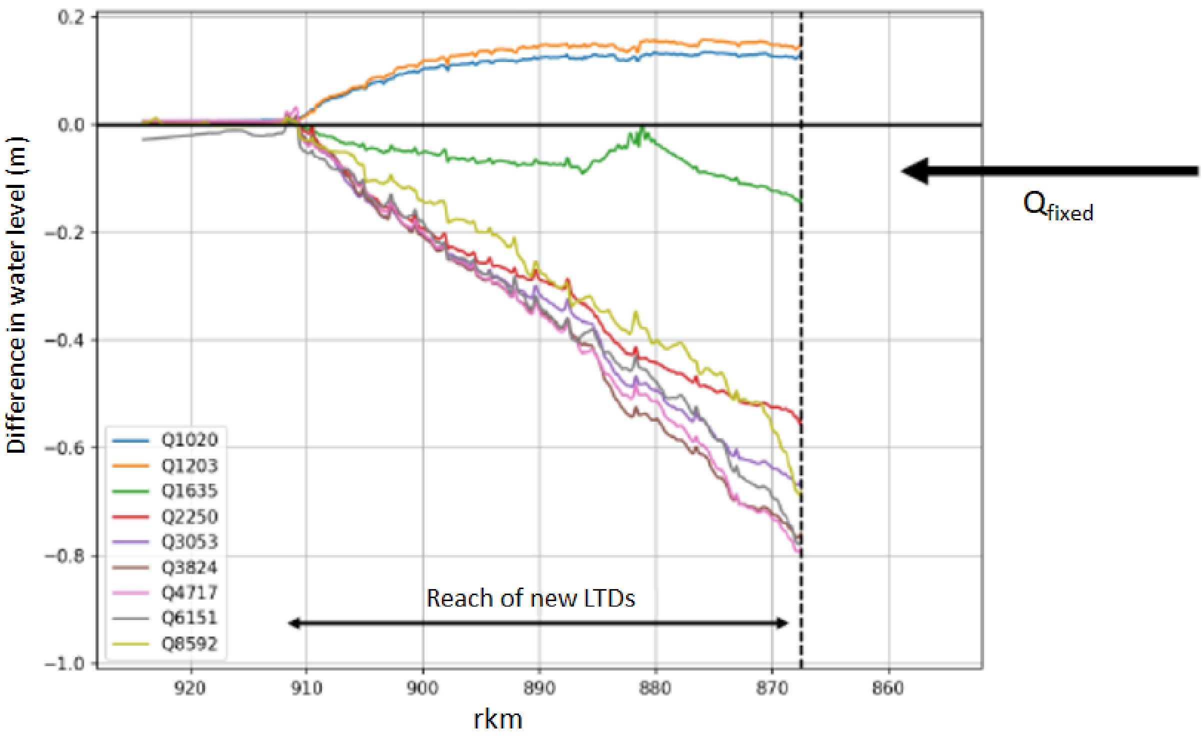

Figure 12: Effect on water level without morphological changes for fixed discharge distribution including new LTDs over the entire Waal for configuration LD-v5. The new LTDs are implemented between rkm 869-911 and the existing LTDs are located between rkm 911-923 (adapted from Sloff et al., 2023).

The configuration LD-v5 leads to a reduction in flow velocity of 0.1-0.15 m/s in the main channel of the Boven-Waal and also in the main channel of the Midden-Waal, which reduces the sediment transport capacity (Sloff et al., 2023). In Figure 13, the yearly sediment transport over the river length can be seen for the reference case and the LD-v5 case. After the fixed layer, around rkm 890, an increase in sediment transport can be observed. At rkm 910 the yearly sediment transport stabilises, this is the location of the existing LTDs. When comparing the yearly sediment transport for the reference case with the LD-v5 yearly sediment transport, it is observed that the yearly sediment transport for LD-v5 flattens out over time. No erosion or sedimentation would occur when the yearly sediment transport gradient is equal to 0 over the river length. Thus, the more horizontal the yearly sediment transport line is in Figure 13, the more desirable since this will stabilise the bed level.

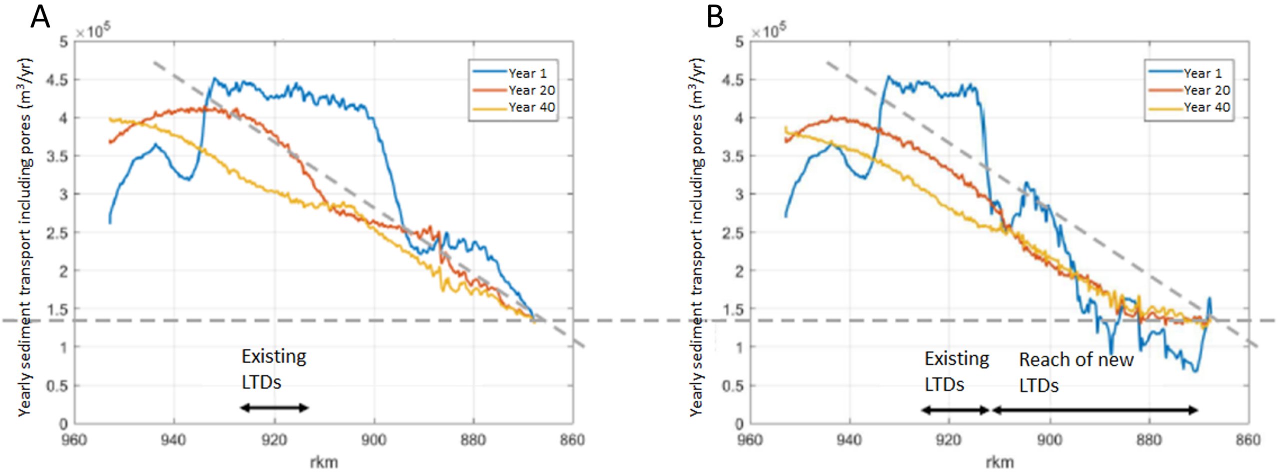

Figure 13: Yearly sediment transport including pores over river length for the reference simulation (A) and the LD-v5 simulation (B). The horizontal dashed line is the optimal yearly sediment transport over river length and the diagonal dashed lines is the modelled trend in yearly sediment transport over river length (adapted from Sloff et al., 2023).

In Figure 14, an overview of the bed level after 20 years for the LD-v5 case is shown for both the Boven-Waal and the Midden-Waal. From this figure, it becomes apparent that LTDs reduce bed degradation in comparison to no measures. However, when comparing the LD-v5 case with the initial case it can be observed that the LTDs are more effective in the Boven-Waal and that erosion continues in the Midden-Waal.

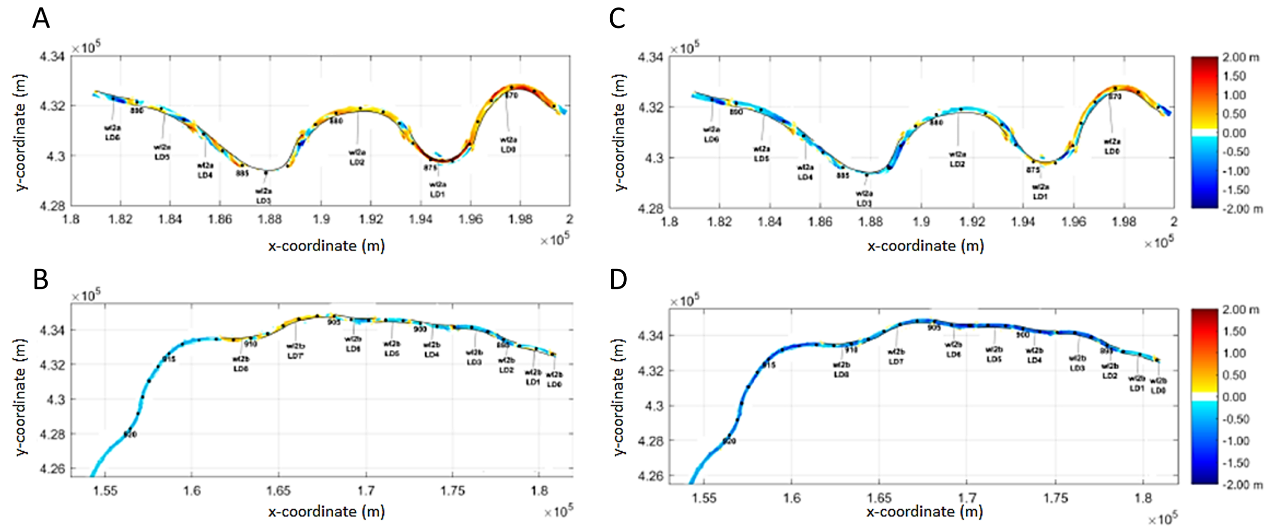

Figure 14: Overview the difference in bed level between the LD-v5 simulation and the reference simulation in the Boven-Waal (A) and Midden-Waal (B) and the difference in bed level between the LD-v5 simulation and the initial situation t_0 in the Boven-Waal (C) and Midden-Waal (D). The numbers in the figure denote the rkm and the existing LTDs start at rkm 912 and the codes denote the partial model and LTD number per partial model (adapted from Sloff et al., 2023).

From Figure 14 it can be concluded that in the case of LD-v5, the erosion stabilises in the Boven-Waal and continues in the Midden-Waal, this is also substantiated by Figure 15. When looking at the top sub-figures (A, C) in Figure 14, the stabilisation in the Boven-Waal can be seen. The bottom sub-figures (B, D) of Figure 14 show that over the years the bed keeps degrading in the Midden-Waal. LTDs aggravate the erosion problems in the Midden-Waal. This is logical since the initial response of the bed is to erode and after some time sedimentation starts. However, before sedimentation can occur, the bed degradation is too large for the LTDs to work properly. When the bed of the main channel degrades and the bed of the riparian channel remains at the same level, the LTDs become less effective since water and sediment is not able to enter the riparian channel during discharges for which the LTDs are designed. This process results in ongoing erosion and makes the LTDs ineffective.

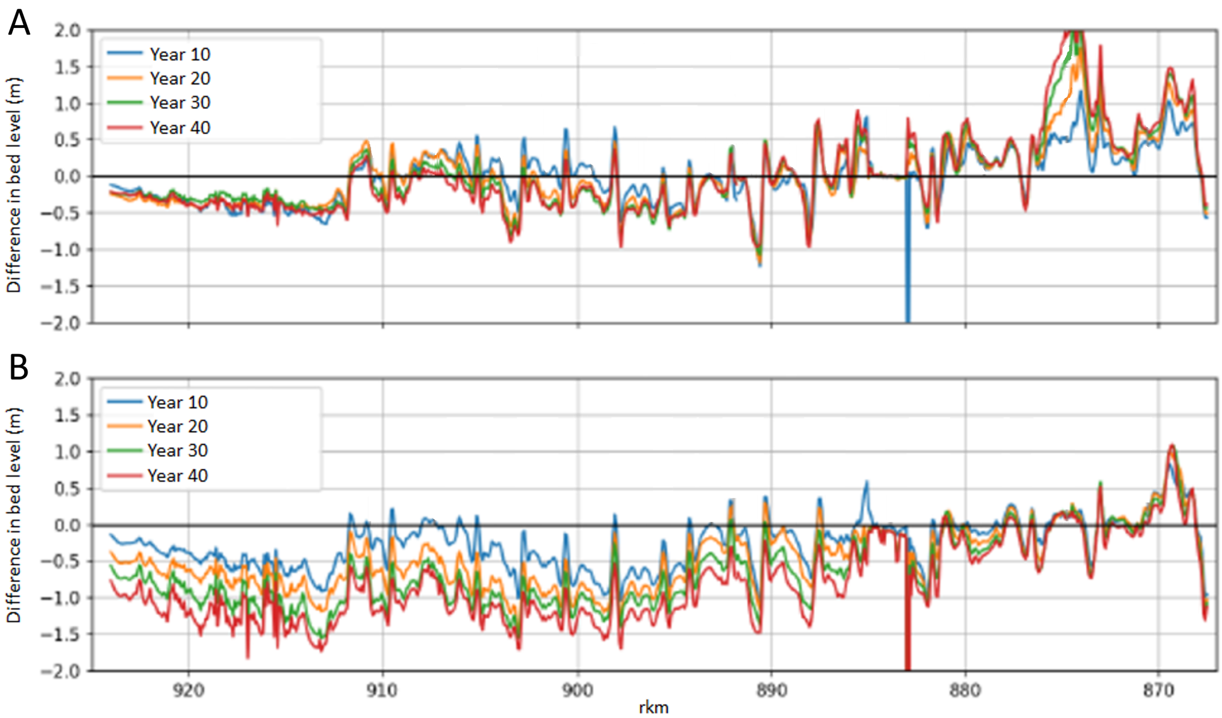

Figure 15: Average change in bed level over time along the Waal for the LD-v5 simulation with respect to the reference simulation (A) and the initial situation (B) (adapted from Sloff et al., 2023).

The LTDs also have several secondary effects. The bed in the Pannerdensch Kanaal is elevated by 0.5 m up to 1 m as a result of the new LTDs in the Waal after 20 years of morphological changes. This comes from the fact that the LTDs lead to lower water levels during high discharges in the Waal leading to higher flow velocities in the Boven-Rijn which increases erosion. The released sediment resulting from erosion in the Boven-Rijn ends up in the Waal and the Pannerdensch Kanaal. This released sediment leads to sedimentation in both the Pannerdensch Kanaal and the Boven-Waal.

4 Model and methods

In this chapter, the methodology of the research is explained. The type of model that is used and how this model works is explained in Section 4.1. The domain that is included in the model is explained in Section 4.2. The input for the model as starting point of the simulations is described in Section 4.3, consisting of model schematisation, boundary conditions, and spin-up time. Next, the calibration of the model is discussed in Section 4.4. In Section 4.5, the different LTD design simulations are described. Finally, the discharge scenarios and simulations for this study are described in Section 4.6.

4.1 Model choice and description

This study makes use of the DVR model. The DVR model is a two-dimensional (2D) morphological model of the Dutch Rhine system, it is in essence developed for the Sustainable Fairway Rhine Delta prediction tool. The DVR model computes simulations in two dimensions (depth-averaged), in the longitudinal and transverse direction of the river. A 2D model is used since a 1D model about LTDs requires simplifications, parameterisations and assumptions regarding sediment transport into the riparian channel. A difference between a 1D and 2D study is that a 2D model can capture transverse variability in flow and bed level. This transverse variability shows the local morphological development at the LTDs. The model is developed to assess proposed sediment management and constructive measures (Van Vuren et al., 2015). The model is able to predict large-scale morphological responses in 2D and is morphologically calibrated for both high and low discharges (Yossef et al., 2008b). In the RvdR programme, the DVR model was set as the official tool for modelling large-scale measures in the Dutch river system (Sloff, 2011). The computational speed of this model is optimised by using a relatively coarse grid, simulation management, and a schematised hydrograph (Sloff, 2011). Simulation management is done via the Simulation Management Tool (SMT), the simulation management tool improves the computational speed of the model by selecting a pre-defined flow field for a set discharge level, which is explained further in Section 4.3.3. In Figure 16, the components of the DVR model are shown.

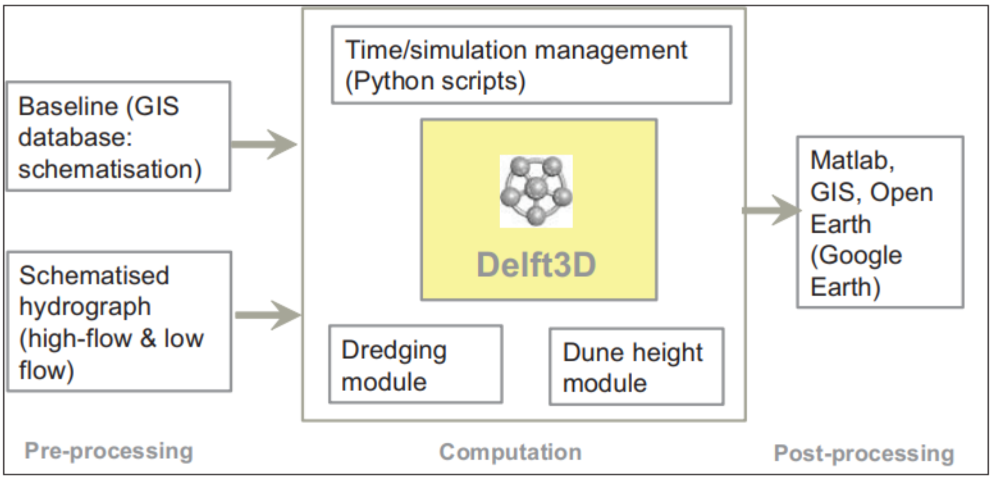

Figure 16: Set-up of the DVR toolbox (Sloff, 2011).

The model is based on the computational core of Delft3D-Flow, which solves numerically the unsteady shallow water equations in two dimensions (depth-averaged). The hydrodynamics in the model are coupled to a sediment transport module and a bed morphology module (Van Vuren et al., 2015). The depth-averaged unsteady shallow water equations are given in Equations (3) and (4).

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial z_w}{\partial x} = -g\frac{u\sqrt{u^2+v^2}}{hC^2} \tag{3}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial z_w}{\partial x} = -g\frac{v\sqrt{u^2+v^2}}{hC^2} \tag{4}$$

In the unsteady shallow water equations, u (m/s) is the velocity in the longitudinal direction, x (m), and v (m/s) is the velocity in the transverse direction, y (m), g (m/s^2) is the gravitational acceleration, h (m) is the water depth, C (m$^{0.5}$/s) is the Chézy roughness coefficient and z_w (m) the water level. The hydrodynamics are coupled to a morphological module in the computational core that computes the sediment transport which results in the bed development, this is done via the Exner equation, (Eq. 5, Deltares, 2013).

$$(1-\epsilon)\frac{\partial z_b}{\partial t} + \nabla \cdot q_s = 0 \tag{5}$$

In the Exner equation, ϵ (-) is the bed porosity, z_b (m) is the bed level, and q_s (m^2/s) is the volumetric sediment flux per unit width. The sediment transport is further determined with either Van Rijn (1984a, 1984b, 1984c) or Meyer-Peter and Müller (1948) formulas. Which formula is used is dependent on the representation of the bed composition, the model distinguishes uniform and non-uniform sediment particles. When the bed composition is represented as non-uniform, the sediment transport is described by a general equation which has the structure of Meyer-Peter and Müller (1948) (Eq. (6)).

$$S = \alpha D_{50}\sqrt{\Delta g D_{50}}\theta^b(\mu\theta - \xi\theta_{cr})^c \tag{6}$$

In which:

$$\theta = (\frac{u}{C})^2\frac{1}{\Delta D_{50}} \tag{7}$$

And α, b, c (-) are calibration factors, D_{50} median grain size (m), θ (-) Shields stress, θ_{cr} (-) critical Shields stress, Δ (-) submerged specific gravity of the sediment, μ (-) ripple factor, S (m^2/s) sediment transport rate and ξ (-) exposure factor for sediment fraction (Meyer-Peter & Müller, 1948).

When the bed composition is uniform, the sediment transport is calculated with the equation of Van Rijn (1984a) (Eq. (8)). Equation (8) is adapted by Yossef et al. (2008b) to calibrate suspended and bed load transport independently.

$$S = \alpha_{sus} \cdot f_{cs}uh \cdot 0.015\frac{D_{50}}{\xi_c}\frac{T^{1.5}}{D_*^{0.3}} + \alpha_{bed} \cdot 0.1sqrt\Delta g D_{50}^3\frac{T^{1.5}}{D_*^{0.3}} \tag{8}$$

In which:

$$T = \frac{\mu_c\tau_{bc} - \tau_{bcr}}{\tau_{bcr}} \tag{9}$$

α_{sus} (-) is a calibration parameter for suspended load transport and α_{bed} (-) is a calibration parameter for bed load transport. ξ_c (m) is the reference height, T (-) a dimensionless transport parameter, D_* (-) a dimensionless particle diameter, f_{cs} (-) a shape factor, τ_{bcr} (N/m^2) the critical bed shear stress, $\mu_c\tau_{bc}$ (N/m^2) the effective bed shear stress and all other parameters as defined before.

4.2 Model domain

The DVR model of the whole Dutch Rhine system consists of sub-domains that are coupled. In Figure 17, the sub-domains in the Dutch Rhine system are shown and the partial models that are included in this study are denoted. Each sub-domain, which can be distinguished by different colours, has a separate computational domain. In this study, six sub-domains are included. The six domains include the Niederrhein starting at Xanten Germany, Boven-Rijn, Pannerdensch Kanaal and the whole Waal. The six sub-domains are coupled to create one domain. When the domains are coupled, the computations are carried out simultaneously, this is called parallel computing (Yossef et al., 2008a). Between the sub-domains, there is communication via internal open boundaries, requiring no additional boundary conditions.

The different domains can use different sediment transport formulations, thus a distinction can be made between non-uniform sediment particles and uniform sediment particles. The Rhine has non-uniform sediment, downstream fining is significant and there is vertical segregation of fine and coarse sediment observed (Van Vuren et al., 2015). As stated by Van Vuren et al. (2015), the vertical segregation process is less important in the Waal and IJssel. Welsch (2021) therefore used a uniform sediment approach in the Waal and IJssel. However, to make the model more realistic, the graded sediment approach is used in all domains in this study. The downside of this choice is that the model is more computationally demanding in comparison to the use of the uniform sediment approach. This is because the graded sediment approach uses ten sediment fractions and the median sediment diameter (D_{50}) can change in space and time. Domains that use the uniform sediment approach only use one sediment fraction, which is equal to the D_{50} at each specified location and this parameter is not able to change in time.

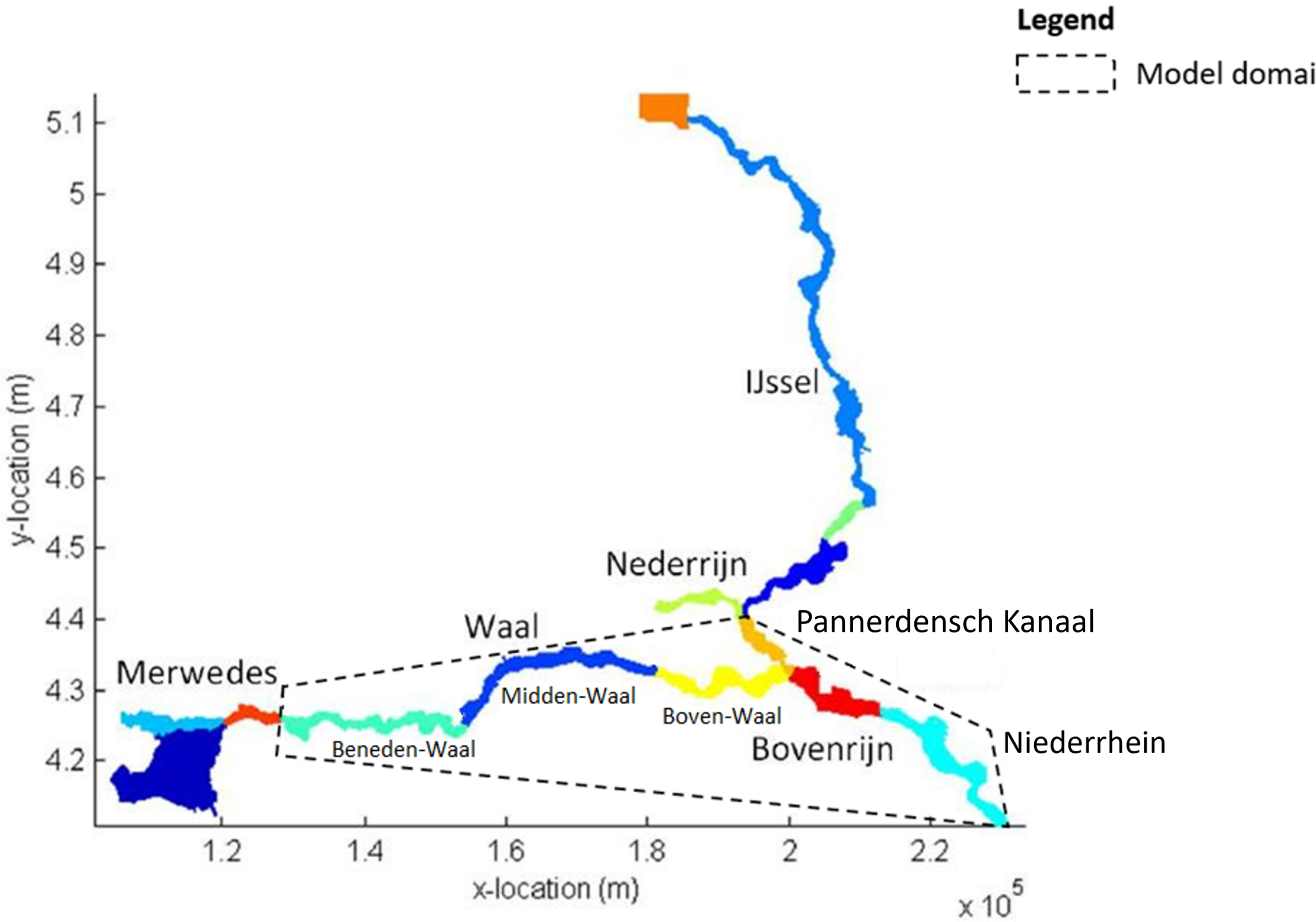

Figure 17: Partial models of the DVR model of the Dutch Rhine system, domains within the dashed lines are included in this study (adapted from Bom and Van Leeuwen, 2020).

Figure 17 shows that the Merwedes, IJssel, and Nederrijn are not included as partial models in this research. The more partial models are included in the study, the longer the computational time of one simulation. This research concerns bed degradation in the Waal and LTDs are implemented in the Boven-Waal and Midden-Waal. The Beneden-Waal partial model is included since this domain is still part of the Waal and the most downstream point in the Beneden-Waal can function as the downstream boundary. If the downstream boundary is located at the end of the Midden-Waal, boundary effects could affect the obtained results in the Midden-Waal. The Pannerdensch Kanaal is included since the discharge distribution at the Pannerdense Kop is modelled with an initial set discharge distribution for different discharges. The IJssel and Nederrijn are excluded from this study since these domains do not add value to this research because the study concerns bed degradation in the Waal. Figure 17 shows at what rkm, one partial model transitions into another.

4.3 Model input

4.3.1 Model schematisation

The model uses a curvilinear grid as the computational grid, the cells in the model are aligned with the direction of the flow in the river. It is aimed to maximize the resolution of the grid in the main channel, however, since a curvilinear grid is used the highest resolutions of the grid are created in the inner bends of the river. The grid cells in the river have a resolution of around 25 m in the transverse direction of the river and 80 m in the longitudinal direction of the river. The model numerically solves the hydraulics and morphodynamics in a duplicated staggered grid. The water and bed levels are computed in the middle of each cell, the fluxes are computed at the boundaries of the cells.

The locations of the LTDs in the model are based on the global design LTDs (Huthoff et al., 2015) and the Room for Living Rivers programme (Sloff et al., 2023). Next to this, the LTDs are located in the inner bends of the river to avoid one channel filling up with sediment by avoiding the bend apex and curvature crossover as mentioned in Section 2.1. In Figure 2, the locations of the LTDs in the model can be seen.

The schematisations of the different LTD designs are based on the design of Huthoff et al. (2015). Table 2 shows the standard used parametrisation of an LTD in the model. The design parameters of the LTDs are described relative to OLR[2]. In the implementation of LTDs in the model, groynes are removed at the side of the LTD and the summer bed width is kept the same. The different schematisations of the simulations are set up by adjusting the bathymetry and this is done by adjusting the elevation of bed level points. Barneveld et al. (2023) created the initial bed level of the model via interpolation between specified points in Baseline. Afterwards, weirs are implemented over the length of the LTDs. Weirs are fixed non-movable constructions that generate energy losses as a result of the constriction of flow. Weirs are implemented in addition to changing the bathymetry to schematise the roughness of the LTDs. The elevation of the weirs could differ from the bed elevation resulting from the interpolated Baseline bed level, however, the model uses the highest elevation point of the two at that point. Thereafter, LTDs are non-erodable in the model, no sediment layers are present at the locations of the LTDs. The main channel, riparian channel and floodplains are erodable since sediment layers are present in these locations of the model. Figure 18, shows the cross-sectional schematisation and the top-view schematisation of an LTD in the model. As can be seen in Figure 18, the coarse resolution of the grid cells limits the options for different configurations of LTDs. An in-depth explanation of the implementation of the LTDs in Delft3D can be found in Appendix A.

[2]OLR: agreed-upon low water level (In Dutch: Overeengekomen lage rivierstand)

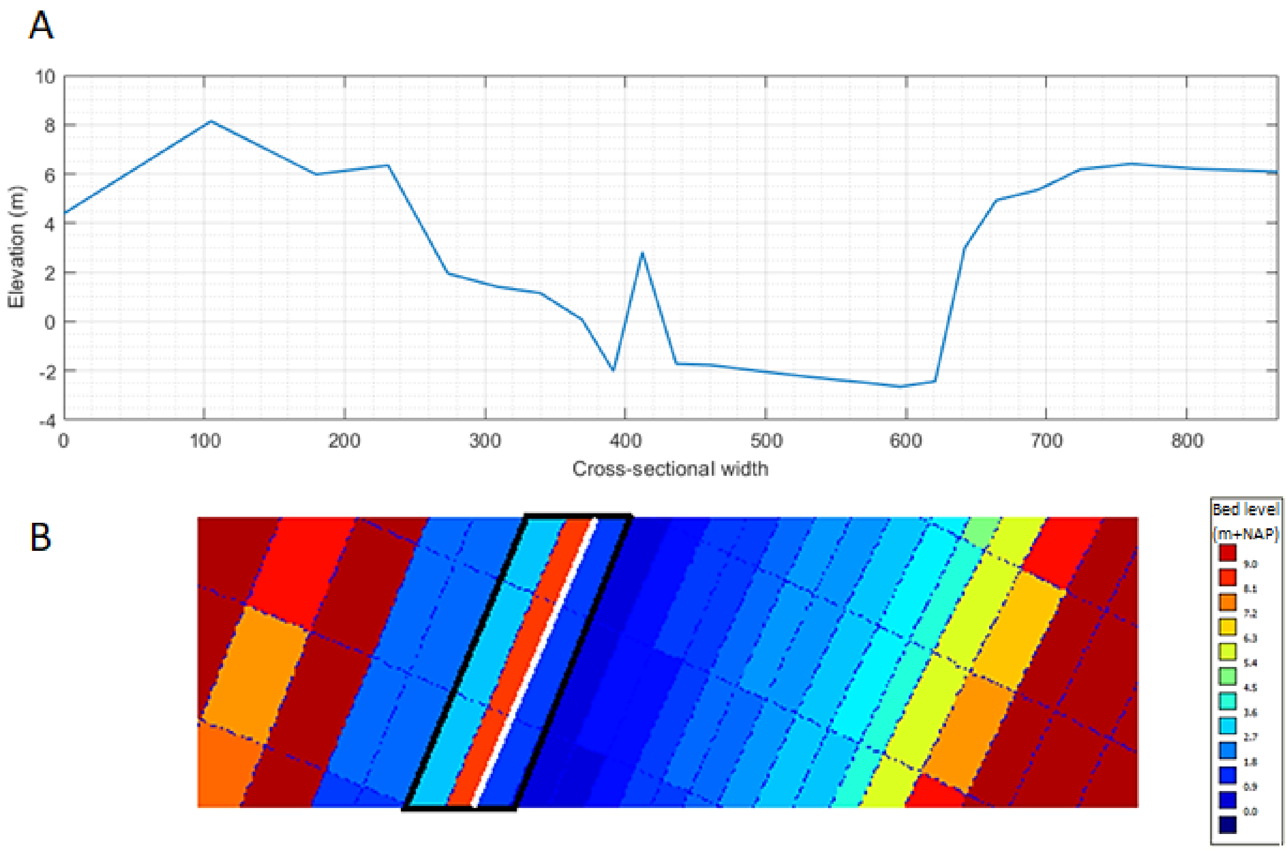

Figure 18: Schematisation of LTD in a river with the cross-sectional schematisation of a LTD in a river (A) and the top-view schematisation of a LTD (B). The black box denotes the cells where no sediment layers are present, the white line denotes the location of the weir on the LTD and the color palette denotes the bed level with respect to NAP.

Table 2: parametrisation of modelled LTDs. Source: Huthoff et al. (2015) and Zuijderwijk and De Jong (2019)

Part of LTD	Parameters	Pilot situation 2018
LTD body	Height	OLR +2 m
	Length	∼3-3.5 km
	Embankment slope	1:2.5
	Material	Quarry stone
Sill	Width	∼225 m
	Height	OLR +0.5 m
Riparian channel	Width	∼100 m
	Depth	Varying from -4.75 m OLR to 0 m OLR

4.3.2 Boundary conditions

The DVR model requires a discharge hydrograph as input, this yearly repeating hydrograph is the hydraulic upstream boundary condition. The hydrograph is discretized to reduce computational time, the discretization results in a sequence of steady-state steps (Sloff, 2011). The discretized hydrograph is used in a multitude of studies for RWS, the study of Bom and Van Leeuwen (2020) on the groyne and riverbank lowering in the Pannerdensch Kanaal is an example. In Figure 19, the hydrograph used as input for the DVR model in this study is given. Using a hydrograph with the sequence of steady-state steps is called a quasi-stationary discharge approach.

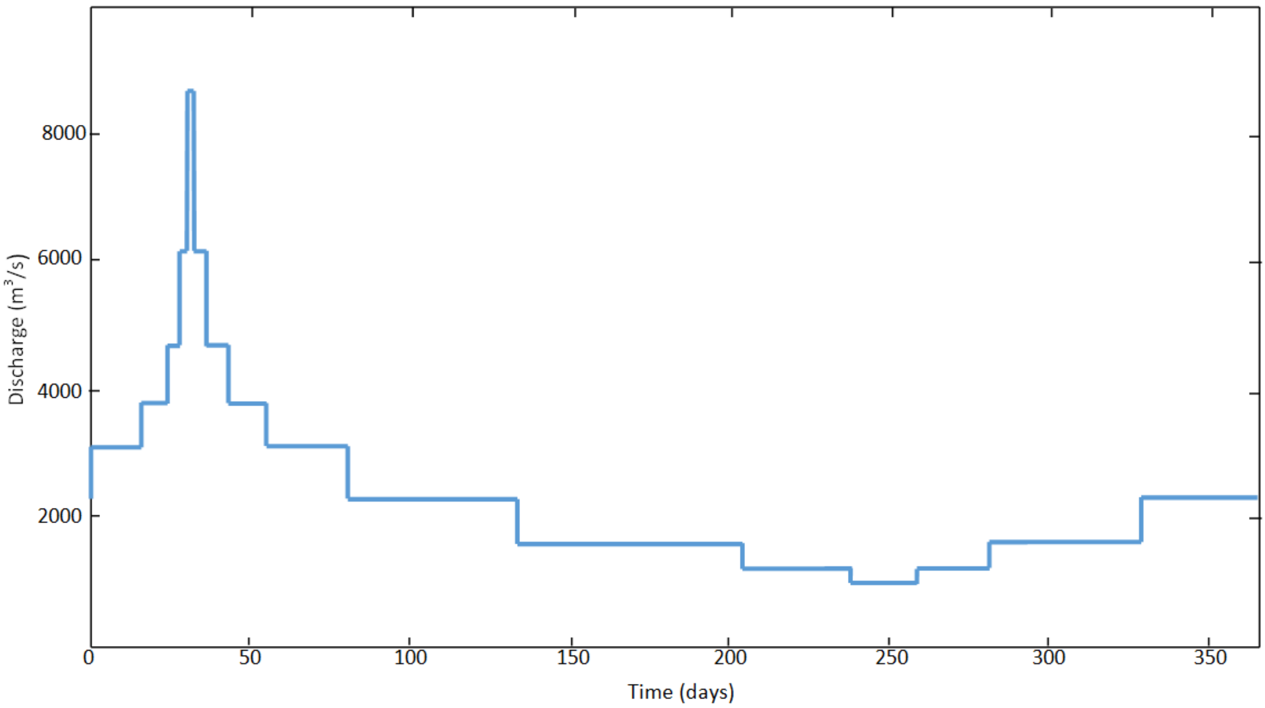

Figure 19: Reference discretized yearly repeating hydrograph used in this study.

Per step of the hydrograph, morphological changes are computed. As the morphological upstream boundary condition, a bed degradation of 1.5 cm/yr is imposed which is in accordance with the large-scale trend (Sloff et al., 2023; Yossef et al., 2008b). However, relative to the flow, morphological changes are small (Sloff, 2011). A morphological factor can be used to speed up the morphological changes and thus reduce computational time. The computed changes in bed level are multiplied with the morphological factor to accelerate the morphology. Overall less flow time is needed to get an equivalent time in morphological changes (Sloff, 2011). To avoid errors in the model, higher discharge levels have higher transport rates, thus a low morphological factor is used. Higher discharges have higher transport rates resulting from higher flow velocities, thus a higher discharge level has a lower morphological factor. This research makes use of the morphological factor to reduce computational time. Discharges >3824 m^3/s have a morphological factor of 120 while a discharge of 1020 m^3/s has a morphological factor of 1440.

According to Paarlberg and Van Lente (2021), it is common in morphological simulations to ignore lateral inflows to the system since the lateral inflows have a small effect. Paarlberg and Van Lente (2021) stated this for a 1D morphological model of the Dutch Rhine branches. The downstream boundary conditions for the model are determined via a $Q - h$ relation. This means that for every discharge at the upstream boundary, there is a specific water depth at the downstream boundary. The bed level and water depth remain fixed over time at the downstream boundary condition, this means that the water level also remains fixed over time. The downside of this method is that changes and interventions in the river system affect the water level at the downstream boundary, however, the water level stays fixed. To counter this, the downstream boundaries are located far downstream of the newly implemented LTDs so this will not have an effect on the results of the new LTDs. The model has two downstream boundary points, the first one being at the end of the Beneden-Waal and the second one being at the end of the Pannerdensch Kanaal. Both downstream boundary conditions have a $Q - h$ relation for every discharge level. In Appendix B, the used downstream boundary conditions at the two downstream boundaries are given.

Next to this, the DVR model uses an active layer. The active layer is the depth of sediment of the riverbed that is subject to erosion and deposition (Houbrechts et al., 2012). The active layer is determined with Equation (10), in line with the studies of Becker (2021) and Niesten et al. (2017). The active layer has a minimum thickness of 0.5 m, which provided realistic results for the Waal and Rijn in both studies.

$$-D_{act} = \delta h \tag{10}$$

The active layer D_{act} (m) is determined by the water depth h and the constant δ. A value of 0.12 is used for δ since good results in previous studies were obtained and the gradients in grain size at the Pannerdense Kop and in the Boven-Waal are in line with observed gradients (Becker, 2021).

4.3.3 Spin-up time

This research used a yearly repeating hydrograph as the upstream boundary condition, which can be seen in Figure 19. This yearly repeating hydrograph is used to reduce computational time. Every time the discharge changes, the flow fields need to adjust to the new conditions. This adjustment time can be reduced by storing and retrieving flow fields that match a certain level of discharge in a database at the end and beginning of a simulation, consecutively (Sloff, 2011). Due to this approach, the flow fields have to adapt to small changes caused by morphological development between two equal discharge steps. This is the case because the recent flow fields are retrieved from the database. The DVR model uses the approach of storing and retrieving flow fields that match a certain level of discharge in a database. The SMT selects the restart file for the relevant discharge level to retrieve the related flow fields.

The starting bed level of the model is spun up instead of using the exact measured bed level, this is done to avoid a strong initial reaction of the model (Becker, 2021). The first step in the spin-up of the model is regarding the sediment composition. The initial input contains a uniform distribution consisting of four layers with ten sediment fractions per partial model. The grain size distribution is spun up for 5 years without morphological changes. The second step in the spin-up of the model is spinning up the morphological response. The second step uses the spun-up grain size distribution as input and this step is performed for 5 years of morphological development. The resulting bed composition and bed level are used as starting points for the simulations.

4.4 Model calibration

Alluvial roughness in the main channel is used as a parameter during the calibration of the model and is composed of a combination of a fixed value and a function of the local water depth and bedforms which are predicted with a bedform prediction module which is based on the Van Rijn equation (Yossef et al., 2008b). The alluvial roughness values were calibrated by adjusting the calibration factor in the alluvial roughness equation at the downstream location of each reach based on the deviation between the measured water depth and calculated water depth of the model (Yossef et al., 2008b). Despite the calibration and choice of equations justified by Yossef et al. (2008b), Flierman (2017) states that uncertainty remains present in the computed sediment transport since this deviates from the measured sediment transport. Sloff et al. (2023) shows that the yearly sediment transport gradient in the DVR model deviates a factor of 3 with measured sediment transport. Comparison of the prognosis by Sloff

(2019) of change in bed level in 20 years with the computed change in bed level in the DVR model in 20 years compared to the current bed level shows differences. A comparison between the prognosis and the results of the DVR model can be seen in Table 3. The model gives results of 2.0 cm/year of bed degradation in the Midden-Waal (Sloff et al., 2023), while the prognosis by Sloff (2019) gives a bed degradation of 0.6 cm/year in the Midden-Waal. The results of the model on bed degradation in the Boven-Waal and Beneden-Waal are similar to the results of the prognosis of bed degradation (Sloff et al., 2023).

Table 3: Comparison of the estimated bed degradation resulting from the prognosis of Sloff (2019) with modelled bed degradation in the study of Sloff et al. (2023).

	Prognosis by Sloff (2019) [cm/yr]	**Results model by Sloff et al. (2023) [cm/yr]**
Boven-Waal	-1.6	-2.2
Midden-Waal	-0.6	-2.0
Beneden-Waal	+0.1	+0.1

An analysis was performed to identify possible improvements to the model. In Appendix C this analysis can be found. During the analysis, it was found that calibrating and thus improving the model would be too complex and time-demanding to perform during this study. In the analysis, the results of the DVR model were assessed whether the results are in line with the expected changes based on the prognosis. Next to this, the results of the change in sediment composition over time are compared to the measured change in sediment composition over time. From the analysis, it was concluded that the model results have similarities with measurements. For example, the model shows coarsening of sediment in the Waal over the years, which is also the case based on measured data. Next to this, deviations from the prognosis were found. For example, the model predicts no erosion in the Pannerdensch Kanaal while in the prognosis by Sloff (2019) erosion of 1 cm/yr is expected in the Pannerdensch Kanaal. The deviations in the model from reality seem relatively small, however, the combination of all deviations amplifies each other in under- and overestimations. Next to this, the coarse grid cells make the model less sophisticated resulting in coarser results. Overall, the model seemed to function properly, but the model could be improved by thorough calibration of the morphological factor per discharge level and recalibrating the calibration factor in the alluvial roughness equation.

4.5 Simulations different LTD designs

To answer the first research question (RQ 1), the first five simulations (S_{actual}, S_{LTDs}, S_1, S_2 and S_3) are set up to test the effects of different parameters on countering bed degradation in the Waal. An overview of all simulations can be found in Table 4. First, simulation S_{actual} is carried out, which is based on the current situation of the Dutch Rhine system, which includes the existing LTDs near Tiel. Next, simulation S_{LTDs} is carried out, which is the same schematisation (LD-v5) as the one in the study of Sloff et al. (2023), which includes the new LTDs in the Boven-Waal and Midden-Waal using the parametrisation of LTDs as found in Table 2 for the new LTDs. The hydrograph used for RQ 1 is the reference hydrograph as shown in Figure 19 which is based on the current discharge regime of the Rhine at Lobith and this hydrograph is repeated 20 times to compute 20 years of morphological changes. Simulation S_{LTDs} can be compared one on one with simulations S_1, S_2 and S_3 to test different designs of LTDs. Configurations S_1, S_2 and S_3 only include adjustments on the new LTDs in the Midden-Waal to reduce bed degradation in this part of the Waal since Sloff et al. (2023) showed that the new LTDs in the Boven-Waal reduced bed degradation in the Boven-Waal, but increased bed degradation in the Midden-Waal.

Simulation S_1 is set up to quantify the effects of a wider riparian channel in the Midden-Waal in comparison to the Boven-Waal. This simulation is compared to simulation S_{LTDs}, in which the riparian channel width is uniform along all LTDs. The riparian channels in the model with LTDs (S_{LTDs}) are around 80 m in width, which is 3 grid cells in the model. In simulation S_1, the riparian channels in the Midden-Waal are increased by around 25 m, which is an additional grid cell in the model. The grid cell increase of the riparian channel results in one grid cell decrease for the main channel.

The second LTD design (S_2) that is set up as a simulation is the lowering of the sill height in the LTDs in the Midden-Waal. In simulation S_{LTDs}, the sill height is at an elevation of +0.5 m OLR. When the sill height is reduced, water flows in the riparian channel at lower discharges. This reduces the width-averaged flow velocity in the main channel, which reduces the sediment transport in the Midden-Waal. The height of the sill is set at 0 m OLR in this simulation, this value is chosen since a local navigation depth of 2.8 m needs to be ensured along the Waal during OLA by RWS (Rijkswaterstaat WVL, 2019). By setting the sill height to 0 m OLR, the minimum navigation depth during OLA is not compromised by the measure. The new LTDs in the Boven-Waal and Midden-Waal in the configuration by Sloff et al. (2023) do not contain side openings, this is kept this way in this research to keep it comparable to the study by Sloff et al. (2023).

In the last simulation (S_3), the crest heights of the new LTDs in the Midden-Waal are lowered from +2 m OLR to +1.2 m OLR. In the Netherlands, groynes may be lowered to a minimum of +1.2 m OLR to remain a recognisable object in the river landscape (Bom & Van Leeuwen, 2020), in this simulation this guideline is followed for LTDs. When the crest height of the LTD is lowered, water is diverted over the crest of the LTD to the riparian channel during lower discharges. The threshold for water entering the riparian channel over the crest of the LTD is during a larger discharge than water entering the riparian channel via the sill. A significantly larger volume of water is able to enter the riparian channel over the crest in comparison to the opening at the sill. In Figure 20, visualizations of different schematisations of the LTD designs are shown.

Table 4: Overview of simulations, adjustments of simulations done on configuration given in Table 2

Simulation	**Explanation simulation**
S_{actual}	Current situation, including the existing LTDs in the Midden-Waal near Tiel
S_{LTDs}	Implementation of new LTDs in the Boven-Waal and Midden-Waal as depicted in Figure 2 using the parametrisation as seen in Table 2
S_1	Widening riparian channel width in the Midden-Waal by 25 m
S_2	Lowering the sill height in the Midden-Waal to 0 OLR
S_3	Lowering the crest height of LTDs in the Midden-Waal to +1.2 m OLR

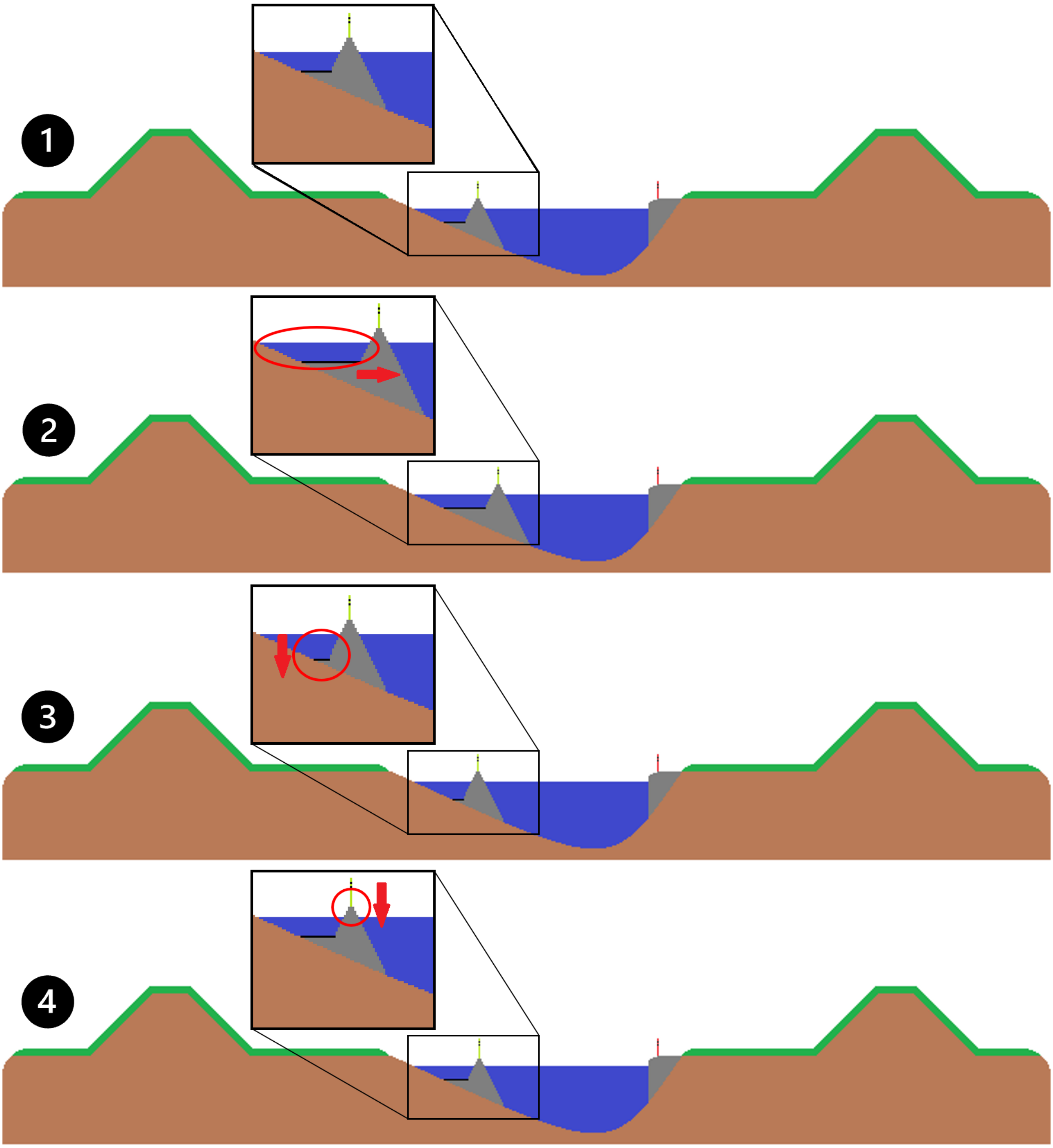

Figure 20: Cross-sectional schematisation of a river with the different schematisations of LTD designs, with S_{LTDs} (1), S_1 (2), S_2 (3) and S_3 (4), where the red shapes indicate the location of the changes with respect to the original LTD design.

4.6 Discharge scenarios

To answer the second research question (RQ 2), different discharge scenarios are set up. The different discharge scenarios are based on KNMI'14 scenarios which are the result of climate change projections. The morphological effects are simulated for 20 years, this time span is chosen to make this study comparable to the results of the study by Sloff et al. (2023). The following two discharge scenarios are based upon KNMI'14 scenarios and translated into discharge scenarios by Sperna Weiland et al. (2015). The first discharge scenario that is translated into a hydrograph is based on the KNMI climate change projection G_l. Climate change projection G_l is based on a +1 °C increase in 2050 with a weak change in atmospheric circulation (Attema et al., 2014). This climate scenario results in a large increase in precipitation during the winter and also an increase in precipitation during the summer. The second discharge scenario that is used is the KNMI climate change projection $W_{H,dry}$, this scenario is also the most extreme scenario that projects that there will be a global temperature increase of 2 °C in 2050 with strong atmospheric circulation (Attema et al., 2014). In this scenario, there is a relatively large precipitation increase in the winter combined with the largest precipitation decrease in the summer. In Figure 21, the discharge scenarios based on the KNMI'14 climate change scenarios are shown. The different discharge scenarios are simulated on the best-performing design of the LTDs and evaluated based on countering bed degradation, increasing water depths during low discharges, decreasing water levels during high discharges, and the effects on the discharge distribution at the Pannerdense Kop.

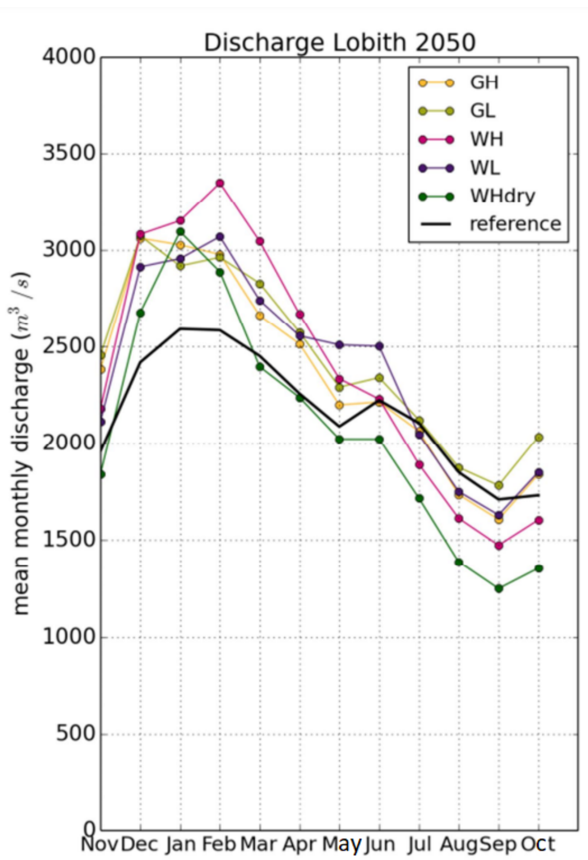

Figure 21: Monthly average discharge of Rhine at Lobith in 2050 of different KNMI climate change projections which are indicated in the legend (adapted from Sperna Weiland et al., 2015).

The discharge scenarios of the Rhine at Lobith in 2050 need to be translated into a yearly repeating hydrograph. This needs to be done to make it suitable input for the DVR model. Two methods are applied on two discharge time-series of the Rhine at Lobith, which differ in the length of measurements. The two methods applied to the two discharge time series data sets were assessed based on the ability to reproduce the reference yearly repeating hydrograph.

The reference yearly repeating hydrograph is based on discharge data from 1971-2009. Next to this, translating a climate change projection into a discharge scenario requires future projections of occurring discharges. Kramer (2016) used discharge time-series from 1901-2015 and moving daily averages of 31 days to project discharge series for climate change projections G_l and $W_{H,Dry}$. The projected discharge series of Kramer (2016) and the reference yearly repeating hydrograph were used to create the yearly repeating hydrographs for climate projections G_l and $W_{H,Dry}$. In Appendix D, the step-to-step approach to creating the different hydrographs for different climate projections can be found. In Appendix D Table 13, the discharge steps with corresponding discharge levels and duration of the climate projections and the standard hydrograph can be found. In Figure 22, the different hydrographs are visualized. Figure 22 shows a comparison to the reference hydrograph, both climate change projections G_l and $W_{H,Dry}$ have a longer peak of discharge, of which G_l has the longest one. Next to this, climate projection G_l has shorter low discharge periods than climate projection $W_{H,Dry}$.

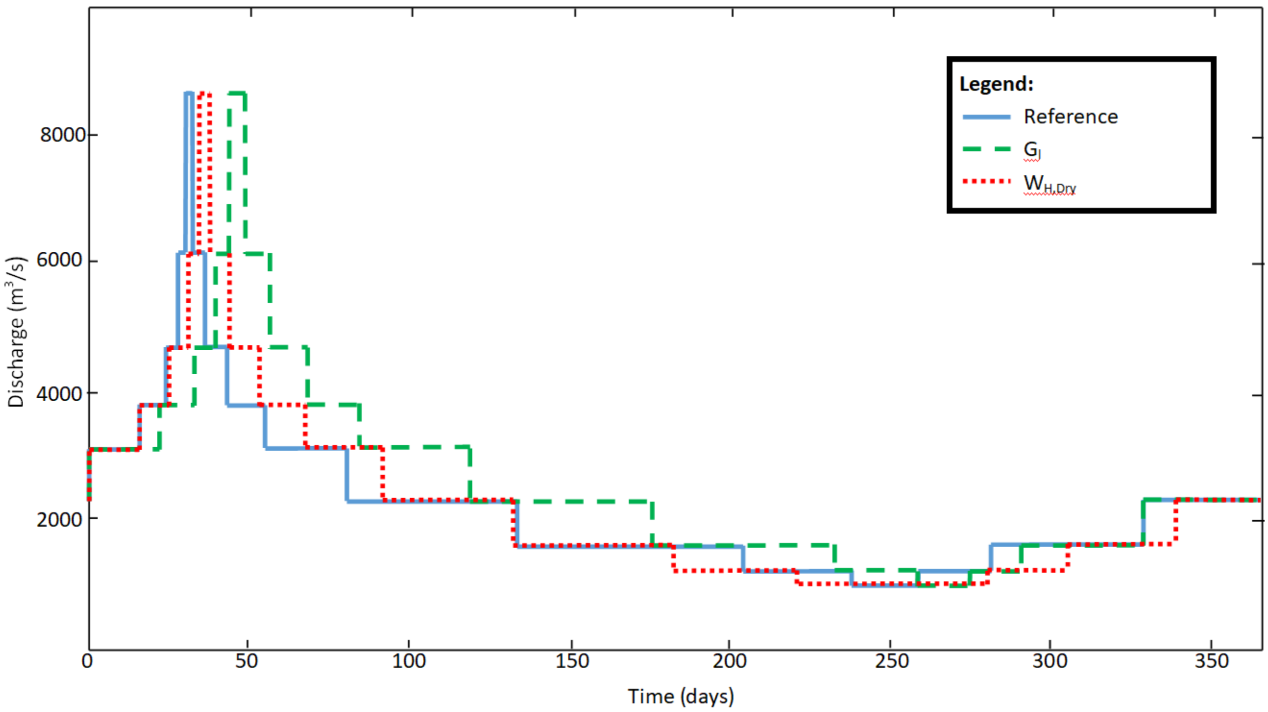

Figure 22: Yearly repeating hydrographs for different climate change projections.

5 Effects of different LTD designs on the Waal

In this chapter, the results of RQ 1 are presented. Hydraulics of the river are responsible for morphological development which has an impact again on the hydraulics. Usually, first, the hydraulics are described to understand the morphological effects. However, in this research, the hydraulics of the river are described after 20 years of morphological changes. As a result, the morphological effects resulting from the different LTD designs are presented first. Next, the hydraulic changes resulting from the different LTD designs are presented. For all the LTD designs, water depths during low discharges, water levels during high discharges, and the discharge distribution at the Pannerdense Kop are assessed.

5.1 Morphological effects of different LTD designs on the Waal

The average change in bed level in the main channel of the Waal determines whether LTDs have a positive effect on reducing bed degradation. The predicted bed degradation in the DVR model in the Midden-Waal of the existing situation (S_{actual}) considerably deviates, with a factor of 4, from the prognosis given by Sloff (2019) in the case of the situation without the new LTDs (S_{actual}). The results of the Midden-Waal will thus be handled with caution. Negative values presented in this section denote erosion and positive values denote sedimentation.

Figure 23 shows that in the case without new LTDs (S_{actual}), gradual erosion occurs in the Boven-Waal and Midden-Waal and slight deceleration of sedimentation occurs in the Beneden-Waal. In the case of the new LTDs (S_{LTDs}), initial sedimentation occurs in the Boven-Waal and Beneden-Waal that turns into erosion over the years. In the Midden-Waal it can be observed that erosion decelerates over the years.

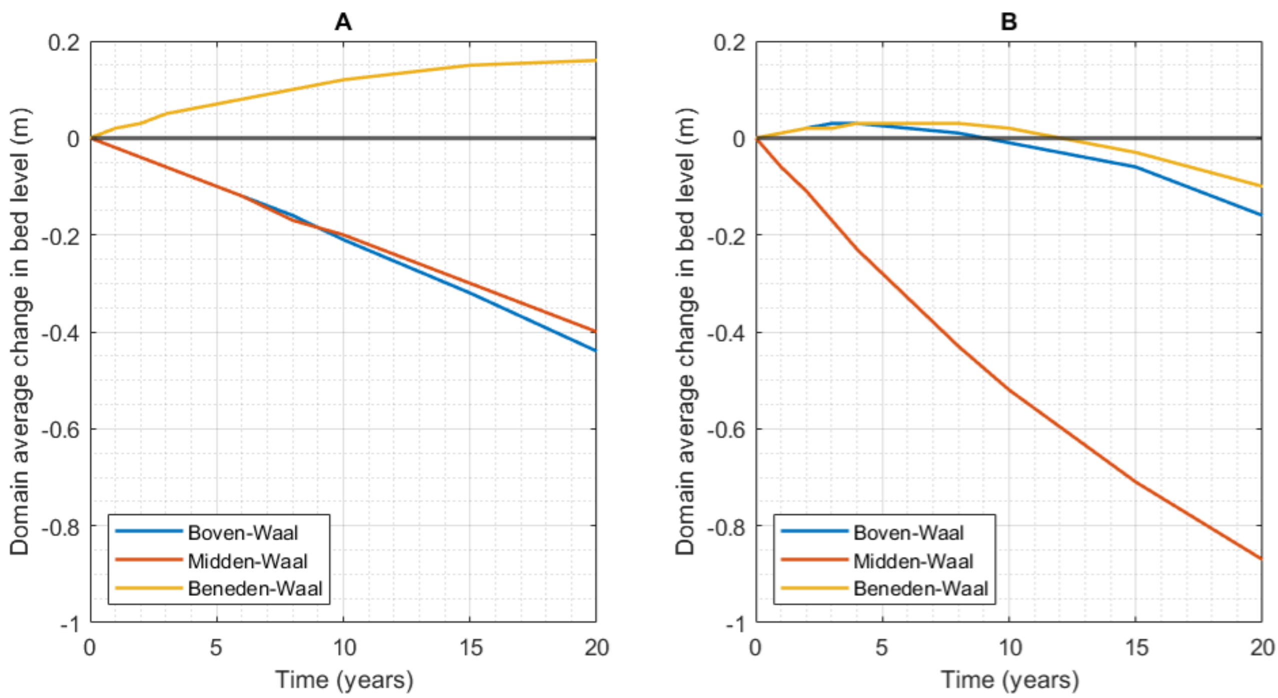

Figure 23: Domain averaged bed degradation in the main channel over the years, difference between the case without new LTDs S_{actual} (A) and the case with LTDs S_{LTDs} (B).

The lower bed level of the main channel in the Waal results in less effective LTDs because water can only enter the riparian channel at higher discharges. This results in higher flow velocities in the main channel during discharge levels where the riparian channels were initially more active, but as a result of the degradation of the main channel, they are less active. Figures 52 and 53 in Appendix C show the change in depth average flow velocities and water depth over time in a riparian channel in the Boven-Waal. During a discharge of 1635 m^3/s the riparian channels become active and for this discharge, a reduction in the riparian channel of the Boven-Waal in discharge per unit width of 11% after 10 years of morphological changes and 21% after 20 years of morphological changes is observed, which shows that the riparian channel becomes less active and effective over time. Figures 54 and 55 in Appendix C show the change in depth average flow velocities and water depth over time in a riparian channel in the Midden-Waal. During a discharge of 1635 m^3/s the riparian channels become active and for this discharge, a reduction in the riparian channel of the Midden-Waal in discharge per unit width of 30% after 10 years of morphological changes and 80% after 20 years of morphological changes is observed, which shows that the riparian channel becomes less active and effective over time.

Figure 24 shows the domain averaged bed level changes for different LTD designs, the values used for the figure can be found in Appendix E in Tables 14-17. Only one graph is shown for the Beneden-Waal since no new LTDs are implemented in this domain and thus the change in bed level is computed over the entire width. In simulation S_{actual}, the existing LTDs near Tiel are the only LTDs in the schematisation. In the results of the main channel of the Boven-Waal and Midden-Waal in Figure 24, the values for S_{actual} are averaged over the same width as the main channel of S_{LTDs}, this approach was also used for the whole width of the different domains for all simulations to keep the simulations comparable.

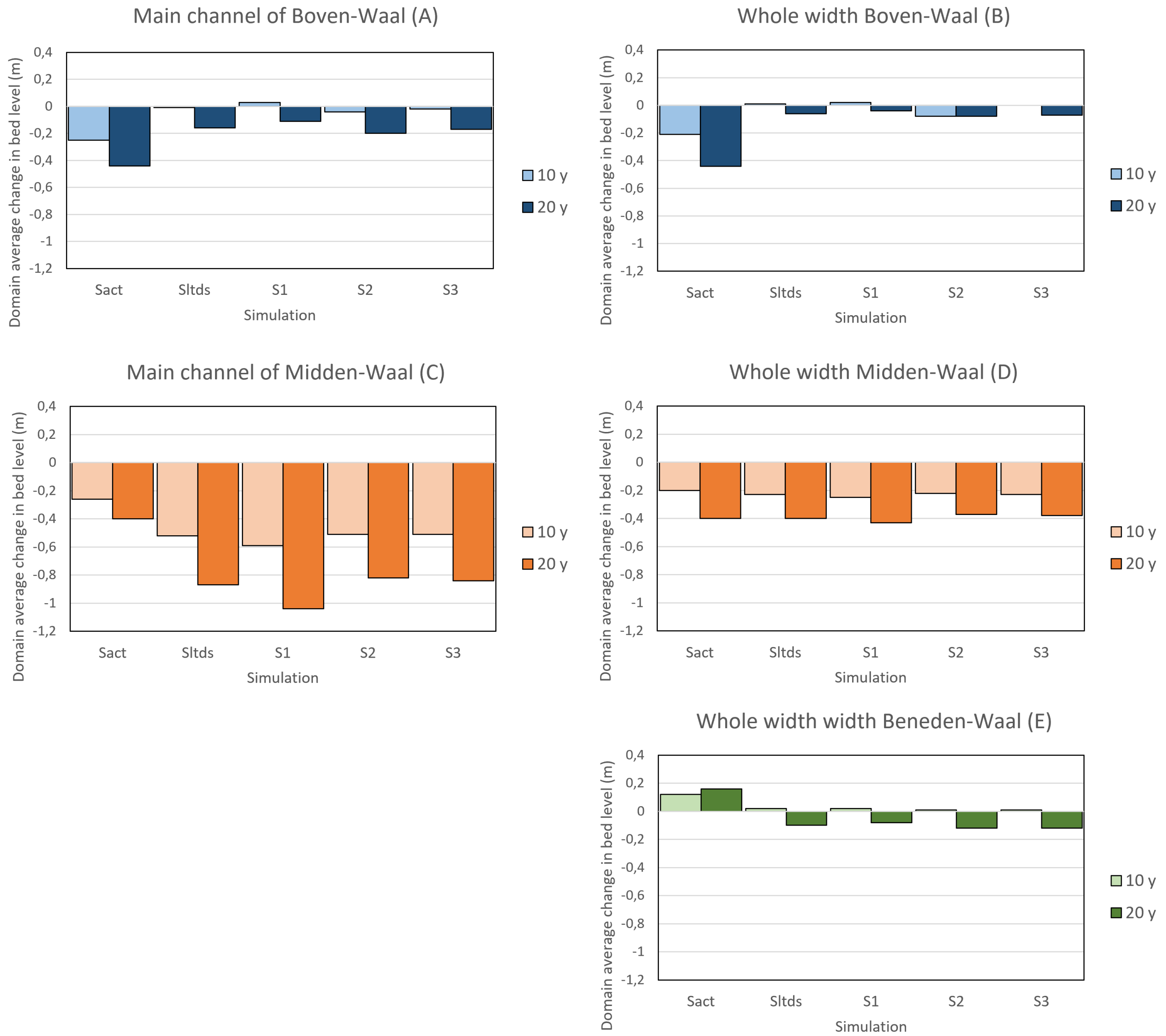

Figure 24: Histograms (A-E) of domain averaged bed level changes for different LTD designs. The graphs on the left denote the domain averaged bed level in the main channel and the graphs on the right denote the domain averaged bed level across the whole river width, thus including the main channel and riparian channel. The Beneden-Waal only has one figure because this domain consists of one channel since there are no LTDs implemented.

Figure 24.A shows the average change in bed level in the main channel of the Boven-Waal after 10 and 20 years of morphological changes. When no new measures are implemented (S_{actual}), large erosion occurs in the main channel of the Boven-Waal. After 20 years of morphological development, it becomes apparent that the main channel of the Boven-Waal experiences erosion in all cases. However, all configurations with the new LTDs result in reduced bed degradation in the main channel of the Boven-Waal after both 10 and 20 years of morphological changes in comparison to the case without the new LTDs (S_{actual}). What becomes apparent is that solely widening the riparian channel (S_1) results in sedimentation in the main channel of the Boven-Waal after 10 years of morphological changes. After 20 years of morphological changes, widening the riparian channel of the new LTDs (S_1) shows the smallest erosion in the main channel of the Boven-Waal. Lowering of the sill (S_2) increases erosion in the Boven-Waal in comparison to S_{LTDs}. Czapiga et al. (2022) states that erosion in the

river is best mitigated when the flow over the sill is minimized, reducing the sediment supply towards the riparian channel and keeping the sediment in the main channel, but the flow over the sill is still important during lower flows regarding ecological purposes. The results of S_2, are in line with the statement regarding erosion from Czapiga et al. (2022). Lowering the crest height (S_3) has similar effects as lowering the sill (S_2). However, comparing S_3 with S_2, S_3 results in slightly less erosion in the Boven-Waal and slightly more erosion in the Midden-Waal.

Figure 24.B shows similar effects as Figure 24.A. The new LTDs reduce bed degradation in the Boven-Waal and widening the riparian channel (S_1) comes out as the best configuration. Figure 24.B shows the bed level changes over the whole river width, thus including the main and riparian channels. Comparing Figures 24.A and 24.B, it can be concluded that either less erosion or deposition occurs in the riparian channels of the new LTDs since the bed degradation averaged over the river width is lower than the bed degradation averaged over the main channel. In the case without new LTDs (S_{actual}), it can be observed after comparing Figures 24.A and 24.B, which is supported by Figure 59 Appendix F, that less erosion or deposition occurs near the river banks in the Boven-Waal since the bed degradation averaged over the river width is lower than the bed degradation averaged over the main channel. A thing that stands out is that after 10 years of morphological changes, the riparian channel with the lower sill (S_2) erodes, while in all the other cases, the bed of the riparian channel has less erosion or deposition in comparison to the main channel. Since the sill is lowered, larger flow velocities in the riparian channel can be expected since there is less resistance for the water flowing into the riparian channel. The reduced resistance results in overall larger flow velocities and thus larger sediment transport.

The results of the main channel of the Midden-Waal in Figure 24.C show that the new LTDs induce erosion in the main channel of the Midden-Waal, after both 10 and 20 years of morphological changes. Widening the riparian channel of the new LTDs (S_1) results in the largest erosion in the main channel of the Midden-Waal. Comparing Figure 24.D with 24.C, it can be observed that sedimentation takes place in the riparian channels of all configurations of the new LTDs. The largest reduction in erosion takes place in the widened riparian channels (S_1). Figure 24.D shows that the bed degradation is similar for all cases.

Figure 24.E shows that the Beneden-Waal experiences sedimentation in the first 10 years of morphological changes during all simulations. The new LTDs in the Boven-Waal and Midden-Waal reduce the overall sedimentation in the Beneden-Waal in the first 10 years of morphological changes. After 20 years of morphological changes, it becomes apparent that LTDs in the Boven-Waal and Midden-Waal result in erosion of the Beneden-Waal. This observation shows that LTDs capture sediment in the riparian channels and thus that less sediment ends up in the Beneden-Waal increasing erosion in the Beneden-Waal. Widening the riparian channel (S_1) of the new LTDs in the Midden-Waal results in the smallest erosion in comparison to the other new LTD configurations. In the case of no measures (S_{actual}), sedimentation will occur in the Beneden-Waal over 20 years of morphological changes.

Figure 24 shows the average change in bed level per model domain after 20 years of morphological changes and Figure 23 shows the average change over time for the different domains. Figure 25 shows the change over the years in the centre of the main channel of the Waal for the existing situation (S_{actual}). In the Boven-Waal, spikes of erosion that keep increasing over time are observed. While in the Midden-Waal, gradual erosion is observed along the whole domain which decelerates over time. Along the Waal, initial sedimentation turns in most locations into erosion over time. However, in the largest part of the Beneden-Waal, sedimentation will take place during the whole simulation of 20 years.

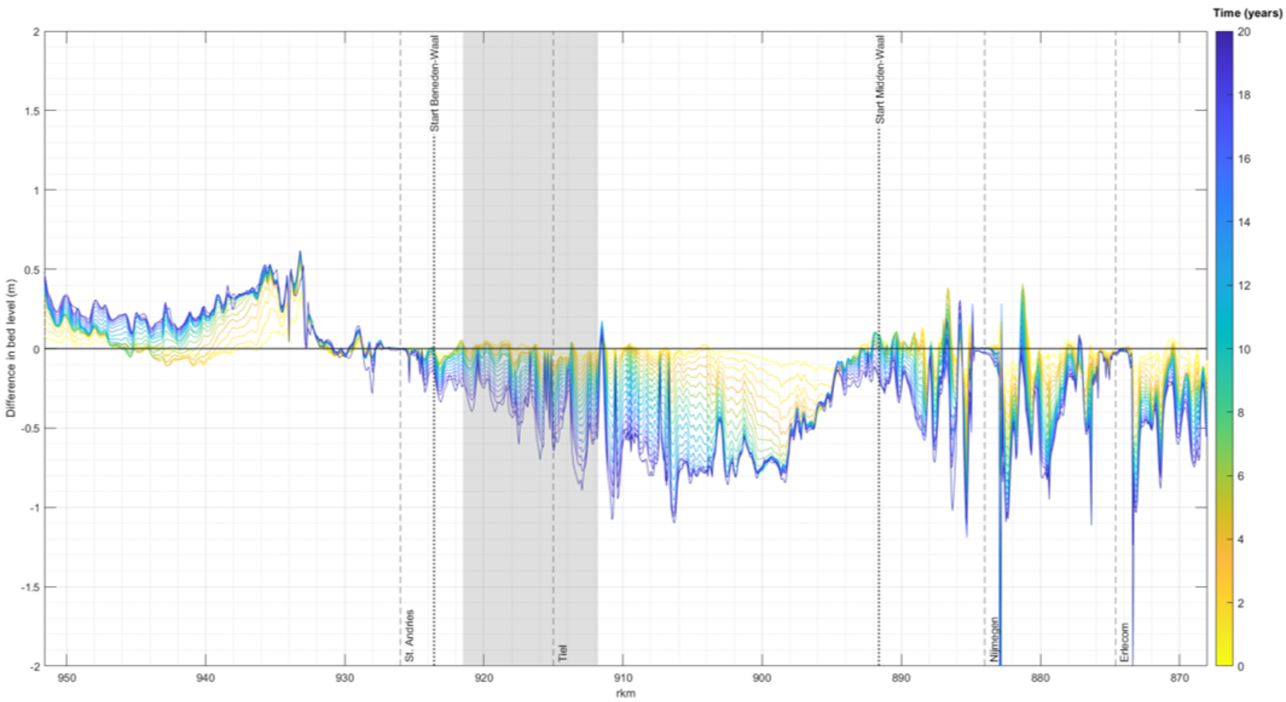

Figure 25: Bed level change in the centre of the main channel of the Waal over the years for 20 years of morphological changes of the existing situation (S_{actual}). Shaded area indicates the existing LTDs near Tiel.

Figure 26, shows less degradation along the Waal in the first years of the simulation with new LTDs in the Boven-Waal and Midden-Waal (S_{LTDs}) in comparison to the existing situation (S_{actual}). In the Boven-Waal sedimentation is observed in comparison to the existing situation. At the locations of the new LTDs in the Midden-Waal (rkm 891.6-911) reduced erosion is seen in the first years of the simulation, however, the erosion seems to decelerate less than in the case of S_{actual}. At the location of the existing LTDs near Tiel (rkm 912-922), increased erosion is seen over all years in the case of the new LTDs (S_{LTDs}) in comparison to the existing situation (S_{actual}). In the Beneden-Waal, both cases show the same sedimentation pattern in the first years, however, over time overall less sedimentation takes place in the case of the new LTDs (S_{LTDs}). Next to this, upstream of the fixed layer at Nijmegen (rkm 883), the scour hole deepens with 14.2 m in 20 years in the existing situation (S_{actual}) and deepens with 4.8 m in 20 years in the situation with the new LTDs in the Boven-Waal and Midden-Waal (S_{LTDs}).

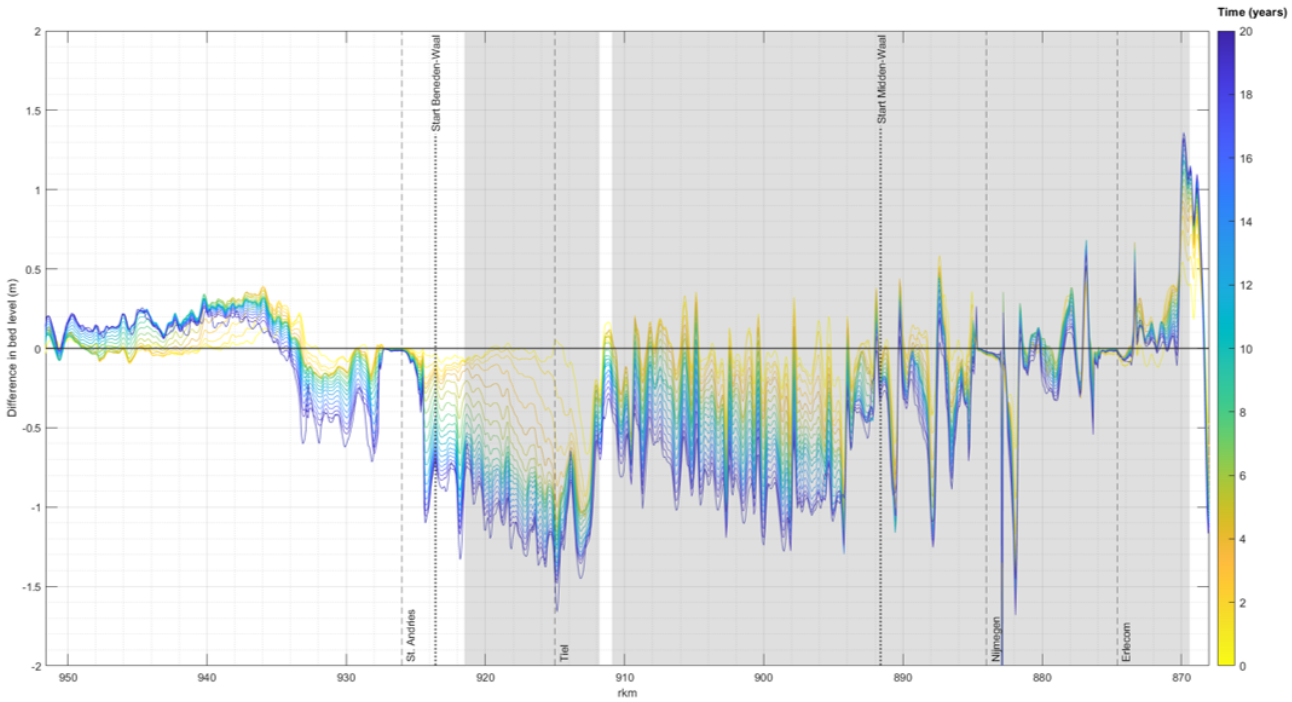

Figure 26: Bed level change in the centre of the main channel of the Waal over the years for 20 years of morphological changes with new LTDs in the Boven-Waal and Midden-Waal (S_{LTDs}). Shaded areas indicate the existing LTDs near Tiel and new LTDs.

Figure 27 shows the changes in the bed level along the centre of the main channel after 20 years of morphological changes.

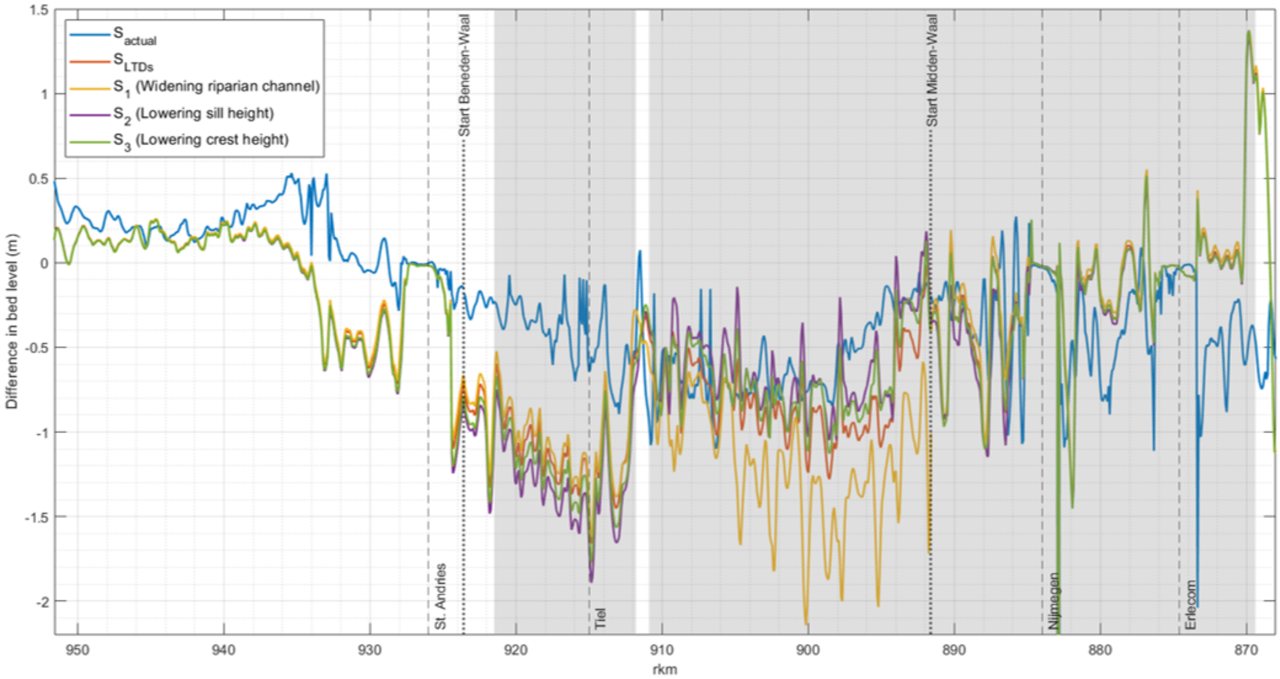

Figure 27: The difference in bed level with respect to the initial situation along the centre of the main channel of the Waal after 20 years of morphological changes. Shaded areas indicate existing LTDs near Tiel and new LTDs.

Figure 27 shows that in the upper part of the Boven-Waal the new LTDs counter bed degradation in comparison to the situation without the new LTDs. Figure 60 Appendix F shows that the bed level rises in the inner bend of the main channel in the first part of the bend and at the second part of the bed level rises in the outer bend of the main channel. The increase in sedimentation in the upper part of the Boven-Waal can be explained by the reduction of depth-averaged flow velocities during discharges above 1635 m^3/s increasing the sedimentation. After 20 years of morphological changes, the new LTDs have a similar effect to the situation without the new LTDs. From the different configurations, it results that widening the riparian channel (S_1) performs the best and lowering the sill (S_2) performs the worst regarding counter bed degradation in the Boven-Waal for both time instances. Lowering the crest height (S_3) performs better than lowering the sill height (S_2), but worse than widening the riparian channel (S_1). Figure 27 shows that the scour hole in front of the bed groynes at Erlecom (rkm 873) during the existing situation changes into a small sediment hump as a result LTDs. The bed groynes at Erlecom (rkm 873-876) and the fixed layer at Nijmegen (rkm 883-885) stand out in Figure 27 since the bed level has little to no changes at these sections.

The results of Figure 27 show that the new LTDs result in an overall lower bed level in the Midden-Waal than the case without the new LTDs after 20 years of morphological changes. In the upper part of the Midden-Waal (rkm 891.6-911), the bed level changes as a result of the new LTDs (S_{LTDs}) result in a similar bed level to the case without the new LTDs (S_{actual}). However, the design with the widened riparian channels (S_1) results in an overall lower bed level in the upper part of the Midden-Waal. In the lower part of the Midden-Waal (rkm 912-923.6), the different designs of new LTDs all perform worse than the case without the new LTDs (S_{actual}). However, in the lower part of the Midden-Waal, where the existing LTDs at Tiel are present, widening the riparian channel (S_1) performs the best out of the LTD designs. In the lower part of the Midden-Waal, the existing LTDs near Tiel (rkm 912-922) are present. The new LTDs thus increase erosion near the existing LTDs, this can be explained by the capturing of sediment in the riparian channels of the new LTDs and leading to less available sediment in the sections downstream of the new LTDs. Lowering the sill height (S_2) and lowering the crest height (S_3) show similar bed degradation patterns as configuration S_{LTDs} in the Midden-Waal after 20 years of morphological changes.

The results of Figure 27 show that the new LTD configurations perform worse than the case without the new LTDs in the Beneden-Waal. At the upstream part of the Beneden-Waal, a large drop in bed level can be observed. The drop at the upstream part of the Beneden-Waal can be explained by the large bed degradation in the Midden-Waal for the different LTD configurations. Figure 27 shows larger bed degradation at the transition from the Midden-Waal to the Beneden-Waal and a larger scour hole in front of the fixed layer at St. Andries (rkm 924) as a result of the new LTDs. Overall, in the lower part of the Beneden-Waal, stabilisation of the bed is observed for all simulations. However, the new LTDs cause the tipping point of erosion to deposition to be further downstream as a result of the propagation of the large erosion of the Midden-Waal. This tipping point of erosion to deposition is in the current situation around rkm 931 and in the configurations with the new LTDs around rkm 935. Out of the different LTD configurations with the new LTDs, widening the riparian channel in the Boven-Waal and Midden-Waal results in the largest sedimentation in the Beneden-Waal.

Figure 28 shows the change in bed level across the cross-sectional width of the river in a single location in the Boven-Waal. It is chosen to see the cross-sectional effects of the widened riparian channels in the Midden-Waal (S_1) since this configuration is the largest cross-sectional adjustment of the river and shows more positive morphological effects in comparison to the lowered sill height and lowered crest height. The results of Figure 28 show that in the case of no new LTDs (S_{actual}), the bed degrades gradually over time and the inner bend of the river erodes faster than the outer bend. With the new LTDs (S_{LTDs}), sedimentation is shown over the main channel of the river after 10 years of morphological changes. After 20 years of morphological changes, the sedimentation in the inner bend of the river continues and erosion occurs in the outer bend. The new LTDs result in sedimentation in the inner bend and reduced erosion in the outer bend. The widened riparian channels in the Midden-Waal (S_1) have little effect on the bed level changes in the Boven-Waal, the sedimentation in the inner bend is slightly increased after 20 years and the erosion is slightly reduced.

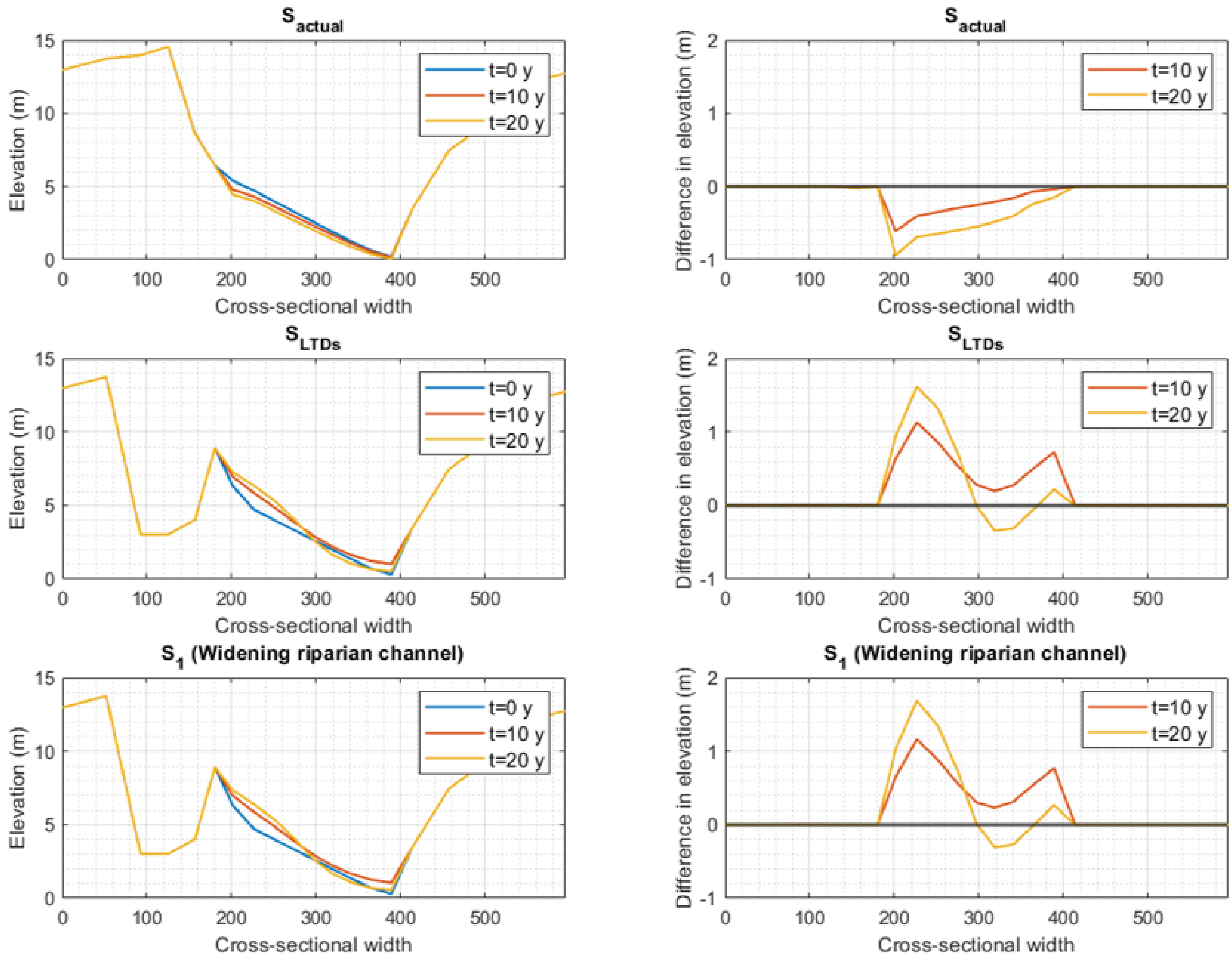

Figure 28: Changes in bed level across the cross-sectional width over time in the Boven-Waal for S_{actual}, S_{LTDs} and S_1 (rkm 869.8).

Figure 29 shows the change in bed level across the cross-sectional width of the river in a single location in the Midden-Waal. The results of Figure 29 show that in the case of no new LTDs (S_{actual}), the bed degrades gradually over time and the outer bend of the river erodes faster than the inner bend. The new LTDs (S_{LTDs}) reduce the cross-sectional width of the main channel that erodes and reduce the deepest point of erosion. The new LTDs result in less degradation in the outer bend of the river and in sedimentation in the riparian channel over time. Widening the riparian channels in the Midden-Waal (S_1) reduces the overall cross-sectional width of the main channel that erodes. After 10 years of morphological changes, the erosion depth of S_1 and S_{LTDs} is similar. However, after 20 years of morphological changes, the widened riparian channels (S_1) result in a larger erosion depth. More sedimentation occurs in the widened riparian channels (S_1) in comparison to the initial LTD configuration (S_{LTDs}).

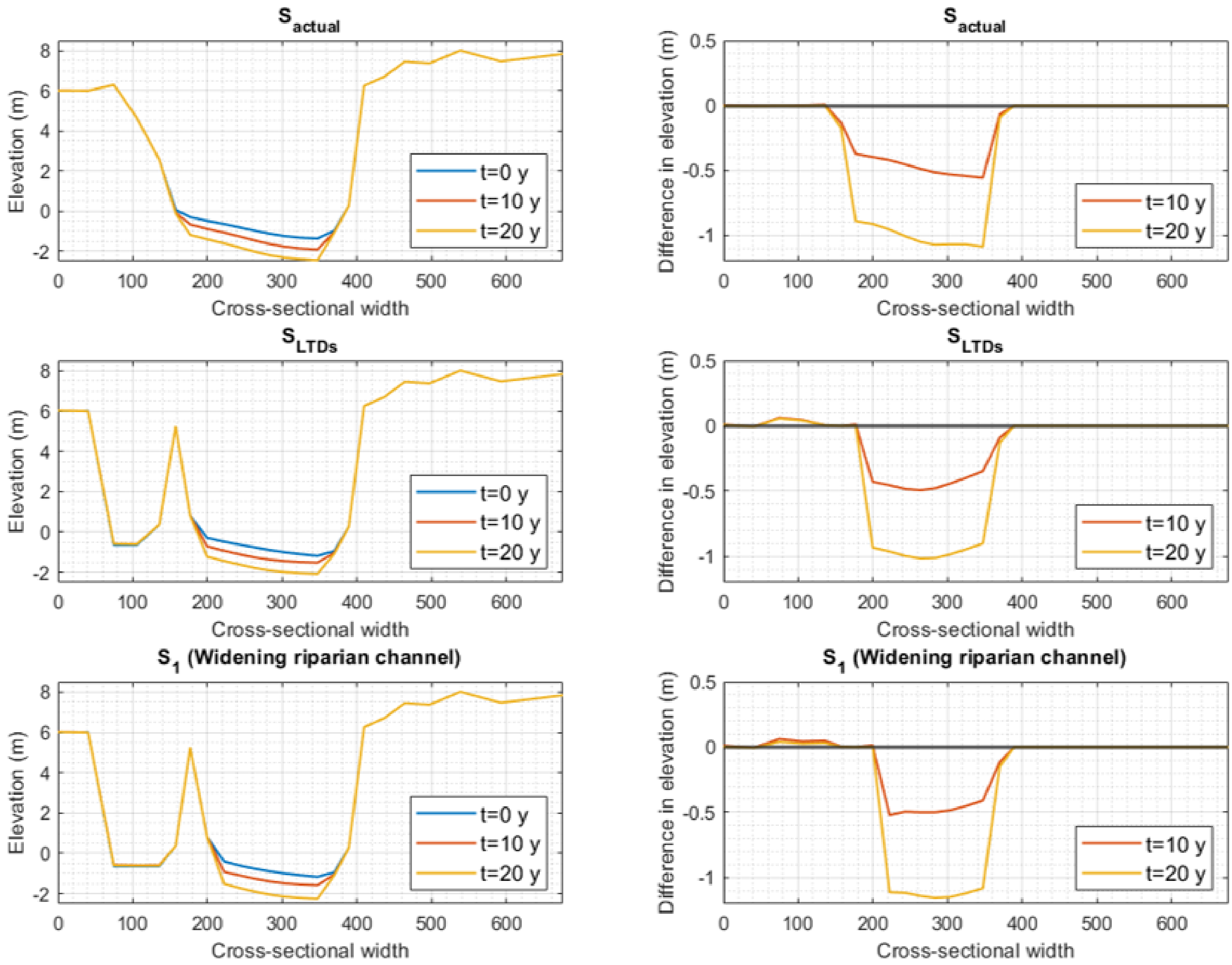

Figure 29: Changes in bed level across the cross-sectional width over time in the Midden-Waal for S_{actual}, S_{LTDs} and S_1 (rkm 906.4).

5.2 Hydraulic effects of different LTD designs on the Waal

Water depth at OLA

The changes in water depth, caused by the implementation of measures, determine whether the new LTDs have a positive effect on the navigability in the main channel. As mentioned in Section 4.5, a navigation depth of 2.8 m in the Waal during OLA needs to be ensured by RWS (Rijkswaterstaat WVL, 2019). Next to this, a width-averaged water depth of 4.0 m also needs to be ensured during OLA in the Waal (Rijkswaterstaat WVL, 2019). During low discharges, LTDs effectively narrow the river and thus increase the water depth in the main channel. In the initial design of LTDs by Zuijderwijk and De Jong (2019), the riparian channel becomes active at a discharge of 400 m^3/s at Lobith. The riparian channels of the modelled LTDs by Sloff et al. (2023) will become active during a discharge of 1635 m^3/s, during which the riparian channel extracts water from the main channel to reduce the water depth in the main channel. Discharges lower than 1635 m^3/s result in a larger water depth in the main channel and discharges of 1635 m^3/s and higher result in a smaller water depth in the main channel in comparison to the situation without LTDs (Sloff et al., 2023). Next to this, the different designs of the new LTDs assessed in this research all have a different effect on the water depth during high discharges. This is because the water flows in the riparian channel during different discharges in different designs and different designs have different backwater effects. In Figure 30, the current situation (S_{actual}) after 20 years of morphological changes is compared to the situation with the new LTDs (S_{LTDs}). The values visualized in the figure are averaged over the width of the main channel of the Waal. As can be seen in Figure 30, there is little difference between S_{actual} and S_{LTDs}. Over the length of the Waal the water depth increases and decreases because of the new LTDs. As can be seen in Figure 30, a width averaged water depth of 4.0 m is not achieved along the Waal. The new LTDs increase shallows in the Boven-Waal (rkm 868-891.6) but reduce shallows in the Midden-Waal (rkm 891.6-923.6). Figure 30 shows that the water depth is affected by morphological changes, over time the scour hole in front of the fixed layer at Nijmegen (rkm 882) deepens and the water depth increases also the amount of this deepening.

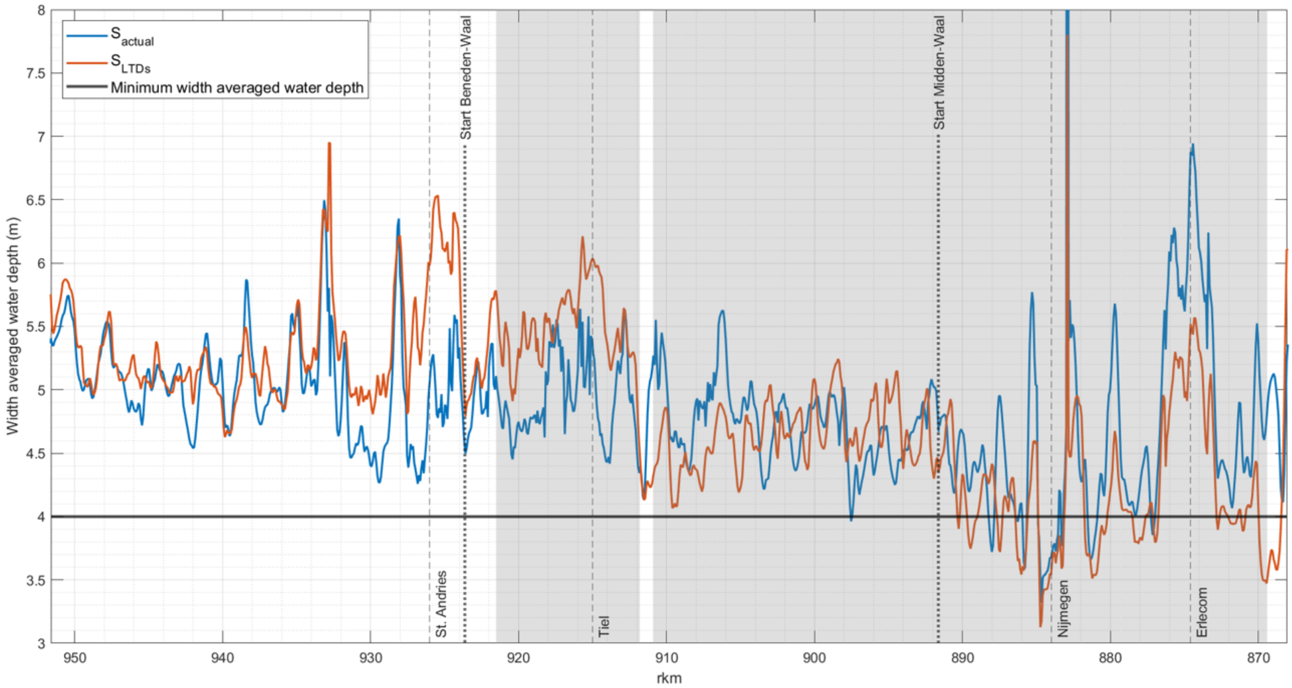

Figure 30: Width averaged water depth during OLA in the main channel along the Waal after 20 years of morphological changes. Shaded areas indicate existing LTDs near Tiel and new LTDs (adapted from Sloff et al., 2023).

In Figure 31, the effect on the water depth caused by the different designs of LTDs is visualized. Similar to the visualization given in Figure 30, the values depicted in Figure 31 are the result of width-averaging in the main channel. As most shallows are located in the Boven-Waal, the results for the different LTD designs are depicted solely in the Boven-Waal. As can be concluded, no LTD design achieves a sufficient width averaged water depth along the Boven-Waal. However, when looking at the results, it can be observed that lowering the sill (S_2) reduces shallows the most as a result of the morphological changes in comparison to the other designs.

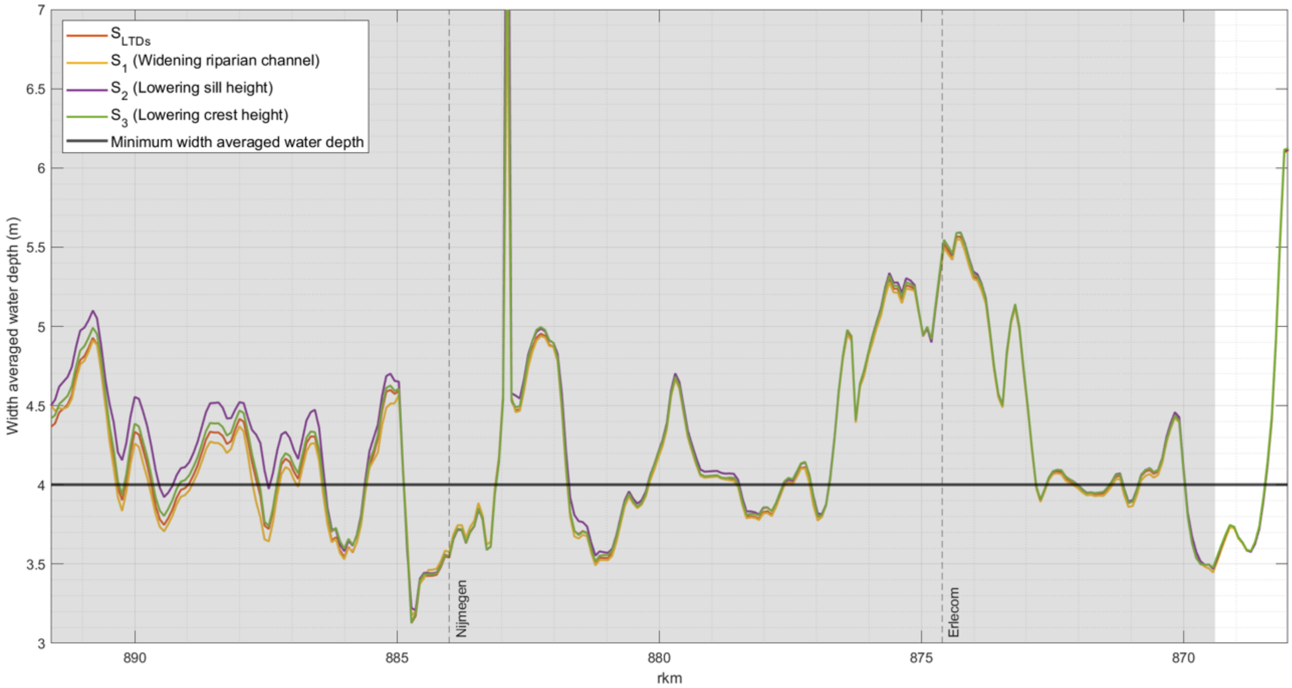

Figure 31: Averaged water depth for the different measures during OLA in the main channel along the Boven-Waal after 20 years of morphological changes. The shaded area indicates the new LTDs.

In Figure 32, the difference in water depth between the different designs and the starting configuration (S_{LTDs}). The Boven-Waal domain contains the smallest water depths and thus only this part is depicted in Figure 32. The fixed layer at Nijmegen (rkm 883-885) with an approximate length of 2 km is seen in Figure 31. As can be seen in Figure 31, there is a large water depth at the upstream part of the fixed layer, suggesting a scour hole. In real life, there is a scour hole present at the upstream and downstream ends of the fixed layer. Figure 32 shows that the different designs result in large differences in the depth of this scour hole. At rkm 885, the downstream end of the fixed layer is shown in Figure 31, and a sharp increase in water depth is observed. Figure 31 shows that the water depth over the whole fixed layer is insufficient. As can be concluded from Figure 32, lowering the sill height increases the water depth the most in the main channel of the Boven-Waal. The conclusions drawn from Figures 31 and 32 are in line and substantiate each other. Widening the riparian channel results in the largest water depth over the fixed layer at Nijmegen.

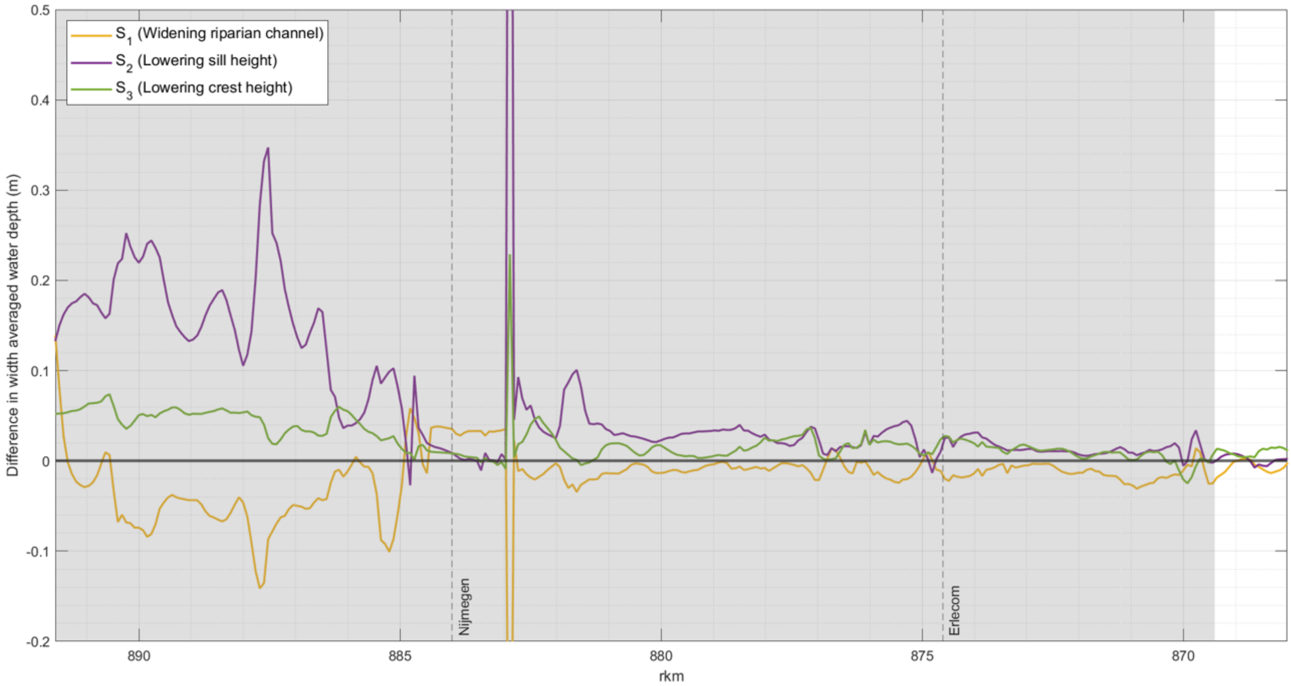

Figure 32: Difference in water depth of different LTD designs in the Boven-Waal compared to S_{LTDs}. The shaded area indicates the new LTDs.

After analysing the width averaged water depth, the local water depth is analysed. After 20 years of morphological development, there are no local shallows (<2.8 m) in the main channel of the Midden-Waal and the Beneden-Waal during OLA for every simulation. However, after 20 years of morphological development local shallows are found in the Boven-Waal for every simulation. Figure 64 Appendix G, shows the adequate local water depth in the Boven-Waal for the different simulations. The simulation without LTDs (S_{actual}) shows the least amount of shallows in the Boven-Waal. For the simulations with the new LTDs, the configuration that lowers the sill of the riparian channel has the least amount of shallows. In the cases with the new LTDs, most shallows appear in the first bend of the Boven-Waal (rkm 870). Sediment builds up against the LTD in the first inner bend of the Boven-Waal. Overall, there is a small increase in insufficiencies in water depth as a result of the new LTDs.

Water level at high discharge

The changes in water level as a result of the new LTDs determine whether the new LTDs have positive effects on flood safety. LTDs are a measure to reduce the water level during high discharges. However, the different designs all have a different effect on the water level during high discharges. In Figure 33, the effect on the water level caused by the different configurations is visualized. The water levels of the different schematisations are compared to the water level of the current situation (S_{actual}) after 20 years of morphological changes during a discharge of 8592 m^3/s at Lobith occurring around once every 8 years (Attema et al., 2014). As can be seen in Figure 33, the water level drops in all cases, even if no measures are taken. The drop in water level of the S_{actual} simulation can be explained by the ongoing bed degradation. If the bed level drops over time and the discharge remains similar over time, the water level also drops over time. Comparing the other simulations to S_{actual} it is observed that the other simulations all reduce the water level during a discharge of 8592 m^3/s at Lobith. In the Midden-Waal, this can be explained by the extra-induced erosion in the main channel because of the new LTDs. However, the same conclusion can not be drawn for the Boven-Waal since the bed degradation is reduced in the Boven-Waal as a result of the new LTDs. The backwater curve effect of the water level drop as a result of large bed degradation in the Midden-Waal explains the lower water levels in the lower part of the Boven-Waal. The fixed layer at Nijmegen (rkm 883-885), can be observed in Figure 33 since the water levels are in all instances around the same elevation. Upstream of the fixed layer of Nijmegen, a drop in water level can also be seen in Figure 33 in comparison to S_{actual}. Since the water level also drops upstream of the fixed layer it can be concluded that the new LTDs have a positive effect on the water level during high discharges.

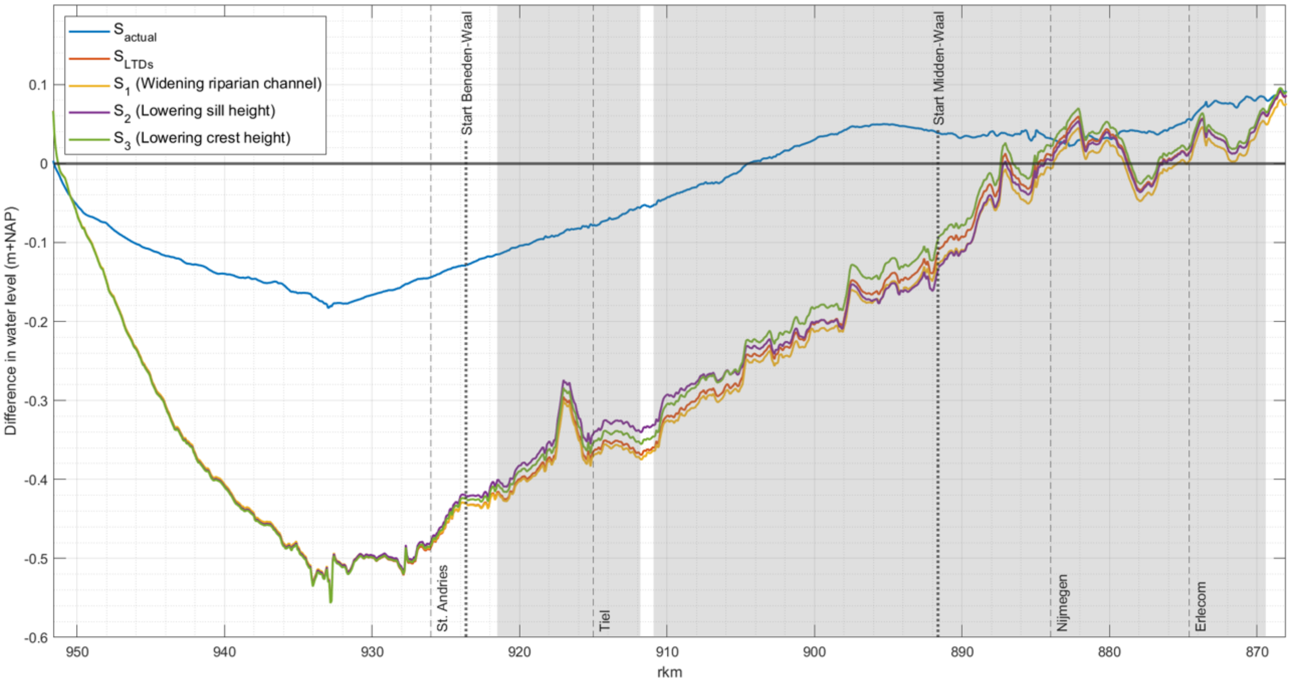

Figure 33: Difference in water level after 20 years of morphological development, comparison to the current water level during a discharge of 8592 m^3/s at Lobith. Shaded areas indicate existing LTDs near Tiel and new LTDs.

Discharge distribution

The discharge in the Waal has increased steadily over the last two decades, at the expense of the Pannerdensch Kanaal, gradually increasing the erosion rate in the Waal (Chowdhury et al., 2023). The quick follow-up of the three peak flows in 1993, 1995, and 1998 initiated the slowly changing discharge distribution. The increased erosion in the Waal resulted in the deposition of sediment in the upper part of the Pannerdensch Kanaal, gradually losing discharge subsequently (Chowdhury et al., 2023).

Different designs of LTDs can have different effects on the discharge partitioning at the Pannerdense Kop. During low discharges (<1635), the Pannerdensch Kanaal requires sufficient discharge to obtain a sufficient supply for the IJsselmeer. The water that is stored in the IJsselmeer is used as a water buffer. Next to this, during high discharges ($\geq$1635 m^3/s), most of the discharge should go to the Waal, since the Waal can cope better with large volumes of water in comparison to the Pannerdensch Kanaal and its tributaries. Thus, to ensure flood safety, it is aimed at not increasing discharge flowing towards the Pannerdensch Kanaal during extreme discharges. In Figure 34, a visualization of the discharge partitioning at the Pannerdense Kop for the different schematisations is given. Next to this, an overview of the results of the discharge partitioning is given in Table 5.

Table 5: Discharge distribution at the Pannerdense Kop during a specified discharge level, with PK denoting the Pannerdensch Kanaal and WL denoting the Waal.

Discharge level (m^3/s)	Branch	S_{actual} (t=0 y)	S_{actual} (t=20 y)	S_{LTDs} (t=20 y)	S_1 (t=20 y)	S_2 (t=20 y)	S_3 (t=20 y)
1020	**PK**	210 (21%)	162 (16%)	231 (23%)	234 (23%)	230 (22%)	230 (22%)
	WL	814 (79%)	863 (84%)	795 (77%)	792 (77%)	797 (78%)	796 (78%)
1203	**PK**	272 (23%)	231 (19%)	291 (24%)	296 (25%)	291 (24%)	291 (24%)
	WL	933 (77%)	975 (81%)	914 (76%)	910 (75%)	915 (76%)	915 (76%)
3053	**PK**	921 (30%)	864 (28%)	780 (25%)	784 (26%)	778 (25%)	776 (25%)
	WL	2131 (70%)	2196 (72%)	2281 (75%)	2276 (74%)	2282 (75%)	2284 (75%)
8592	**PK**	2998 (35%)	2895 (34%)	2481 (29%)	2491 (29%)	2480 (29%)	2476 (29%)
	WL	5594 (65%)	5714 (66%)	6130 (71%)	6121 (71%)	6132 (71%)	6135 (71%)

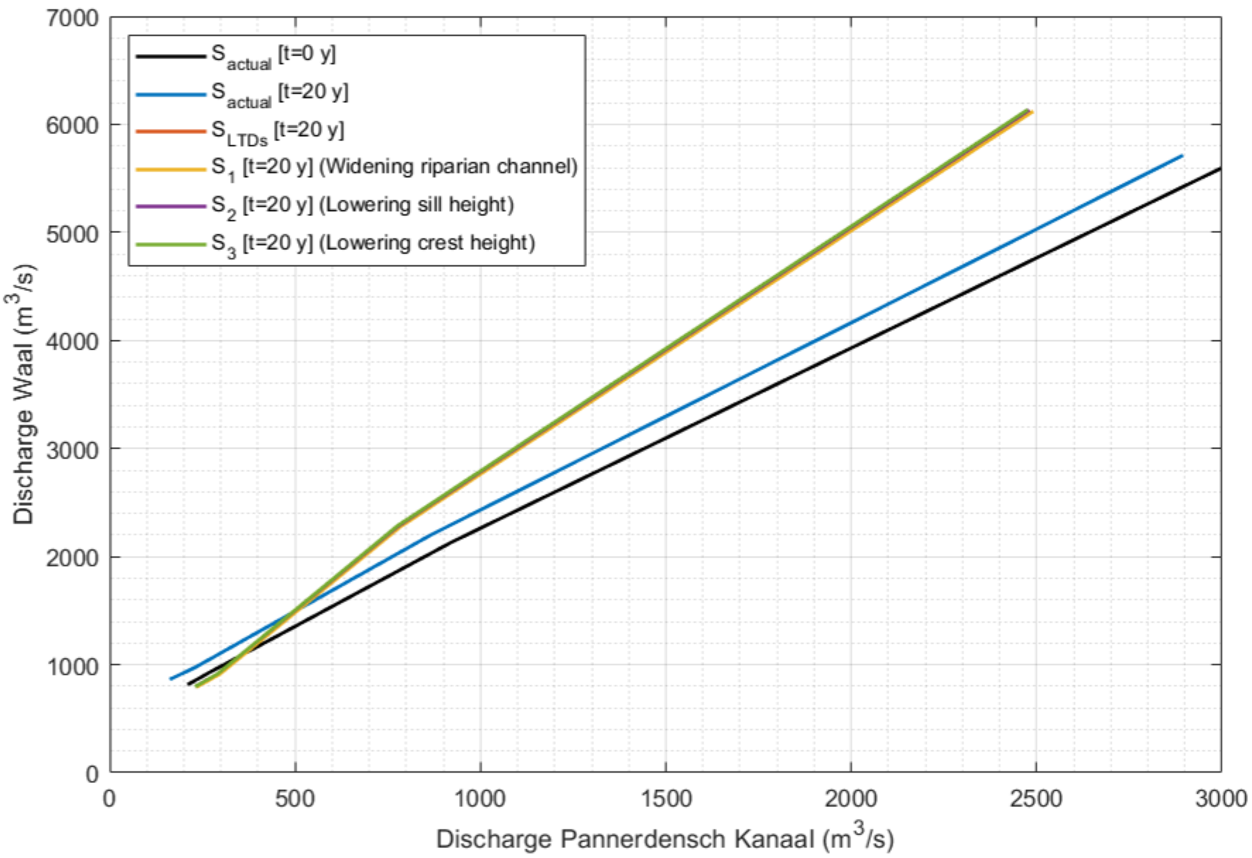

Figure 34: Discharge distribution at the Pannerdense Kop for the different simulations.

From Table 5, it can be concluded that the new LTDs increase the volume of water flowing into the Pannerdensch Kanaal during low discharges. Next to this, it can be concluded that during high discharge a larger volume of water flows towards the Waal. Widening of the riparian channel results in the most water flowing towards the Pannerdensch Kanaal during low discharges. Decreasing the crest height results in the largest volume of water flowing towards the Waal during high discharges.

5.3 Conclusion on the effects of different LTD designs in the Waal

The research question *"How do different designs of longitudinal training dams affect bed degradation in the river Waal using a standard hydrograph?"*, is answered by the analysis of the results of RQ 1.

It is concluded that the different parts of the Rhine branches all affect each other regarding changes in bed level. In the first 10 years of simulation, the clear effects of LTDs and their different designs can be seen per domain. In the simulations that included the new LTDs, it is concluded that the large prediction in bed degradation in the Midden-Waal resulted in the propagation of erosion to the downstream part of the Boven-Waal and the upstream part of the Beneden-Waal. Overall, the new LTDs result in sedimentation in the main channel in the first 10 years of the Boven-Waal and Beneden-Waal. However, in the next 10 years, erosion is seen in the main channel in these domains. After the LTDs are implemented, adaptive sediment management in the form of nourishments can help to negate the initial negative effect of the new LTDs until the LTDs are effective enough to stabilise the bed (Sloff et al., 2023).

Regarding water depths, it is shown that the bottlenecks of insufficient water depths are located in the Boven-Waal. The implementation of the new LTDs worsens the total area of shallows in the Boven-Waal. It was shown that lowering the sill of the new LTDs resulted in the least shallows of all new LTD simulations. Regarding flood safety, it is shown that the implementation of new LTDs increased flood safety along the whole Waal. Widening the riparian channel design resulted in the largest flood safety along the Waal. The discharge distribution at the Pannerdense Kop changes as a result of the implementation of the new LTDs. The implementation of the new LTDs results in a positive effect on the discharge distribution both during low discharges and high discharges. During low discharges, the new LTDs cause more water to flow into the Pannerdensch Kanaal, improving the water supply to the water buffer that is the IJsselmeer. During high discharges, the new LTDs result in less water flowing into the Pannerdensch Kanaal, improving flood safety along the tributaries of the Pannerdensch Kanaal. Of all new LTD simulations, widening of the riparian channel (S_1) results in the most water flowing towards the Pannerdensch Kanaal during low discharges. Decreasing the crest height (S_3) results in the largest volume of water flowing towards the Waal during high discharges.

Overall, widening the riparian channel (S_1) comes out as the most promising design of the new LTD designs for the Boven-Waal and Midden-Waal. Widening the riparian channel counters bed degradation the best in the Boven-Waal in comparison to all other simulations. However, widening the riparian channel results in the largest bed degradation in the Midden-Waal. Widening the riparian channel counters bed degradation the best in the Beneden-Waal in comparison to the simulations that include the new LTDs. Also, widening the riparian channel results in the largest water level decrease along the Waal during high discharges thus increasing the flood safety the most. During low discharges the widening of the riparian channel results in the largest discharge flowing into the Pannerdensch Kanaal. The widening of the riparian channel in the Midden-Waal comes out as the most promising design of the new LTDs and is, therefore, the schematisation that is used in the following research question.

6 The influence of climate change projections on the effect of LTDs in the Waal

In this chapter, the results of RQ 2 are presented. Similar to the structure of RQ 1, first the morphological effects resulting from LTDs during different climate change projections are presented. Next, the hydraulic changes resulting from the LTDs during different climate change projections are presented. The simulation with the new LTDs and the widened riparian channel in the Midden-Waal (S_1) is used as the simulation on which the effects of the new LTDs in combination with climate change projections are shown since this simulation was the best-performing simulation of RQ 1. Next to this, the current situation, thus only with the existing LTDs near Tiel, is also simulated with the different climate projections to show the effects of climate change on the current system.

6.1 Morphological effects of LTDs on the Waal for different climate change projections

The results present the effects of climate change projections G_l and $W_{H,Dry}$ for 10 and 20 years of morphological development. The average change in bed level for solely the main channel is presented and the average change in bed level over the whole river width, which includes the main channel and riparian channel, are presented both for different climate change projections. The results of the Midden-Waal are handled with caution as a result of the large predictions for this river section. Negative values presented in this section denote erosion and positive values denote sedimentation. Figure 35 shows the domain averaged bed level changes for an LTD design under the influence of climate change, the values used for the figure can be found in Appendix E in Tables 18-21. Only one graph is shown for the Beneden-Waal since no new LTDs are implemented in this domain. In simulation S_{actual}, the existing LTDs near Tiel are the only LTDs in the schematisation. In the results of the main channel of the Boven-Waal and Midden-Waal in Figure 35, the values for S_{actual} are averaged over the same width as the main channel of S_{LTDs}, this approach was also used for the whole width of the different domains for all simulations to keep the simulations comparable.

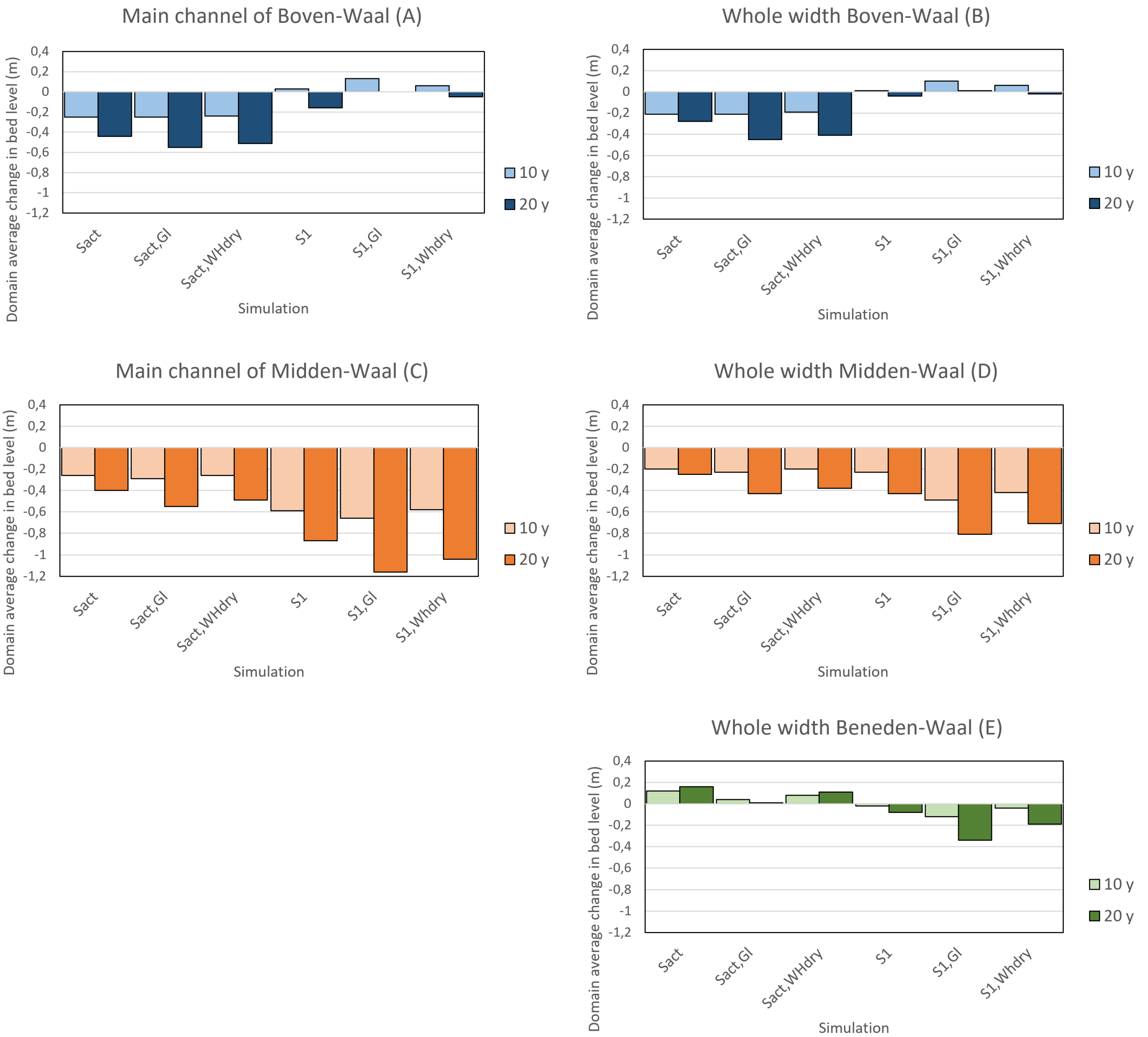

Figure 35: Histograms (A-E) of domain averaged bed level changes for LTDs under the influence of climate change. The graphs on the left denote the domain averaged bed level in the main channel and the graphs on the right denote the domain averaged bed level across the whole river width, thus including the main channel and riparian channel.

Figure 35.A shows the average change in bed level in the main channel of the Boven-Waal after both 10 and 20 years of morphological changes for different climate change projections. In the case of no new LTDs in the Boven-Waal and Midden-Waal (S_{actual}), it becomes apparent that climate change projections G_l and $W_{H,Dry}$ result in an increase in bed degradation in the main channel of the Boven-Waal of which G_l increases bed degradation the most. When new LTDs are implemented in the Boven-Waal, the climate change projections increase sedimentation in the Boven-Waal in the first 10 years of morphological changes. After 20 years of morphological changes, the climate change projections in combination with new LTDs result in less erosion than without new LTDs (S_{actual}), for which climate change projection G_l results in the least erosion in the main channel of the Boven-Waal. After 20 years of morphological changes, with and without climate change the new LTDs will result in less bed degradation.

Figure 35.B shows similar effects as Figure 35.A. In the case without new LTDs (S_{actual}), overall less erosion is seen in Figure 35.B. This shows that either deposition or less erosion occurs at the river banks in comparison to the main channel in the Boven-Waal. In the riparian channels of the new LTDs in the Boven-Waal and Midden-Waal either sedimentation or less erosion occurs during all climate change scenarios. For climate change projections G_l and $W_{H,Dry}$ in combination with the new LTDs reduced erosion is observed in Figure 35.B in comparison to no climate change with new LTDs.

Looking at the results of the main channel of the Midden-Waal in Figure 35.C, it is observed that climate change projections G_l and $W_{H,Dry}$ increase erosion in the case with and without the new LTDs. Climate change projection G_l results in the largest erosion in the main channel of the Midden-Waal for situations with and without the new LTDs. Climate change projection G_l in combination with the new LTDs results in the overall largest erosion in the main channel of the Midden-Waal. Comparing the results of 10 and 20 years of morphological changes it becomes apparent that the erosion decelerates in the last 10 years of morphological changes. Comparing Figure 35.D with 35.C, it is observed that either less erosion or sedimentation takes place in the riparian channels of the new LTDs in comparison to the main channel and that either less erosion or sedimentation takes place on the river banks of the cases without the new LTDs in all climate change projections.

Figure 35.E shows that the implementation of the new LTDs in the Boven-Waal and Midden-Waal results in erosion in the Beneden-Waal instead of sedimentation that occurs in the cases without the new LTDs for all climate change projections. In the case of the new LTDs with the widened riparian channel (S_1), it is seen that erosion accelerates in the last 10 years of morphological changes for all climate change projections. Climate change projection G_l results in the largest erosion in the case of the new LTDs. In the case without LTDs, climate change projections G_l and $W_{H,Dry}$ reduce the sedimentation in the Beneden-Waal, of which climate change projection G_l reduces the sedimentation the most.

Figure 36 shows the change in bed level along the centre of the main channel of the Waal for different climate change projections after 20 years of morphological development. The new LTDs (S_1) result in sedimentation in the Boven-Waal and increase erosion in the Midden-Waal. Figure 36 shows that new LTDs in the Boven-Waal and Midden-Waal counter bed degradation in comparison to the simulations without new LTDs for the different climate change scenarios in the Boven-Waal. Climate change projection G_l results in the largest bed degradation in the cases of both S_{actual} and S_1 in the Midden-Waal. Both climate change scenarios result in increased bed degradation in the Beneden-Waal. At the upstream part of the Beneden-Waal, an erosion pit is observed, which is caused by the large bed degradation in the Midden-Waal and the fixed layer located at Sint Andries (rkm 925-928). Along the lower part of the Beneden-Waal, erosion alternates with sedimentation for both S_1 and S_{actual}. However, climate change scenario G_l combined with new LTDs result in overall erosion in the lower part of the Beneden-Waal.

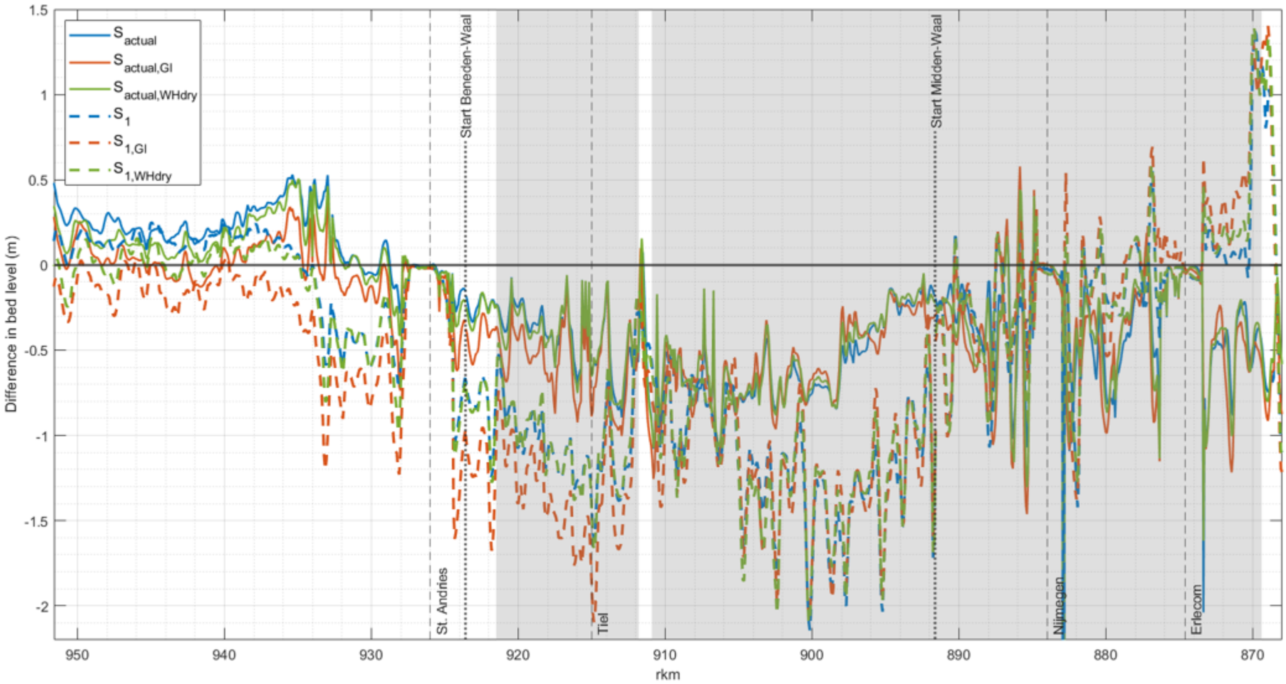

Figure 36: The difference in bed level with respect to the initial situation along the centre of the main channel of the Waal for different climate change projections after 20 years of morphological changes. Shaded areas indicate existing LTDs near Tiel and new LTDs.

6.2 Hydraulic effects of LTDs on the Waal for different climate change projections

Water depth at OLA

After analysing the results of RQ 1 it becomes apparent that LTDs aggravate shallows in the Boven-Waal (rkm 868-891.6). Figure 37, shows the width-averaged water depth along the Waal for climate change projections. The difference between climate change scenario G_l and $W_{H,Dry}$ is small, in the order of centimeters. In the Boven-Waal, the new LTDs result in more shallows and climate change scenario G_l results in the shallowest shallows in the Boven-Waal. During low discharges, the present shallows can result in parts of the navigation channel being unnavigable and in ships navigating with reduced loads to reduce the draft of the ship. In the Midden-Waal and Beneden-Waal (rkm 891.6-951.7), the new LTDs in combination with climate change result in an overall larger water depth. In the upper part of the Midden-Waal (rkm 891.6-911), climate change scenario G_l results, similar to the Boven-Waal, in the lowest overall water depth in the case with and without the new LTDs. In the lower part of the Midden-Waal (rkm 911-923.6) and the Beneden-Waal (rkm 923.6-951.7), climate change scenario G_l results in an overall larger water depth in comparison to climate change scenario $W_{H,Dry}$. As shown in Figure 51 Appendix C, this is the result of the increased flow velocities in the Midden-Waal during low discharges leading to more sediment supply towards the lower part of the Midden-Waal and the Beneden-Waal (rkm 911-951.7), where the flow velocities are lower during low discharges.

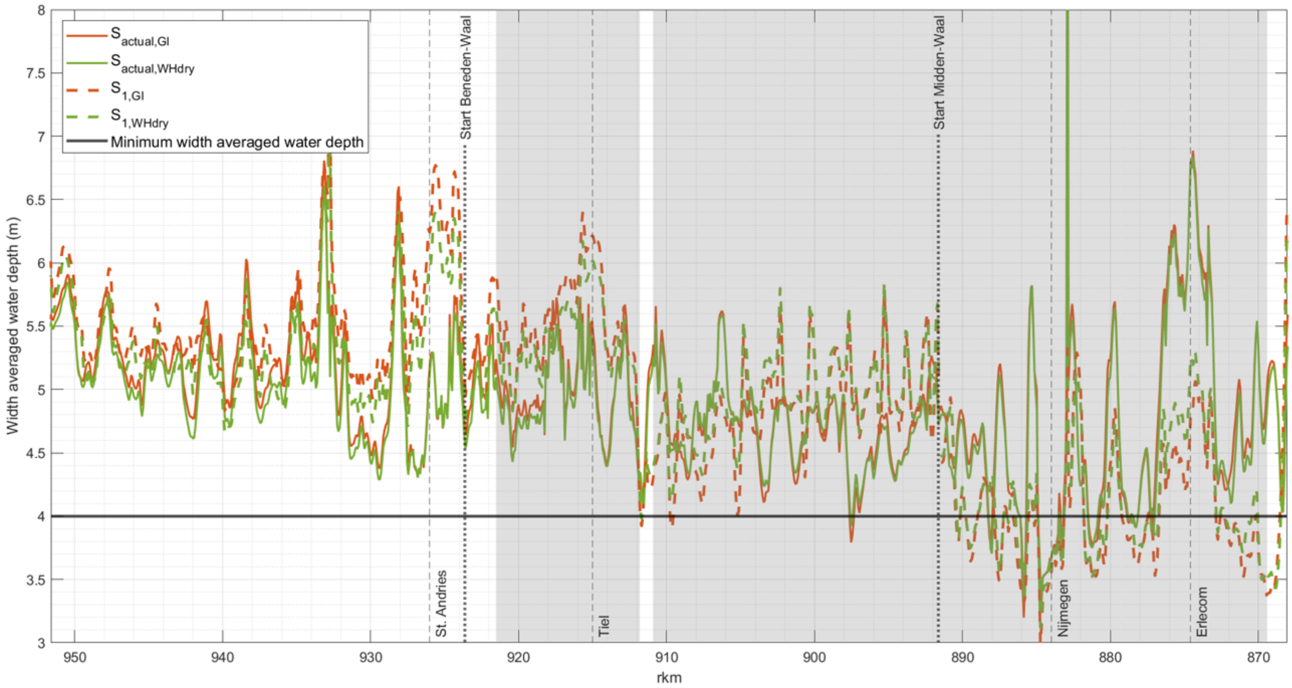

Figure 37: Width averaged water depth during OLA in the main channel along the Waal after 20 years of morphological changes. Shaded areas indicate existing LTDs near Tiel and new LTDs.

Appendix G Figure 65, shows a visualization of adequate local water depths in the Boven-Waal. Since Figure 37 shows that the most width-averaged shallows occur in the Boven-Waal (rkm 868-891.6), the local water depth is solely analysed for the Boven-Waal. Climate change scenario G_l results in more local shallows (<2.8 m) in the Boven-Waal than climate change scenario $W_{H,Dry}$ in the cases with and without the new LTDs. The largest area of local shallows is seen in the first inner bend of the Boven-Waal (rkm 870). The observed local shallows are all located in the inner bend of the Boven-Waal. In the cases with the new LTDs, larger shallows in the inner bend are seen at different locations in comparison to the cases without the new LTDs. Sediment builds up against the LTDs in the inner bend and in combination with the narrowing of the main channel this results in more shallows in the inner bend of the Boven-Waal.

Water level at high discharge

Figure 38 shows the effect of the new LTDs in combination with climate change projections on flood safety along the Waal. In the case without the new LTDs (S_{actual}), the water levels for all climate change scenarios are similar. However, climate change scenario G_l deviates from rkm 900-945 and results in the highest water levels, while the reference climate change scenario results in the lowest water levels of schematisation S_{actual}. In the case of the new LTDs and the widened riparian channel (S_1), the same pattern is observed where G_l results in the lowest flood safety and the reference scenario in the highest flood safety as a result of the highest and lowest water levels consecutively. The new LTDs result in overall lower water levels along the Waal, which is similar to the conclusion of RQ 1. With climate change, the water levels along the Waal will decrease as a result of the new LTDs due to the degraded main channel and effective river widening, thus improving flood safety. In the case of no climate change and the new LTDs (S_1) the water levels will be the lowest of all the assessed water levels.

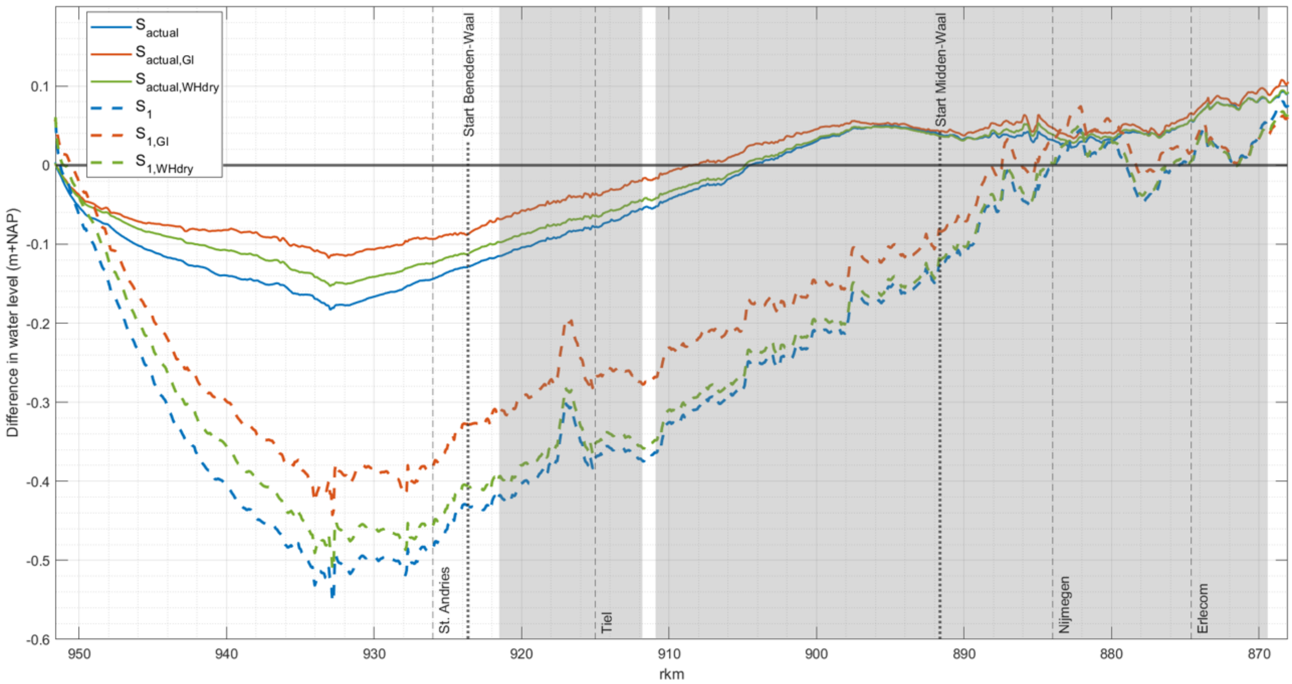

Figure 38: Difference in water level after 20 years of morphological changes, comparison to the initial water level of S_{actual} during a discharge of 8592 m^3/s at Lobith. Shaded areas indicate existing LTDs near Tiel and new LTDs.

Discharge distribution

The increasing discharge towards the Waal is countered by introducing the new LTDs in the Boven-Waal and Midden-Waal, this is concluded in RQ 1. However, climate change will also affect the discharge distribution at the Pannerdense Kop as a result of changing discharge regimes. Without taking any measures in the existing river system, the portion of the water flowing towards the Pannerdensch Kanaal during all discharges will reduce over the years. Concluding from Table 6, an even smaller portion of water will flow towards the Pannerdensch Kanaal during low discharges (<1635) when climate change scenario G_l takes place. When no measures are taken in the Dutch Rhine system and climate change scenario $W_{H,Dry}$ takes place, a slight increase in discharge towards the Pannerdensch Kanaal is shown during low discharges. Climate change scenario G_l in combination with LTDs results in more discharge flowing towards the Pannerdensch Kanaal during low discharges in comparison to the case without climate change. Climate change scenarios G_l and $W_{H,Dry}$ increase the discharge towards the Pannerdensch Kanaal in combination with the new LTDs (S_1), however, the discharge towards the Pannerdensch Kanaal remains lower than without the new LTDs (S_{actual}). Climate change scenario $W_{H,Dry}$ in combination with the new LTDs shows a similar but attenuated effect as climate change scenario G_l.

Table 6: Discharge distribution at the Pannerdense Kop during a specified discharge level, with PK denoting the Pannerdensch Kanaal and WL denoting the Waal.

Discharge level (m^3/s)	Branch	S_{actual} (t=0 y)	S_{actual} (t=20 y)	$S_{actual,Gl}$ (t=20 y)	$S_{actual,WHdry}$ (t=20 y)	S_1 (t=20 y)	$S_{1,Gl}$ (t=20 y)	$S_{1,WHdry}$ (t=20 y)
1020	**PK**	210 (21%)	162 (16%)	156 (15%)	164 (16%)	234 (23%)	252 (25%)	243 (24%)
	WL	814 (79%)	863 (84%)	871 (85%)	861 (84%)	792 (77%)	775 (75%)	782 (76%)
1203	**PK**	272 (23%)	231 (19%)	228 (19%)	233 (19%)	296 (25%)	316 (26%)	307 (25%)
	WL	933 (77%)	975 (81%)	981 (81%)	974 (81%)	910 (75%)	892 (74%)	898 (75%)
3053	**PK**	921 (30%)	864 (28%)	856 (28%)	865 (28%)	784 (26%)	798 (26%)	792 (26%)
	WL	2131 (70%)	2196 (72%)	2204 (72%)	2195 (72%)	2276 (74%)	2264 (74%)	2269 (74%)
8592	**PK**	2998 (35%)	2895 (34%)	2889 (34%)	2900 (34%)	2491 (29%)	2515 (29%)	2504 (29%)
	WL	5594 (65%)	5714 (66%)	5726 (66%)	5711 (66%)	6121 (71%)	6101 (71%)	6109 (71%)

Figure 39 shows a visualization of the discharge distribution at the Pannerdense Kop for different climate change scenarios. In Figure 39 a clear distinction between the simulations with and without the new LTDs is seen, mainly an increase in discharge portion towards the Pannerdensch Kanaal during low discharges is observed. Figure 39 is in line with the aforementioned results.

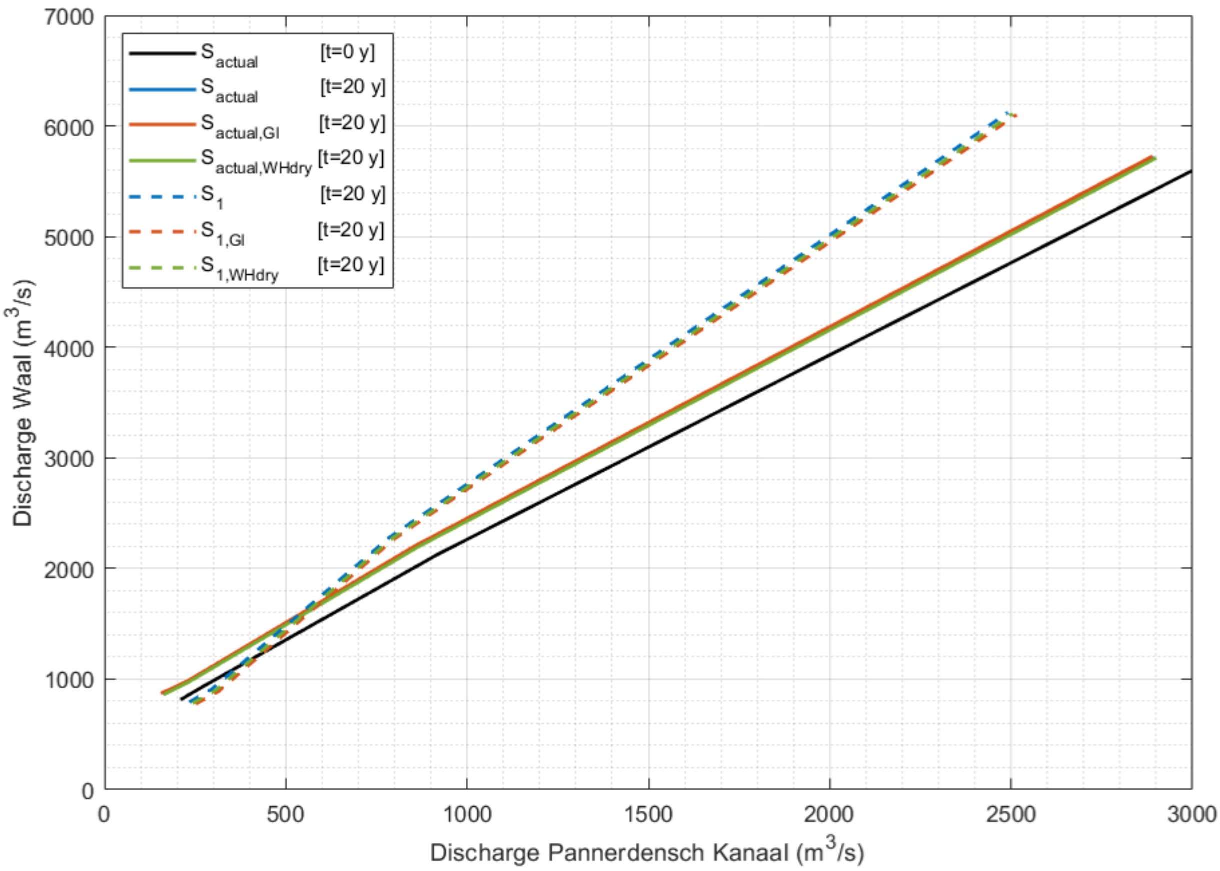

Figure 39: Discharge distribution at the Pannerdense Kop for different climate change projections.

6.3 Conclusion on the influence of climate change projections on the effect of LTDs in the Waal

The research question *"What is the effect of the best performing longitudinal training dam design in the river Waal on the morphodynamic evolution for different discharge scenarios based on climate projections?"*, is answered by the analysis of the results of RQ 2.

Concluding from the results, climate change affects the morphodynamic evolution in the Waal. Without the new LTDs, both climate change projections result in increased erosion in the Boven-Waal and Midden-Waal and result in a reduction in sedimentation in the Beneden-Waal. In the first 10 years, the erosion in the Boven-Waal and Midden-Waal resulting from climate change is similar to the results of no climate change, however, after 20 years the erosion has accelerated as a result of climate change. In addition, the degrading bed of the main channel results in lower flow velocities in the riparian channel over the years since riparian channels do not degrade accordingly and thus increase the discharge threshold for which the riparian channels are effective, resulting in increased flow velocities in the main channel. In both climate change projections in combination with the new LTDs, sedimentation is increased in the Boven-Waal after 10 years of morphological changes in comparison to no climate change. After 20 years, the sedimentation turns into erosion, but in the case of climate change scenario G_l, the bed of the main channel in the Boven-Waal is overall at the same elevation after 20 years of morphological changes. Climate change scenario $W_{H,Dry}$ in combination with the new LTDs results in erosion in the Boven-Waal after 20 years of morphological changes, however, this erosion is lower than without climate change. In the Midden-Waal, erosion is induced as a result of climate change, both in cases with and without the new LTDs. In the Beneden-Waal, the new LTDs result in erosion instead of sedimentation, presumably as a result of the large bed degradation in the Midden-Waal. Climate change in combination with the new LTDs will aggravate the erosion in the Beneden-Waal.

Regarding water depths, it is shown that the bottlenecks of insufficient water depths are in the Boven-Waal, which is also concluded in RQ 1. The implementation of the new LTDs worsens both the width-averaged water depth and local water depth. Climate change scenario G_l results in the most shallows in the Boven-Waal and the upper part of the Midden-Waal in comparison to climate change scenario $W_{H,Dry}$, both in the cases with and without the new LTDs. Regarding flood safety, the new LTDs result in a larger flood safety as a result of lower water levels. Climate change scenario G_l in combination without new LTDs improves the flood safety along the Boven-Waal and the upper part of the Midden-Waal but worsens the flood safety along the Beneden-Waal and the lower part of the Midden-Waal. In all cases of the new LTDs in combination with climate change projections, flood safety is increased in comparison to all cases without the new LTDs. The new LTDs without climate change result in the largest overall flood safety of the assessed simulations. Climate change scenario G_l in combination with the new LTDs ($S_{1,Gl}$), flood safety is reduced the most in comparison to all the new LTD simulations of RQ 2.

The discharge distribution at the Pannerdense Kop is improved during low discharges as a result of climate change in combination with the new LTDs. In the case without the new LTDs, climate change results in a worse discharge distribution during low discharges at the Pannerdense Kop. Climate change scenario G_l in combination with the new LTDs results in the best low discharge distribution, instead of the worst discharge distribution in the case without new LTDs. During high discharges, the climate change scenarios in combination with the new LTDs decrease the discharge towards the Waal, reducing the flood safety along the Pannerdensch Kanaal and its tributaries.

7 Discussion

This chapter gives a discussion on the results of this study. The results of this study are compared to the findings of other studies and the differences are discussed. The given remarks in this section help to interpret the results and also the reliability of the results. Section 7.1 discusses the reliability of the results that are obtained via the used method in this study. The potential of the new LTDs to counter bed degradation in the Waal and the influence of climate change on the effect of LTDs is discussed in Section 7.2 to provide information for the IRM programme.

7.1 Reliability of the results and used method

This section elaborates on the used methodology and the reliability of the obtained results following this approach. This is substantiated by discussing the modelling approach of this study in Sections 7.1.1 and 7.1.2. Next, the results of this modelling approach are discussed in Section 7.1.3. This comparison is made to reflect on the obtained results in this study and whether these results are plausible.

7.1.1 Modelling of LTDs in the Delft3D DVR model

The large grid cells of the DVR model, which vary in the summer bed between 20-25 m, limit the design options for LTDs in this study. Flow velocities that occur in a grid cell are an average at the grid location and thus if the grid is more refined, higher peaks and lower lows in flow velocity can be represented in the model. Thus, a coarser grid translates into more averaged results. Next to this, the coarse grid limits the design of LTDs. For example, increasing the riparian channel width is done by 25 m since this is the grid cell width. Only adjustments of 25 m in width can be implemented in the model as a result of the coarse grid.

The coarse grid cells lead to difficulties in schematising the LTDs in the model. The new LTDs in the Boven-Waal and Midden-Waal do not contain openings along the dam itself, while the existing dams near Tiel do contain these openings. The openings in the existing dams near Tiel are schematised by lowering the height of the three grid cells in the cross-sectional direction for the length of the opening. The openings of the new LTDs are difficult to schematise since at the location of the openings, the LTD itself is lower in height and follows the shape of the LTD until the opening height. The difficulty is mainly in the schematisation following the shape of the LTD since the shape between elevation points in the model is linearly interpolated. Currently, the openings are not schematised at all in the model, increasing the overall roughness of an LTD since the height of the LTD is overrated at the location of the opening and reducing the amount of water flowing towards the riparian channel. Next to this, at the location of the openings water is diverted towards the riparian channel only over a small range of discharges, this diversion of flow results in lower flow velocities in the main channel since the flow direction is diverted from the longitudinal direction of the river (De Ruijsscher et al., 2020b). During discharges for which openings would be present, the increased roughness of the LTDs results in lower flow velocities in the main channel, while the excluded openings result in higher flow velocities. It is unknown what the total difference in flow velocities in the main channel of the Waal is as a result of this schematisation choice. Limited by the coarse grid cells, this study only includes a few LTD designs. However, more parameters of the LTD can be subject to adjustments to optimise LTDs. For example, De Ruijsscher et al. (2020b) states that changing the angle of the LTD with respect to the main channel changes the flow field around the bifurcation between the main channel and riparian channel which can optimise the functioning of the LTD.

LTDs result in 20 m of effective narrowing of the main channel in comparison to the initial situation with groynes on both sides of the river (Sloff et al., 2023). The widening of the riparian channel simulation resulted in a reduction of the main channel by another 25 m. Widening the riparian channel partially in the direction of the main channel and partly in the direction of the floodplains would be more realistic to ensure sufficient navigation width. However, the coarse grid of the DVR model leads to the choice of either sacrificing the width of the main channel or the floodplain. In this case, a grid cell of the main channel is sacrificed. This choice leads to underestimation of erosion during high discharges since the river has a smaller flow area resulting in larger flow velocities and erosion is overestimated during low discharges resulting from the narrowed main channel which increases flow velocities. Since the low discharges take up a large part of the yearly repeating hydrograph, an overall overestimation in erosion is the expected result from the choice to reduce the width of the main channel. Reducing the crest height would result in thinner LTDs due to the triangular shape of LTDs, however, the coarse grid cells of the LTDs are not able to capture this reduction in width. Since the LTDs are not narrowed, the LTDs narrow the main channel more than they should and thus increase flow velocities during low discharges, overestimating erosion during low discharges.

In this research, the model is spun-up for 5 years without morphological changes for the grain size distribution, afterwards the model is spun up for an additional 5 years for the morphological response. This is done to prevent strong initial reactions of the model. The DVR model used in this study is based on the model from Becker (2021), which used the same spin-up routine. This is also in line with the study of Flierman (2017) in which it is stated that the model shows unstable behaviour regarding bed level changes since there are many variations over small areas during the spin-up time. The resulting bed level after the spin-up time in this study differs at some locations from the initial bed level that results from measurements.

The formulas used in the DVR model were calibrated by Yossef et al. (2008b), however, the deviations between the model results and the prognosis given by Sloff (2019) show that the model can use improvements regarding calibration. The calibration can be done by revising the calibration factor in the alluvial roughness equation. The results of the different new LTD designs in this study can be compared with S_{LTDs}, which is the final configuration of the study by Sloff et al. (2023). From these comparisons, judgement on the different designs of the new LTDs can be given to conclude whether the design reduces bed degradation more than another design. By improving the calibration of the model, quantitative results result in more reliable absolute values. Since the model can use improvements regarding calibration in some domains, the absolute values obtained in this study need to be handled with care. Overall, the DVR model is currently the best model out there for large-scale morphological studies and functions properly but improvements can be made via further calibration. Currently, the morphological module of D-Flow Flexible Mesh, which seems a promising model for large-scale morphological studies, is still in development and it is expected that this development still takes several years.

7.1.2 Boundary conditions

The model used in this study is trimmed to a specific study area. Since the model is trimmed, it requires upstream and downstream boundary conditions. In this case, the upstream and downstream boundary conditions are placed at a significant distance from the area of interest to avoid boundary effects. For the upstream boundary condition, a quasi-stationary discharge approach is used. The quasi-stationary discharge approach is a simplification to reduce computational time by the discretization of the discharge. The discharge is discretized in discharge levels that occur for a certain duration. The discharge levels do not go below 1020 m^3/s and not above 8592 m^3/s, while in real life this occurs. The higher the discharge, the higher the flow velocity and thus the higher the sediment transport at that point. Next to this, the hydrographs used for the reference case and the different discharge scenarios remain equal during the simulation period. However, as can be observed in the climate change projections by Attema et al. (2014), the climate changes over time and thus the discharge regime of the Rhine and its tributaries changes. An underestimation of discharge level durations as a result of climate change at the upstream boundary condition might lead to an underestimation in erosion. At the downstream boundary condition, a $Q - h$ relation is used, and the bed level and water depth remain fixed over time. Changes in the river, such as the implementation of new LTDs, can affect the bed level, water depth and thus water level at the downstream boundary condition which is not represented in the model. Also, sea level rise can affect the water levels at the downstream boundary conditions for all discharges, it is expected that the water levels in the river will increase due to climate change. The underestimation in water levels downstream leads to an overestimation in flow velocity and thus erosion. Next to this, the downstream boundary conditions fix the water level at the downstream boundary to a set level per discharge level at Lobith. However, results show that the new LTDs result in lower water levels in comparison to the current situation during high discharges along the Waal. The new LTDs result in up to 55 cm reduction in water level during a discharge of 8592 m^3/s at Lobith at the beginning of the Beneden-Waal. The water depth and bed level at the downstream boundary are fixed for the set discharge levels. The fixed bed level and water depth result in large water depths just upstream of the downstream boundary condition, which is not realistic.

The sediment supply in the model imposed on the upstream boundary of the Boven-Rijn is based on a bed degradation of 1.5 cm/year, which is based on the erosion in the Boven-Waal (Sloff et al., 2023). However, current trends of the Boven-Rijn show little to no erosion (Sloff, 2019). Sloff et al. (2023) implemented a morphological upstream boundary condition of 1.5 cm/yr, which resembles the large-scale trend. However, Sloff (2019) expects an erosion of 0 cm/yr in the Boven-Rijn. The imposed morphological upstream boundary condition results in an overestimation of erosion.

7.1.3 Model output

A problem regarding the output of the model is the ongoing bed degradation in the river. The bed level drops while the LTDs remain at the same elevation, this causes water to flow in the LTDs only at higher discharges compared to the initial situation. This leads to the LTDs losing their function and becoming less effective and induces erosion since the flow velocities during low discharges increase due to a larger water depth. Figures 52 and 53 in Appendix C show the change in depth average flow velocities and water depth over time in a riparian channel in the Boven-Waal. During a discharge of 1635 m^3/s, the riparian channels becomes active and for this discharge a reduction in the riparian channel of the Boven-Waal in discharge per unit width of 11% after 10 years of morphological changes and 21% after 20 years of morphological changes is observed, which shows that the riparian channel becomes less active and effective over time. Figures 54 and 55 in Appendix C show the change in depth average flow velocities and water depth over time in a riparian channel in the Midden-Waal. During a discharge of 1635 m^3/s the riparian channels become active and for this discharge, a reduction in the riparian channel of the Midden-Waal in discharge per unit width of 30% after 10 years of morphological changes and 80% after 20 years of morphological changes is observed, which shows that the riparian channel becomes less active and effective over time. The amount of discharge that is reduced in the riparian channel will now flow through the main channel, increasing flow velocities and increasing erosion in the main channel. The effectiveness of a riparian channel in the Midden-Waal reduces faster than the Boven-Waal due to the fast eroding bed. The effectiveness of a riparian channel in the Boven-Waal declines gradually over time, while the decrease in the effectiveness of a riparian channel in the Midden-Waal accelerates over time. The DVR model shows a large gradient in sediment transport which can explain the fast eroding bed in the Midden-Waal. The output of the model of the existing situation (S_{actual}) shows a larger gradient in sediment transport compared to measurements. Measurements of 2011 in the Waal show a gradient in sediment transport of around 140.000 m^3/year while the model predicts a gradient sediment transport of around 350.000 m^3/year with the new LTDs (Sloff et al., 2023). In the model, the yearly sediment transport increases along the Boven-Waal and Midden-Waal with peaks up to 550.000 m^3/year in the Midden-Waal. The difference between the measured gradient in yearly sediment transport and the modelled yearly sediment transport can suggest an over-prediction in erosion in the model.

In Table 7, a comparison between the results of the model schematisation from Becker (2021) (S_{actual}) and the prognosis of bed degradation based on measurements by Sloff (2019) is given. Next to this, the results of the model schematisation S_{LTDs} are also given. The prognosis by Sloff (2019) is the expected change in bed level per year until 2050 based on historical trends in bed level changes via the multibeam-echosounder measurements dataset of RWS. Model schematisations S_{actual} and S_{LTDs} are modelled for 20 years of morphological changes for the bed level and discharge regime of the current Dutch Rhine system.

Eerden (2022) state that the existing LTDs near Tiel show the desired effect of countering bed degradation at the locations of the LTDs. Sloff et al. (2023) state that LTDs can help to stabilise the current bed level. However, the results from Sloff et al. (2023) also show the pronounced erosion in the Midden-Waal. Table 7 shows a large deviation in erosion predictions for the Midden-Waal. The modelled erosion is more than 3 times as large as the expected erosion based on the prognosis. Based on the prognosis, the model gives out unrealistic results. Also, based on purely the theoretical functioning as explained in Section 2.1.2, LTDs are the solution in the Waal to counter bed degradation. However, it is plausible that the model is correct and that the prognosis is not, based on the model results caution must be taken with implementing additional LTDs in the Waal.

Table 7: Comparing modelled bed degradation results to the expected bed degradation based on measurements. The prognosis by Sloff (2019) is the predicted average change per year up to 2050 and the modelled results (S_{actual}) are the modelled average changes per year for the upcoming 20 years.

	Prognosis by Sloff (2019) [cm/yr]	**Result S_{actual} [cm/yr]**
Boven-Waal	-1.6	-2.2
Midden-Waal	-0.6	-2.0
Beneden-Waal	+0.1	+0.1

Concluding, the DVR model is currently the best suitable model for large temporal and spatial scale 2D morphological studies since the computational time of the simulations is relatively low as a result of the quasi-stationary discharge approach in combination with the SMT. The model gives out decent results regarding bed degradation in the Boven-Waal and Beneden-Waal, however, the reliability of the model is questioned for the Midden-Waal. The question arises whether the prognosis by Sloff (2019) or the model results are more realistic for the expected changes in bed level until 2050 since both can be true. Overall, the model is deemed reliable, however, the results still need to be handled and used with caution since it is a model and not reality.

7.2 The potential of LTDs to counter bed degradation in the Waal and the influence of climate change on the effect of LTDs

The IRM programme has set the goal to stop the ongoing erosion in the Dutch Rhine system (Sloff et al., 2023). Based on the results of this study, insight can be provided into the effects of new LTDs in the Boven-Waal and Midden-Waal under the influence of climate change.

In this research, only the measure LTD is researched, other measures were omitted. The first 10 years of morphological development in the simulations show promising results, however, erosion accelerates in the last 10 years of the 20-year simulations. Also, this study focused on the bed development in the main channel of the river, however, the morphological development in the riparian channel is disregarded. Flores et al. (2022) has shown that in the riparian channel, aggradation occurs near the LTD and that degradation or bank erosion occurs in the littoral zones. An understanding of the morphological development in the riparian channel and an optimised LTD design can help in reducing the bank erosion in the riparian channel.

This research builds upon the study by Sloff et al. (2023), using the schematisation of this study as a basis. Schematisations used in this research are created by altering the LTD design, however, additional interesting simulations can be performed. An example of a potentially interesting simulation is modelling solely LTDs in the Midden-Waal or Boven-Waal. The final results of the study by Sloff et al. (2023) are replicated in this study by performing simulations S_{actual} and S_{LTDs}. S_{LTDs} is the final and best-performing simulation regarding countering bed degradation in the study by Sloff et al. (2023). In the study by Sloff et al. (2023) it is shown that the new LTDs reduce bed degradation in the Boven-Waal, decrease the water level during high discharges and increase the portion of discharge towards the Pannerdensch Kanaal during low discharges in comparison to doing nothing. The best-performing LTD design in this study is the LTDs with the widened riparian channel (S_1). In the sensitivity analysis performed by Van Linge et al. (2017), it was shown that lowering the sill height has more influence on the discharge distribution for water levels below the crest height between the riparian channel and the main channel in comparison to widening the riparian channel. In this study, it is shown that widening the riparian channel affects bed degradation more than lowering the sill. The amount of sediment entering the riparian channel is dependent on the discharge it receives, however, the widened riparian channel design will result in different flow velocities in the main channel and riparian channel than the lowered sill design. The bed degradation is thus not only dependent on the discharge distribution between the riparian channel and the main channel.

The study by Sloff et al. (2023) did not include climate change. This study assesses the morphological evolution of the riverbed under the influence of two climate change projections. Climate change is dependent on countless factors, thus it is impossible to project the exact future climate. Approaching climate change with two climate projections shows the variability in the effects of different climate change scenarios in the results and indicates the range in which different climate change projections can affect the functioning of the Dutch Rhine system. Currently, projections for 2050 are used, as the IRM programme runs until this year. However, the LTDs should still have their effectiveness after this year and thus projections for 2100 are also interesting. The 2050 climate change projections are imposed at the upstream boundary as a yearly repeating hydrograph, overestimating the effects of climate change. Effects of climate change on the discharge regime of the Rhine happen over the years and not instantly as imposed in the model. Next to this, in 20 years it is 2043 and not 2050, thus climate change is over-imposed in the model since values for 2050 are used.

This study shows the potential of LTDs to reduce bed degradation in the Boven-Waal. Various studies are performed with measures that potentially reduce bed degradation in the Waal. Rorink (2022) performed research on the potential of side channels to mitigate the large-scale bed degradation in the Dutch Rhine system via a 1D-modelling approach. It was shown that a combination of side channels in the Waal and Pannerdensch Kanaal that become active at 1000 m^3/s at Lobith reduce bed degradation rates up to 30-35% over the coming 100 years. Rorink (2022) states that side channels can result in a reduction in bed degradation of ∼0.5 cm/yr in the Boven-Waal and ∼0.2 cm/yr in the Midden-Waal over the coming 100 years. The results of Rorink (2022) show that side channels induce deposition of 0.4 m in the Boven-Waal and 0.3 m in the Midden-Waal at locations of side channels in comparison to the situation without side channels over a period of 100 years. De Lange (2022) performed research on sediment nourishments in the Waal to counter bed degradation via a 1D-modelling approach. It was shown that after 50 years large sediment nourishments ($6.93 \cdot 10^5$ m^3) in the Waal are able to reduce erosion up to 5 cm over the eroding bed and up to 4 cm upstream of the nourishment. Reoccurring nourishments are needed to stabilise the riverbed. Van der Deijl (2021) states that 0.17 Mm^3/yr of sediment is needed to stabilise the current bed level via nourishments. In comparison, the implementation of new LTDs in the Boven-Waal and Midden-Waal is able to stabilise the bed in the Boven-Waal. Next to this, the erosion in the Midden-Waal is induced as a result of the implementation of the new LTDs. Nourishments can stabilise the bed if the nourishments are performed regularly. The existing LTDs near Tiel show that deposition exceeds the pre-construction trend of erosion during the 5 years after construction (Czapiga et al., 2022). At the location where LTDs are present near Tiel, the bed level has risen after construction (Eerden, 2022).

Experts suggest nourishments, to maintain a defined bed level until the LTDs are effective in reducing bed degradation (Sloff et al., 2023). Experts mention that adaptive sediment management is required, in the form of dredging and nourishing (Sloff et al., 2023). This means a continuation of the current management of dredging and nourishing and performing additional nourishments if needed until the LTDs function properly. The initial morphological effects of the LTDs are mitigated with this strategy. The LTDs can lead initially to temporary downstream erosion and with the nourishing and dredging strategy this can be mitigated. Nourishments should be implemented at sections where sediment is required, for example, nourishment in the Boven-Rijn is not effective since this upstream nourishment only has an effect after decennia on the Rhine branches regarding erosion (Sloff et al., 2023).

Overall, a first insight is given into the effectiveness of different designs of LTDs via a 2D-modelling approach. This research shows that the overall design of LTDs can be improved, however, customization of each LTD is needed to make the LTDs optimal. To obtain optimal LTDs, a sensitivity analysis per LTD is required to customize each LTD. Next to this, a first glance is given at the functioning of LTDs under the influence of a changing climate. Longer and different climate change projections can be used to analyse the effects of LTDs on alternative and longer climate change projections. As a complement, this research shows an approach to create a yearly repeating hydrograph for a climate change projection. The obtained yearly repeating hydrograph for the specific set year can be chosen to repeat yearly or change the hydrograph yearly according to the expected climate change rate.

8 Conclusions and recommendations

The objective of this research was to gain insight into the effect of different designs of LTDs under the influence of climate change to counter bed degradation in the Waal. This was done via a 2D-modelling approach using the DVR model, which is based on the Delft3D-4 computational core coupled with Python scripts. The effectiveness of different LTD designs was analysed by modelling multiple new LTD schematisations and comparing them with a schematisation without new LTDs. Next to this, the best-performing new LTD design was simulated with different climate projections and compared to the simulation with and without new LTDs under the influence of climate change. All simulations were carried out for a duration of 20 years of morphological changes. In this chapter, the conclusions of this research are presented by summarizing the effects of different LTD designs and the effects of LTDs under the influence of climate change. Next, recommendations for the IRM programme and follow-up research are given.

Conclusions
This research aimed to address the morphological effects of different designs of LTDs in the Waal and to assess the effect of climate change on the effectiveness of LTDs. The answers to the sub-questions of this research and the gained knowledge during the process of the research have led to the answer to the posed main research question:

What are the effects of different designs of longitudinal training dams on countering bed degradation for different discharge scenarios in the river Waal?

The implementation of the new LTDs in the Boven-Waal and Midden-Waal resulted in a reduction in erosion in the Boven-Waal after 20 years of morphological changes. Next to this, erosion was induced in the Midden-Waal and the Beneden-Waal, however, the results of the Midden-Waal were handled with caution. Overall, the new LTDs in the Boven-Waal and Midden-Waal induced erosion in the Midden-Waal. The large erosion in the Midden-Waal propagated to the upstream part of the Beneden-Waal. LTDs were redesigned in the Midden-Waal to reduce erosion. Regarding countering bed degradation, both lowering the sill heights and lowering the crest height of the LTDs worsened the effect of the new LTDs in the Boven-Waal and Beneden-Waal and these designs had little effect on countering bed degradation in the Midden-Waal. Widening the riparian channel reduced bed degradation in the Boven-Waal and the Beneden-Waal. However, widening the riparian channel resulted in additional erosion in the Midden-Waal. Specifically, widening the riparian channel resulted in the largest water level reduction during high discharges and improved the discharge distribution at the Pannerdense Kop the most by having the largest increase in the proportion of the discharge that flows to the Pannerdensch Kanaal during low discharges, but the differences between the different designs were small. The implementation of the new LTDs worsened the number of local shallows in the Boven-Waal but increased the overall water depth in the Midden-Waal. Overall, widening the riparian channel of the new LTDs in the Midden-Waal improved the Waal the most based on the assessed criteria.

This research showed that climate change affects the morphodynamic evolution in the Waal. Without the new LTDs, climate change resulted in additional erosion in the Boven-Waal and Midden-Waal and reduced the sedimentation in the Beneden-Waal. In the case of climate change, the new LTDs improved the navigation depth, flood safety and discharge distribution at the Pannerdense Kop in comparison to the situation without new LTDs. Climate change in combination with the new LTDs resulted in sedimentation in the Boven-Waal instead of erosion. Next to this, in the Midden-Waal additional erosion was seen in the case with and without the new LTDs as a result of climate change. However, in the Beneden-Waal little erosion was seen in the case with the new LTDs instead of little sedimentation as a result of climate change. Climate change scenarios G_l and $W_{H,Dry}$ resulted in increased bed degradation along the Waal in the case with and without new LTDs, of which climate change scenario G_l resulted in the largest overall bed degradation in the Waal.

Recommendations
This research aimed to add to the knowledge gap surrounding LTDs to counter bed degradation in the Waal under the influence of climate change. Recommendations are given for further research regarding LTDs to counter bed degradation.

The model can be improved by bringing the sediment composition in the model closer to the measured sediment composition. This could be achieved by further detailing the grain sizes in the model. Currently, the grain size trends in the Boven-Waal are extrapolated to the Midden-Waal. Measurements of bed deposition at the pilot LTDs near Tiel exceed the modelled bed deposition in the DVR model (Sloff et al., 2023). Using measurements of the bed composition in the Midden-Waal as the basis for the bed composition in the model instead of the extrapolated bed composition of the Boven-Waal can make the model more reliable.

A higher resolution model can give more reliable and realistic results for measures for the IRM programme. With this model, the location of the LTDs and their riparian channels can be optimised. Currently, the width of the riparian channel and main channel is dependent on the dimensions of the grid cells. Also, the refinement of the grid cells will make it possible to schematise the inlets of the LTDs more accurately and to assess more designs of LTDs. The current coarse grid limits riparian channel adjustments and the schematisation of the inlets. Next to this, a sensitivity analysis via a 2D-modelling approach on the widening of the riparian channel design will help to find the optimal range of values for the parameter, which is an effective parameter regarding the morphological development of the main channel. However, the downside of a higher-resolution model is that the computational time will increase. The additional modelling with a refined model will help to understand the effect of LTDs better, which is needed for decision-making. Continuation of the measurements at the pilot location near Tiel will help to understand the long-term effect of LTDs better. However, bed degradation will not wait for future decisions on the approach to tackling bed degradation, thus decisions have to be made before the long-term effect of LTDs can be proven with measurements at the pilot near Tiel. Overall, I would suggest additional morphological modelling studies to prove that the resulting bed degradation of the DVR model is false or not before decisions are made on whether to implement LTDs or not.

The use of adaptive sediment management in combination with new LTDs can solve the initial erosion resulting from the new LTDs. A volume of 0.17 Mm^3/yr of sediment is needed to stabilise the current bed level, it is expected that the implementation of LTDs will reduce the required volume of sediment to stabilise the bed (Eerden, 2022; Van der Deijl, 2021). Adaptive sediment management can help to compensate for the initial negative effects of the new LTDs until the LTDs are effective enough to stabilise the bed. Thus nourishments and dredging works are recommended to maintain the bed level during the evolution of the bed after the implementation of the new LTDs. Next to this, modelling the adaptive sediment management approach in combination with optimised LTDs per location in a refined model will give more realistic results regarding the possibilities of the new LTDs. The studies of De Ruijsscher et al. (2020a), Eerden (2022), Sloff et al. (2023), Barneveld et al. (2023) and this research show that LTDs are a promising measure that can help to counter the ongoing bed degradation. LTDs in combination with other measures on the same and other parts of the Dutch Rhine system can improve the functioning of the system as a whole. Examples of such measures are groyne lowering, side channels and nourishments.

Next to this, longer simulations in combination with a longer climate projection will give more insight into the long-term bed evolution of the Dutch Rhine system. After the optimised LTDs per location are determined and the effects of LTDs in combination with nourishments and dredging works are studied, the sequence of implementation of the LTDs is the logical following step to research. The sequence of implementation of LTDs will affect the morphological evolution in the Dutch Rhine system. For example, starting downstream and moving upstream with the construction of the LTDs can have a different effect on the morphological evolution in comparison to the process of starting upstream with constructing and moving downstream. In this study, a yearly repeating hydrograph is used to approach climate change. However, as climate change occurs over time it would be more realistic to impose a yearly changing hydrograph from the current climate to the expected climate projection. This yearly changing hydrograph can be either linear change or exponential change or random change over time based on the expected climate change rate.

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Appendices

A Elaboration on the implementation of LTDs in Delft3D

The implementation of measures in Delft3D-4 is commonly done via Baseline. The measure is first schematised in GIS based on the current Baseline protocol. Afterwards, the measure is merged into the schematisation of the river. Using Baseline, a conversion is done to Delft3D-4 input files, and the new situation is projected on the predefined grid. However, in this case, the measures are implemented directly in the Delft3D-4 input files. This is done since the DVR schematisation of the study by Sloff et al. (2023) and Barneveld et al. (2023) needed simple adjustments to come to the specified measures. In this section, U-direction and V-direction are mentioned. U-direction is the longitudinal direction with respect to the river, while the V-direction is the cross-sectional direction with respect to the river.

The LTDs are implemented in the following way in the model schematisation. First, the LTDs are implemented by adapting the bottom depth in the model. In the V-direction, the LTDs are three grid cells wide. The middle cell contains the height of the LTD and the outer cells comprise the slope of the structure. Second, LTDs are schematised by adding weirs at links for the length of the structure. Weirs are used to comprise the energy losses over structure. At last, the three grid cells which comprise the LTD do not contain a sediment layer. This is done to avoid erosion and sedimentation of the dam itself. Per measure, the taken steps to set up the schematisation are described below.

Widening of riparian channel

The locations of the LTDs are identified via the bottom depth and the implemented weirs in the model. The LTDs, consisting of three grid cells, are moved one grid cell in the direction of the main channel (V-direction) to achieve the 25 m widening of the riparian channel. This is done by copying the bottom depth of those three cells and moving those cells one grid cell in the direction of the main channel. The cell that is created for the riparian channel is given the same bottom depth value as in the V-direction adjacent riparian channel cell. This is done since the bed level of the riparian channel is at the same elevation as the bed level of the main channel, thus the existing riparian channel bed level is already at this same elevation. In Figure 40, the widening of the riparian channel is visualised. Afterwards, the existing weirs at the LTDs of the reference model are shifted one cell in the direction of the main channel (V-direction). After, the sediment layers at the new locations of the LTDs are set to 0, resulting in no erosion or sedimentation at these locations. However, the empty sediment layer cells in the newly widened riparian channel require sediment layers. It is assumed that these empty sediment layer cells had the same sediment composition as in the V-direction adjacent riparian channel cell. Thus, the same sediment composition is achieved in these cells by copying the sediment layers of the adjacent cells. At last, the sill also had to be widened by 1 cell to cope with the new location of the LTD. The sill is extended one cell towards the main channel (V-direction). The extension is done by copying the depth of the sill in the adjacent cell in the V-direction, adding a weir, and removing the sediment layer at the extension of the sill.

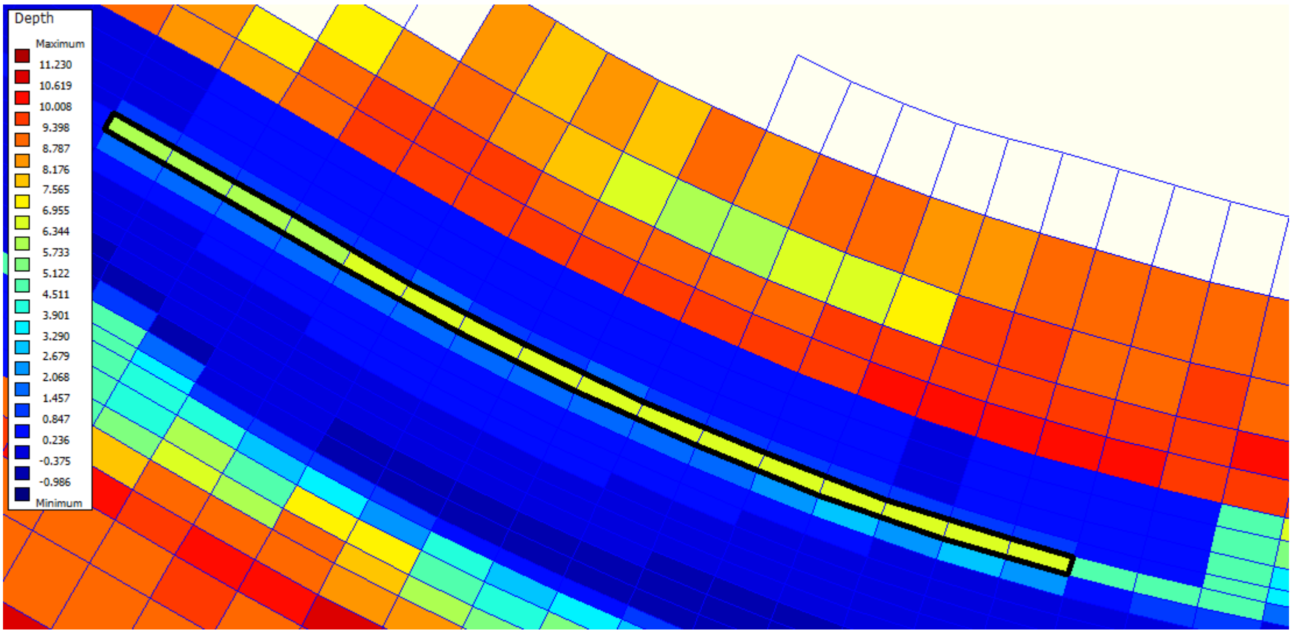

Figure 40: Visualization of bottom depth of riparian channel widening schematisation, in black denoted is the center cell of the LTD.

Lowering of sill height

Sills are present at the start of the LTDs, which function as the inlet for the riparian channel, and the LTDs created in the reference schematisation do not contain any openings. Thus, the implementation of this schematisation required solely the lowering of the sills. In Figure 41, the location of the sill is visualized. The sills in the reference schematisation have an elevation of +0.5 m OLR. Thus, to achieve an elevation of 0 m+NAP the sills are lowered by 0.5 m for this simulation. Next to this, the weirs present at the sill also require lowering, these are also lowered by 0.5 m.

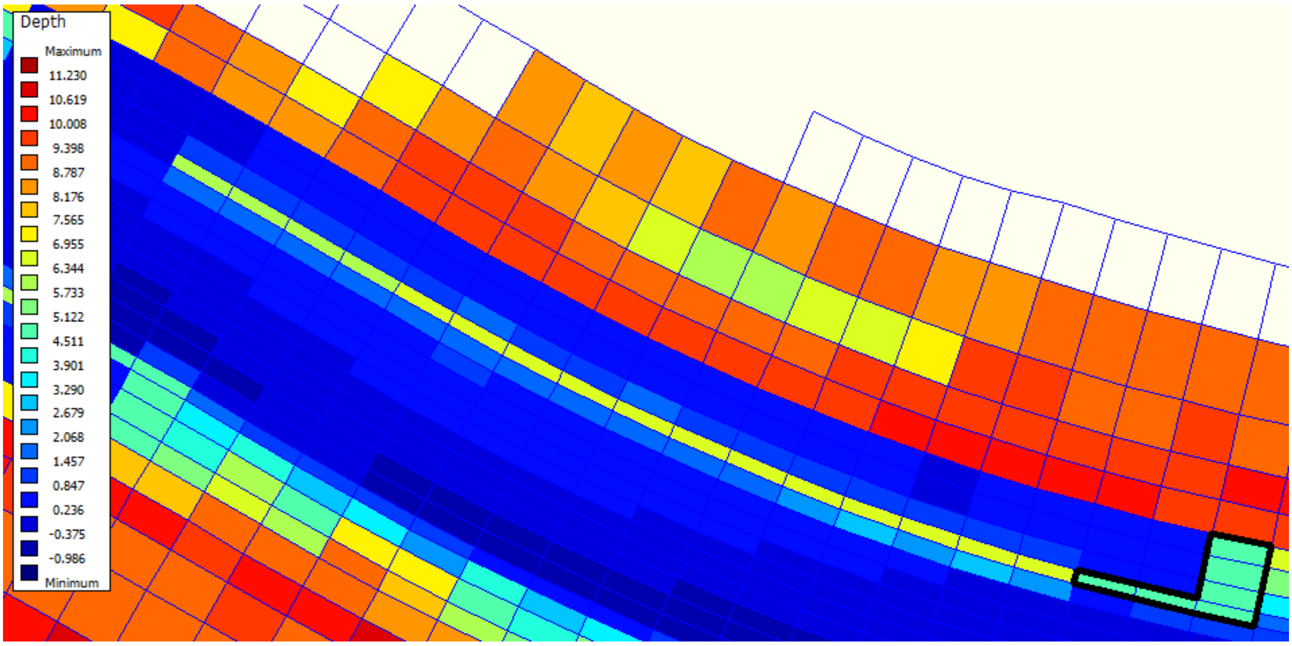

Figure 41: Visualization of bottom depth of sill schematisation, in black denoted is the sill of the LTD.

Lowering of crest height

The locations of the LTDs in the reference schematisation are identified during the setup of the widening of the riparian channel simulation. To set up this simulation, solely the height of the crest had to be lowered. This is done by adjusting the depth in the model schematisation and by adjusting the height of the weirs in the schematisation. The crest height in the reference schematisation has an elevation of +2 m OLR. To achieve a crest height of +1.2 m OLR, the crest height is lowered by 0.8 m in both the bottom depth input file and the weir input file.

B Downstream boundary conditions

Table 8: $Q - h$ relation of the downstream boundary condition of the model at the IJsselkop, partial model pk2 (Achtersloot et al., 2019; Becker, 2021)

Q. Pannendensch kanaal (m^3/s)	**h IJsselkop (m+NAP)**
188	6.87
518	8.33
1260	10.26
1886	11.86
2585	12.86
3469	13.48
4240	13.92

Table 9: $Q - h$ relation of the downstream boundary condition of the model at Gorinchem, partial model wl2c

Q Lobith (m^3/s)	**Q Waal (m^3/s)**	**h Waal-rkm 953 (m+NAP)**
1020	832	0.7164
1203	953	0.7799
1635	1240	0.9298
2250	1639	1.1457
3053	2144	1.4326
3824	2629	1.7081
4717	3233	2.1042
6151	4212	2.7482
8592	5745	3.4847

C Analyses of DVR model

In this Appendix, an analysis is done on the output of the DVR model to identify possible improvements for the DVR model. First, an analysis is done on the bed degradation per model domain. This is done by assessing averaged bed degradation values over the years. Afterwards, the bed degradation is visualized in two-dimensional maps to find outliers in the results of the bed degradation. Second, an analysis is performed on the changes in bed degradation at the Pannerdense Kop. This bifurcation point is located on the downstream boundary of the Boven-Rijn domain and is possibly sensitive to modelling artefacts. Third, an analysis is done on the grain size distribution changes in the Waal. The grain size distribution in a river determines the magnitude of morphological changes. Heavy sediment particles require a large amount of energy to be put into motion. At last, an analysis of flow velocities in the Waal is performed. Sediment transport is dependent on the flow velocity, small changes in flow velocities can cause large changes in sediment transport.

Analysis on bed degradation per model domain

The bed degradation over the years for the different model domains is assessed by averaging the bed degradation in the domains. It is assessed whether the bed degradation appears to be linear over the years or whether it is accelerating or decelerating. If the trend of erosion or sedimentation seems a steady transition over the years, it does not imply any modelling artefacts. However, erosion or sedimentation can be underestimated or overestimated. In Figure 42, an overview of the averaged difference in bed level per domain is shown. In the model that does not contain the new LTDs (No measures), the expected erosion in the Boven-Waal and Midden-Waal is observed. The expected sedimentation in the Beneden-Waal and the expected erosion in the Boven-Waal comply with the prognosis given by Sloff (2019). The model schematisation with the new LTDs shows a clear increase in erosion in the Midden-Waal. In the other domains, sedimentation occurs in the first few years. However, after 10 years of sedimentation in the Boven-Waal and Beneden-Waal, erosion occurs. The bed level elevation of the Midden-Waal drops fast and eventually, the bed level of the adjacent domains transition to this trend. If the adjacent domains do not transition to a lower elevated bed, the transition with the Midden-Waal will become a large drop or ramp which is not realistic. When looking at the change in bed level of the Midden-Waal, the erosion decelerates after 10 years. This implies that the erosion in the Boven-Waal results in more sediment ending up in the Midden-Waal.

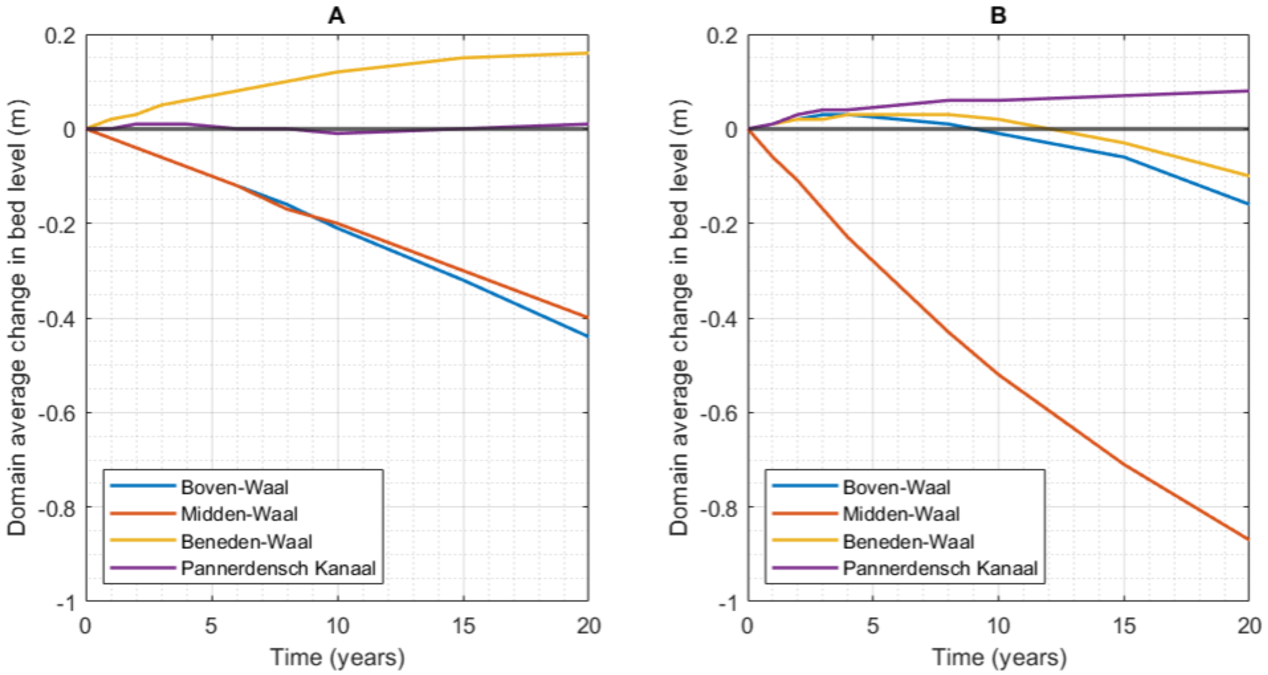

Figure 42: Domain averaged bed degradation in the main channel over the years, difference between the case without LTDs S_{actual} (A) and the case with LTDs S_{LTDs} (B).

The domains in the Waal are vast and contain locations of erosion and sedimentation. To understand better what happens in each of the domains of the Waal, each of the domains is split up into two parts. An overview of the partial model domains is shown in Figure 43. In the Boven-Waal sections of sedimentation over the years and a section of erosion alternating with sedimentation is observed. Thus, the Boven-Waal is split up into the parts of which the first contains the sedimentation and the second contains the alternating sedimentation and erosion. The boundary of the split is located upstream of the fixed layer at Nijmegen. The Midden-Waal is split-up at the location where the newly implemented LTDs end and where the existing LTDs start. In the Beneden-Waal a clear transition from erosion to sedimentation is observed, thus at this location, the Beneden-Waal is split up.

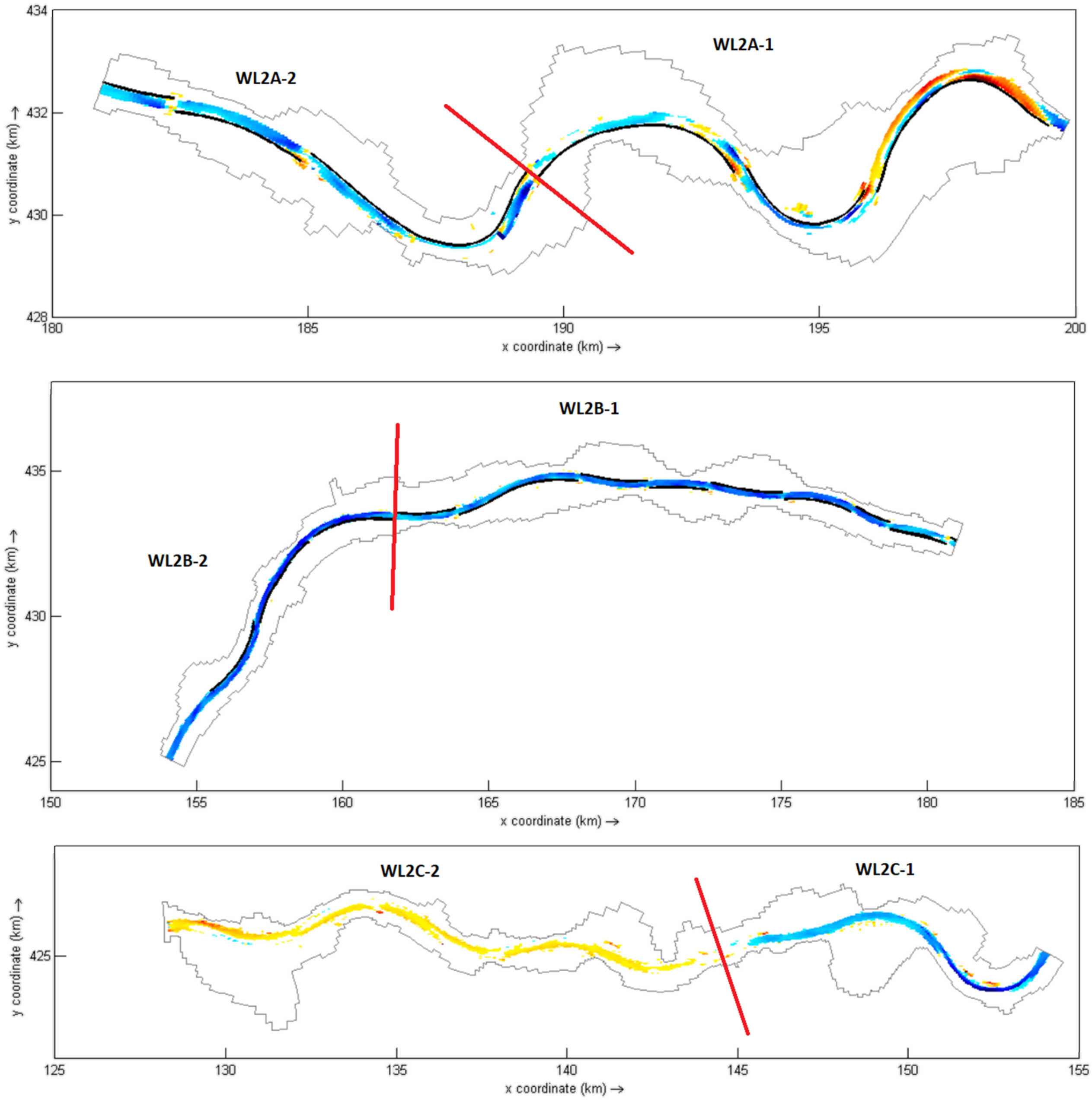

Figure 43: Split-up parts of model domains for which averaged bed degradation is calculated.

In Figure 44, the results of the averaged difference in bed level for the partial domains are shown. In the Boven-Waal a clear distinction between the sedimentation in the upper part (WL2A-1) and erosion in the lower part (WL2A-2) is shown. In the lower part of the Boven-Waal, first a deceleration in erosion is observed. However, after 10 years the erosion shows to be accelerating once again. This is caused by the elevation difference of the bed between the Midden-Waal and the Boven-Waal over the years. The same pattern is observed in the upper part of the Beneden-Waal, substantiating this observation. The erosion in the Upper part of the Midden-Waal (WL2B-1) remains steady over the years. In the lower part (WL2B-2) the erosion decelerates over the years, which is also in accordance with the observation.

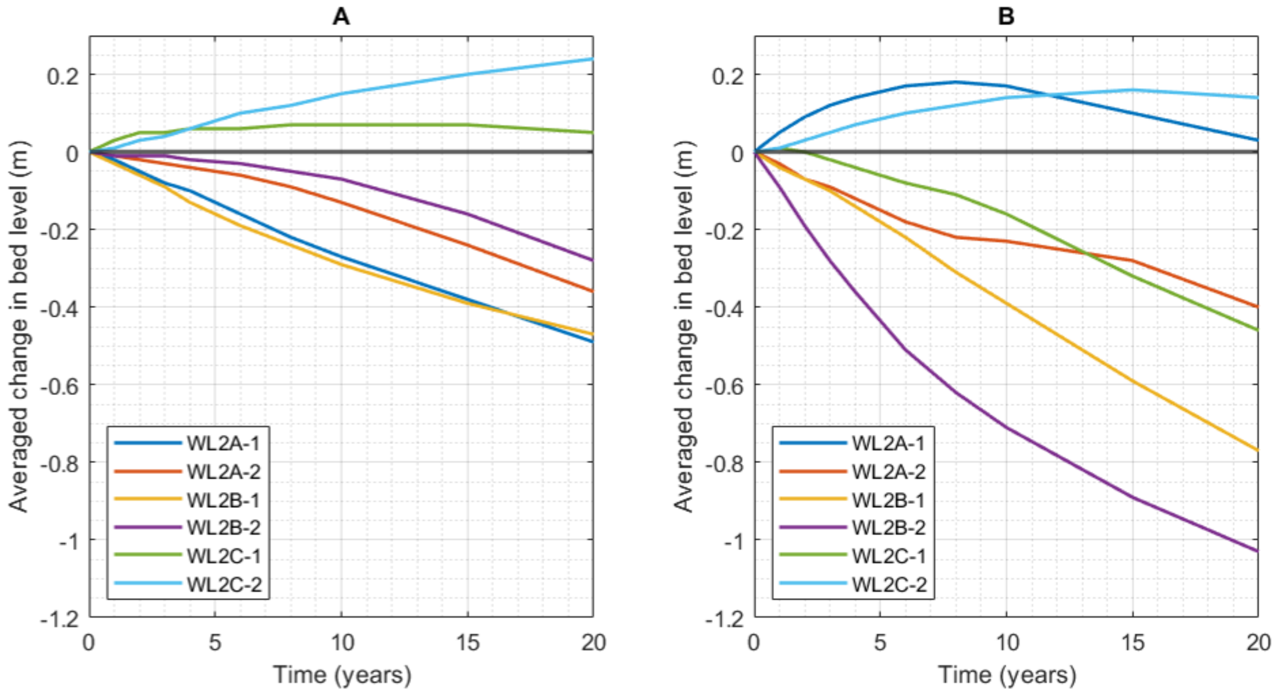

Figure 44: Partial domain averaged bed degradation in the main channel over the years, difference between the case without LTDs S_{actual} (A) and the case with LTDs S_{LTDs} (B).

After analyzing the two-dimensional maps of the change in bed level over the years, no shocking findings are done and the model behaves as expected. Without the new LTDs, sedimentation occurred in the inner bends and erosion occurred in the outer bends. With the LTDs, sedimentation occurred at the inlets and the outlets of the LTDs. The confluence of the flow of the main channel and the flow out of the riparian channel reduces the flow velocity at this location. A pattern of erosion is observed in the main channel of the Midden-Waal, both in the model of the current situation and in the situation with the new LTDs. However, in the model with the new LTDs, a larger erosion pattern is observed, which also can be concluded from Figures 42 and 44.

Analysis on changes at the Pannerdense Kop

After analyzing the two-dimensional maps of the change in bed level over the years, the only thing that stood out is the sedimentation and erosion at the Pannerdense Kop and in the Pannerdensch Kanaal. In the case without new LTDs, erosion is observed at the transition towards the Waal and stabilisation is observed at the transition towards the Pannerdensch Kanaal. While in the case of LTDs in the Waal, more intense erosion is observed at the transition towards the Waal and sedimentation is observed at the transition towards the Pannerdensch Kanaal. Presumably, more sediment is transported towards the Pannerdensch Kanaal and less towards the Waal.

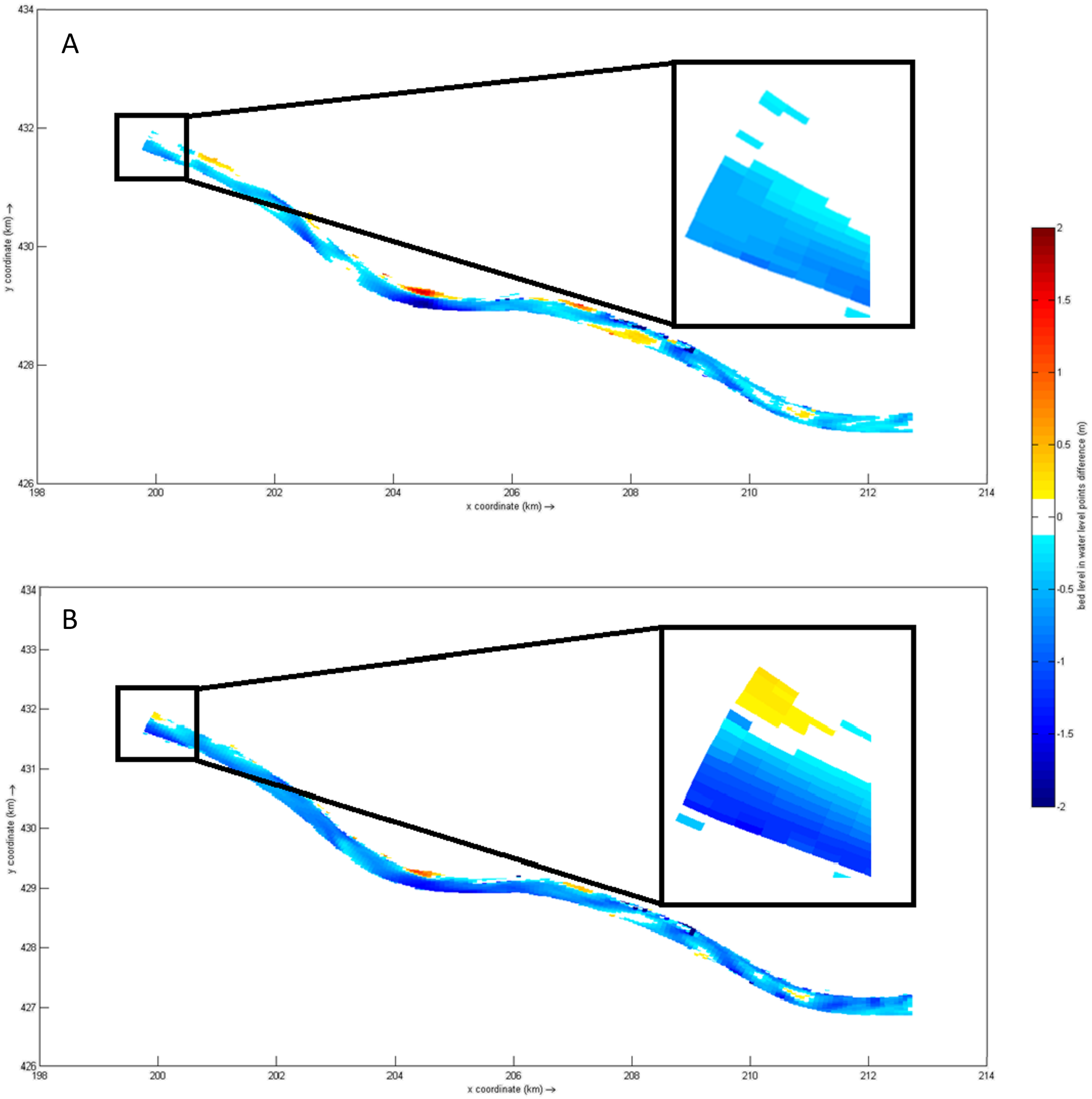

Figure 45: Change in bed level after 20 years in the Boven-Rijn, in black highlighted is the Pannerdense Kop. The change in bed level without the new LTDs is denoted (A) and the change in bed level with the new LTDs is denoted (B).

In Figure 42 and 44, the averaged sedimentation over the years in the Pannerdensch Kanaal can be seen. As can be observed in the figures is that the sedimentation in the case with new LTDs is larger than in the case without new LTDs. Without new LTDs, the Pannerdensch Kanaal is stabilised regarding bed degradation, while sedimentation occurs when LTDs are implemented in the Waal. Next to this, the pattern of sedimentation and erosion also differs between the two cases. In the case without new LTDs, sedimentation and erosion alternate along the Pannerdensch Kanaal. In the case of LTDs in the Waal, sedimentation occurs at the upper part of the Pannerdensch Kanaal and slight erosion occurs in the lower part. The new LTDs in the Waal appear to be increasing the sediment transport towards the Pannerdensch Kanaal and decreasing the sediment transport towards the Waal.

Analysis on grain size distribution changes

An analysis is performed on the grain size distribution (D_{50}) changes over the years and compared to historical changes in grain size distribution. The historical changes in discharge distribution come from measured data in the centre of the Waal. Next to this, the initial grain size distribution is compared to this measured grain size distribution. With this analysis, it is checked whether the initial grain size distribution in the model is realistic and whether the changes in discharge distribution over the years are realistic. At last, the difference in grain size distribution changes between the model schematisation without new LTDs and with new LTDs is analysed.

The bed composition around the Pannerdense Kop has coarsened since the late 1990s (Chowdhury et al., 2023). The coarsening of the surface suggests coarsening of the sediment supply over time, the grain size distribution of the bed surface is related to the grain size distribution of the sediment flux (Parker & Toro-Escobar, 2002). The coarsened sediment supply also has led to bed surface coarsening in the Waal, it is expected that this bed surface coarsening will continue. Thus, the model should show an increasing grain size over time.

As can be concluded from Figure 46, the bed composition has coarsened over the years. In 1984, the bed composition appeared to be uniform over the Waal. In 2020, a gradual decrease in grain size is observed along the Waal. When interpreting the measurements of Figure 46, it must be kept in mind that there were 77 measurement locations in 1984 versus 185 measurement locations in 2020. The increase in measurement locations improves the reliability of the trend line.

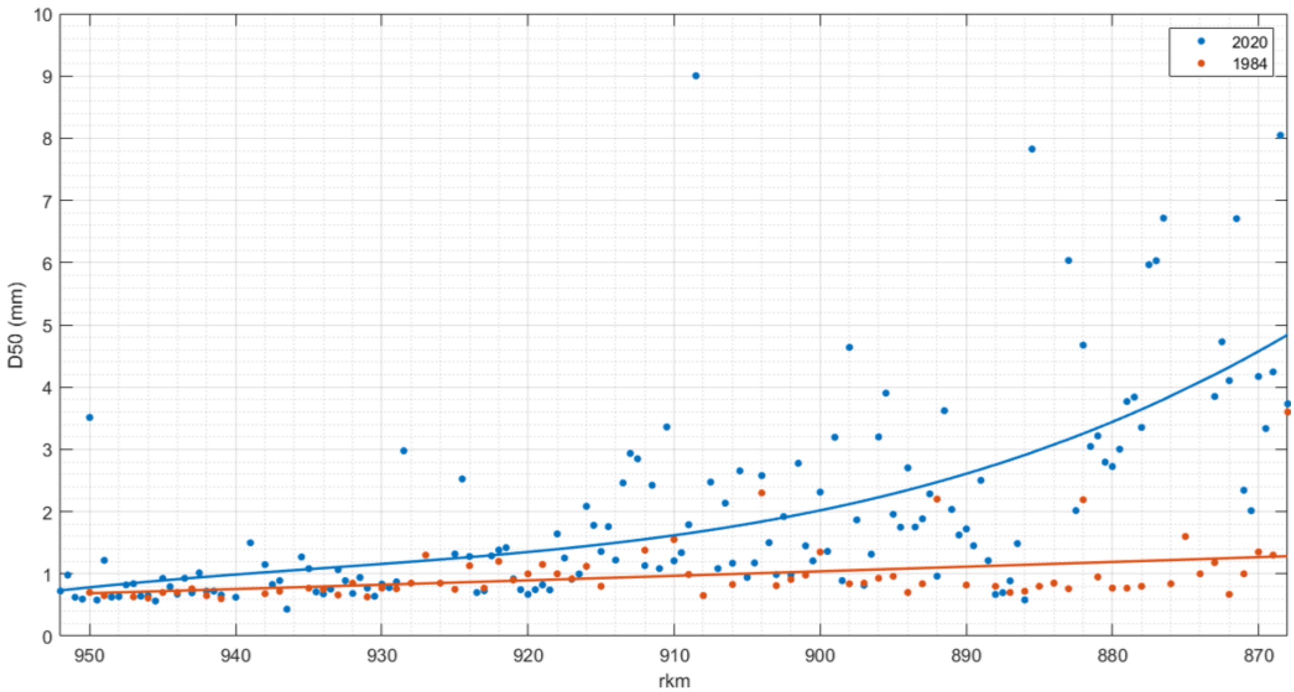

Figure 46: Measured change in D_{50} over the years in the centre of the Waal.

In Figure 47, the initial median sediment grain size (D_{50}) is depicted along the Waal and the median sediment grain size after 20 years with the model schematisation of the current situation. As can be concluded from Figure 47 is that the median grain size is coarsening over time in the Boven-Waal and Midden-Waal.

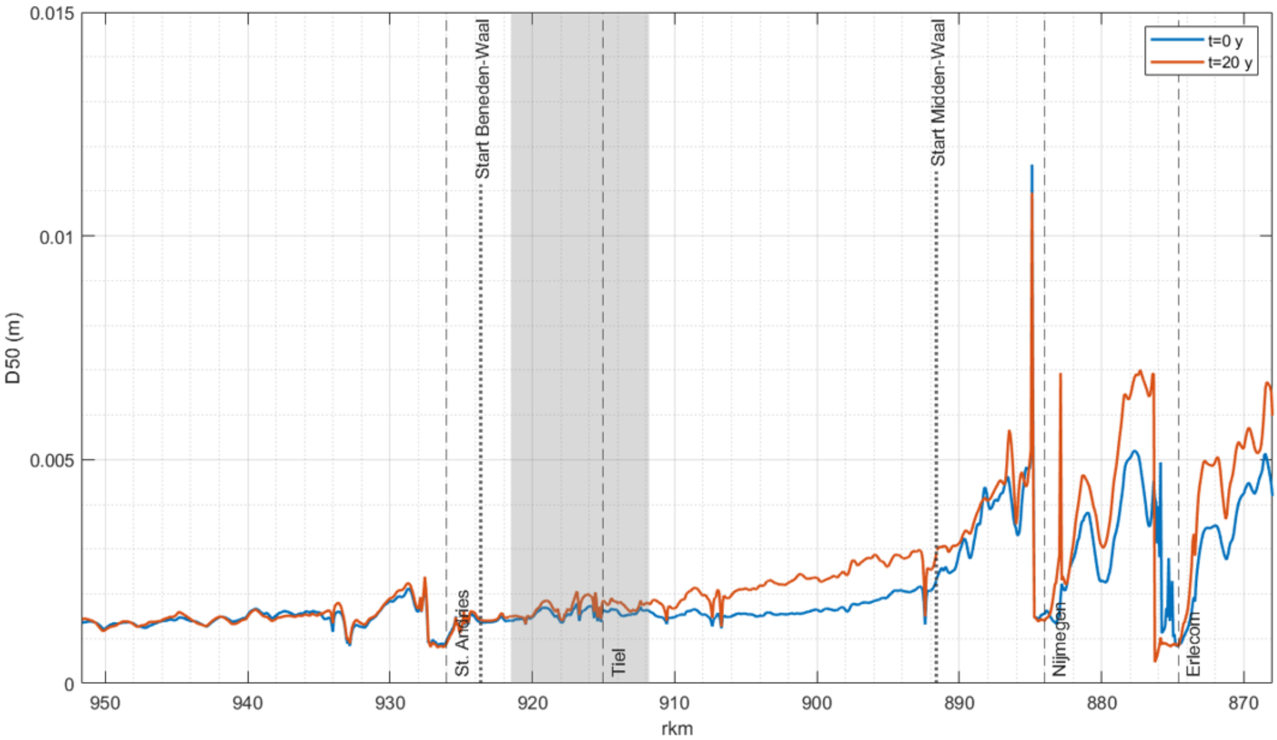

Figure 47: Modelled change in D_{50} over time along the centre of the Waal of the current situation. The shaded area indicates the existing LTDs near Tiel.

In Figure 48, the initial median sediment grain size (D_{50}) is depicted along the Waal and the median sediment grain size after 20 years with the model schematisation with new LTDs. Similar to the simulation of the current situation, the median grain size is coarsening over time in the Boven-Waal and Midden-Waal.

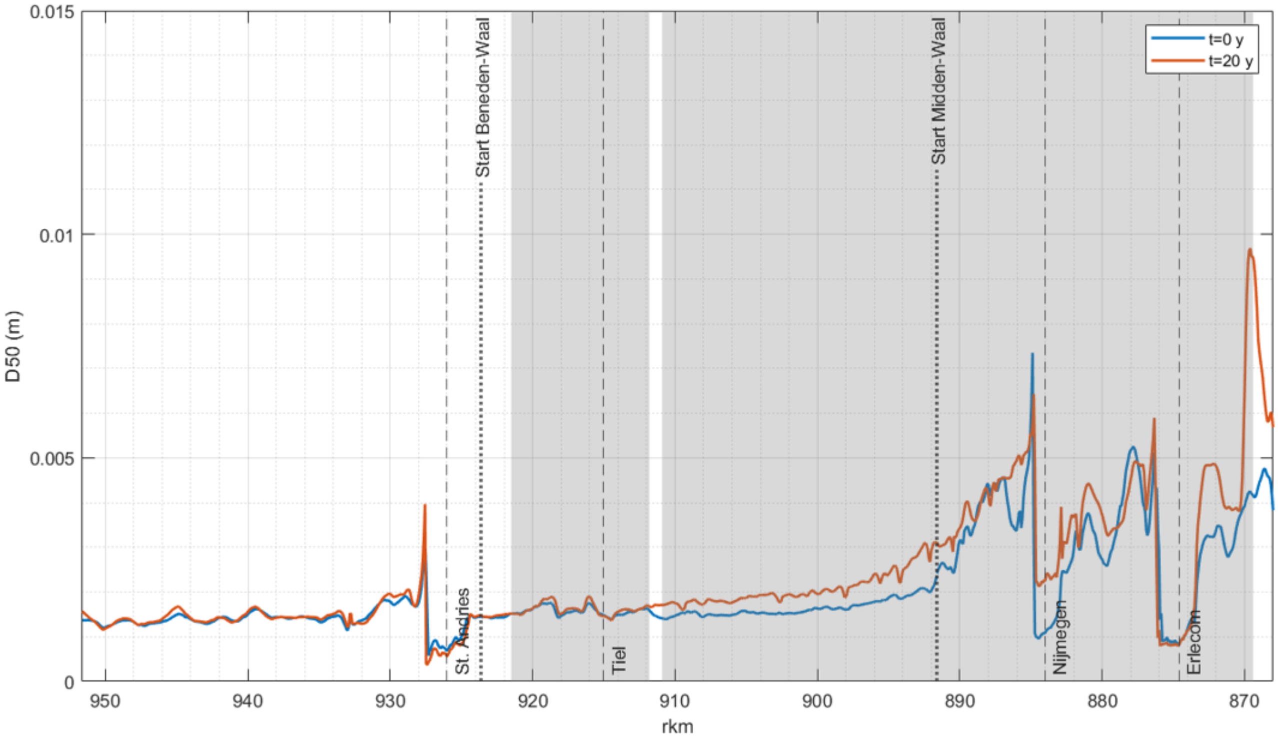

Figure 48: Modelled change in D_{50} over time along the centre of the Waal, including LTDs in the Waal. Shaded areas indicate existing LTDs near Tiel and new LTDs.

When comparing the measured median grain size with the modelled median grain size it becomes apparent that the median grain size is modelled well. The model shows similar grain sizes compared to the measured grain sizes and the model also shows that the sediment in the Waal is coarsening over time, which is also the case in real life. This is also expected, since the grain size in the Boven-Waal is determined with measured data, and the grain size distribution of the Boven-Waal is extended towards the Midden-Waal. This can be observed in the linear decrease of the grain size distribution in the Midden-Waal, while in the Boven-Waal multiple peaks in median grain size can be observed. When comparing Figure 47 with Figure 48, it becomes clear that in the Midden-Waal less coarsening of the sediment takes place when new LTDs are implemented in the Boven-Waal and Midden-Waal. Next to this, large sediment particles remain more in the upper part of the Boven-Waal.

Analysis on flow velocities

The flow velocities along the Waal are analysed to identify remarkable points. The flow velocities are solely assessed for the Midden-Waal since erosion is the largest in this domain. In Figure 49, the flow velocity for the case without LTDs is compared to the case with LTDs along the centre of the Midden-Waal for different discharges. From Figure 49, it becomes apparent that LTDs increase flow velocities during low discharges, but decrease flow velocities during high discharges. From Figure 50 it is concluded that after 20 years of morphological development, the difference in flow velocities during low discharges becomes larger. Next to this, the difference in flow velocities during high discharges decreases. The hydrograph that is used as input contains mainly low discharges. In essence, high discharges are the most important regarding sediment transport since the highest flow velocities occur during high discharges. However, as can be concluded from Figures 49 and 50, flow velocities during low discharges increase and might become important for sediment transport. The flow velocities in the model without LTDs already lead to overestimations in bed degradation and implementing the new LTDs lead to even higher overestimations caused by the increase in flow velocities during low discharges. However, the additional overestimation caused by the increase in flow velocities during low discharges is thus presumably not realistic since high discharges are in essence the most important for erosion.

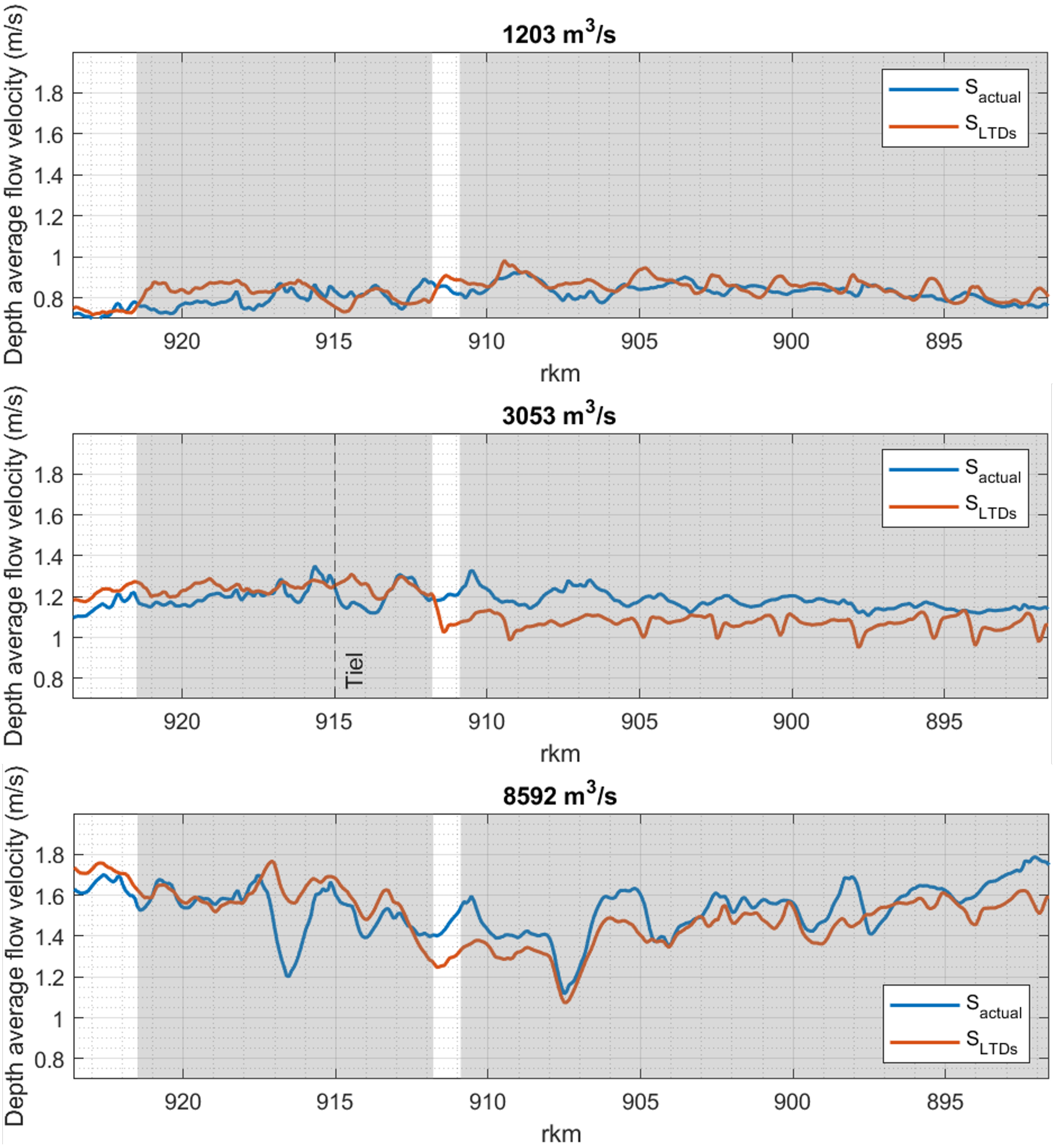

Figure 49: Initial depth averaged flow velocities in the centre of the river in the Midden-Waal for different discharges. Shaded areas indicate existing LTDs near Tiel and new LTDs.

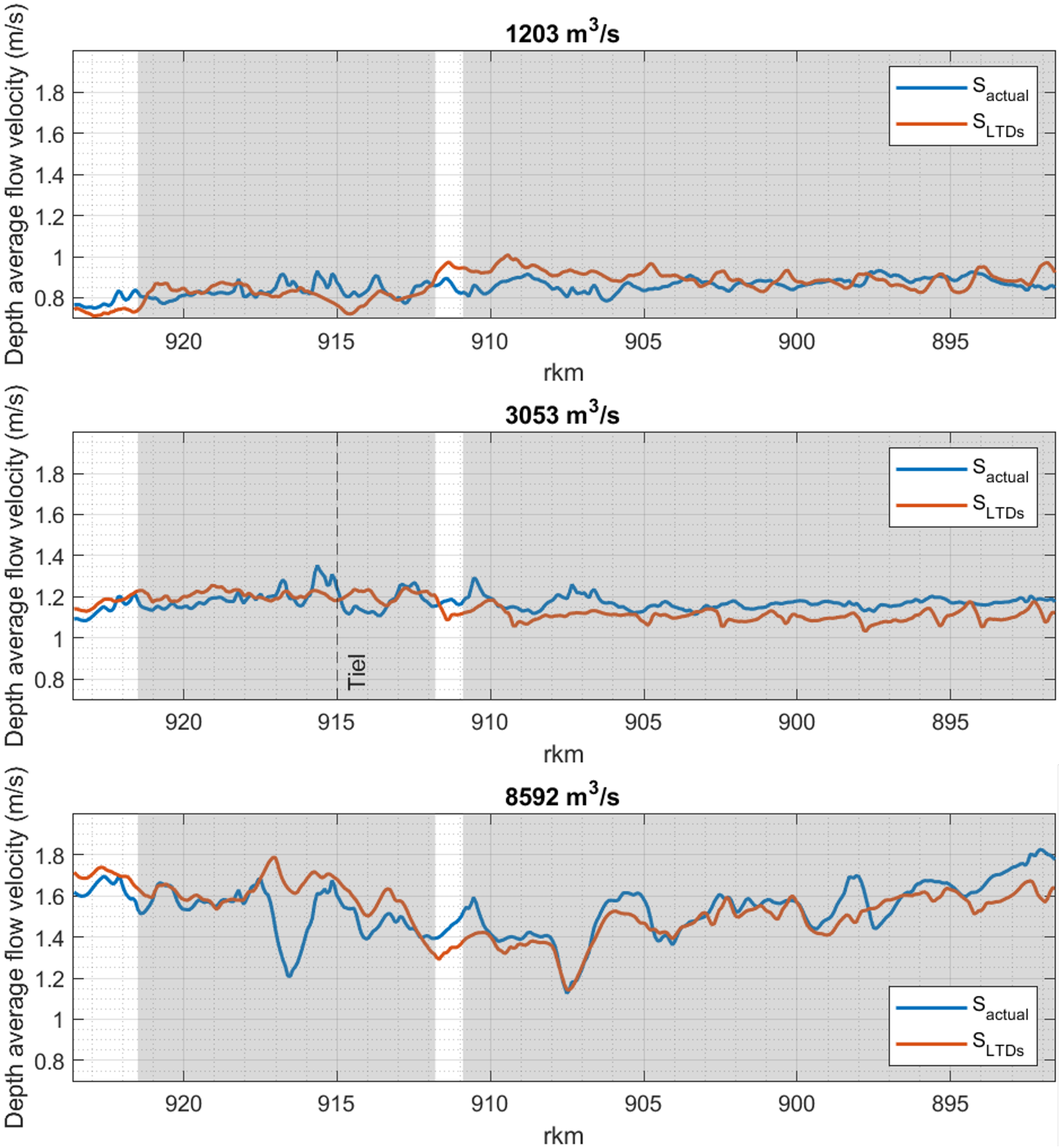

Figure 50: Depth averaged flow velocities in the centre of the river in the Midden-Waal for different discharges after 20 years of morphological changes. Shaded areas indicate existing LTDs near Tiel and new LTDs.

Figure 51, shows the difference between the case with the standard implemented LTDs following from the reports of Barneveld et al. (2023) and Sloff et al. (2023) and the widening of the riparian channel case. As expected, the flow velocities in the main channel increase since the main channel is narrowed. A difference up to 0.18 m/s is found, which explains the large erosion rates in the S_1 simulation.

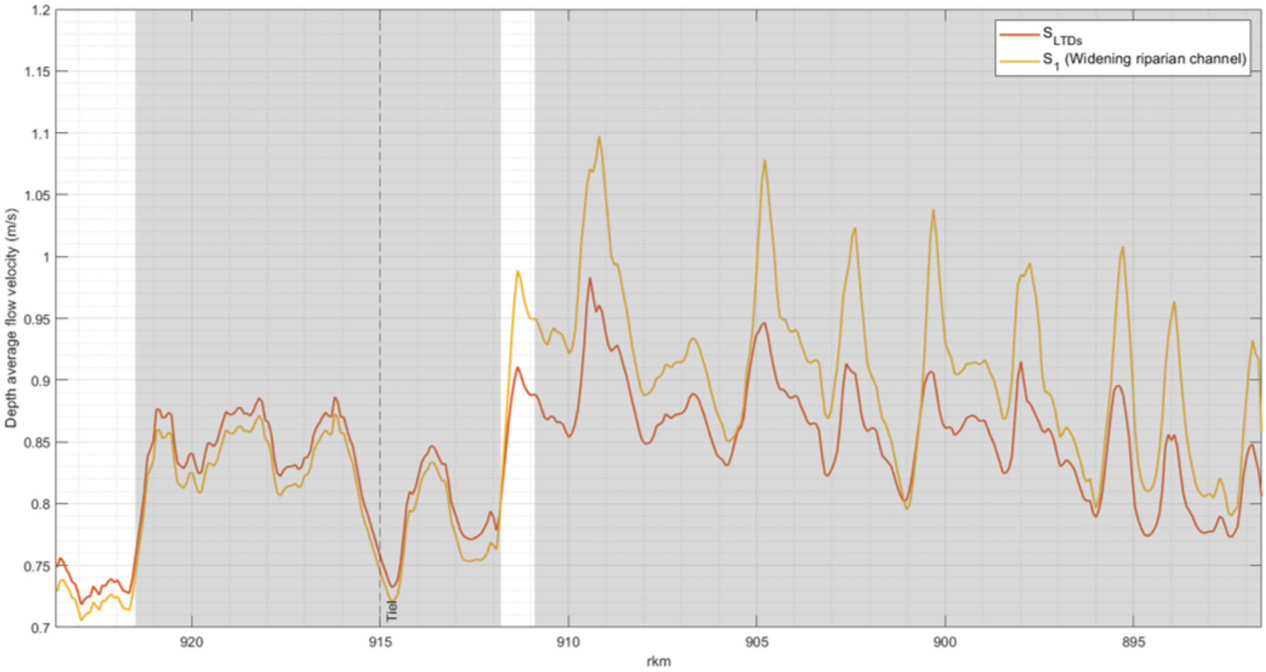

Figure 51: Initial depth averaged flow velocities of S_{LTDs} and S_1 in the Midden-Waal during a low discharge (1203 m^3/s).

Analysing effectiveness riparian channel over time

Figures 52 and 53 show that the riparian channel of the LTD in the Boven-Waal becomes less effective over time. After 10 years of simulation, a reduction in flow velocities of 0.04 m/s and a reduction in water depth of 0.1 m is observed in comparison to the first year of the simulation. This results in a discharge per unit width reduction of 11% after 10 years of simulation. After 20 years of simulation, a reduction in flow velocities of 0.08 m/s and a reduction in water depth of 0.2 m is observed in comparison to the first year of the simulation. This results in a discharge per unit width reduction of 21% after 20 years of simulation.

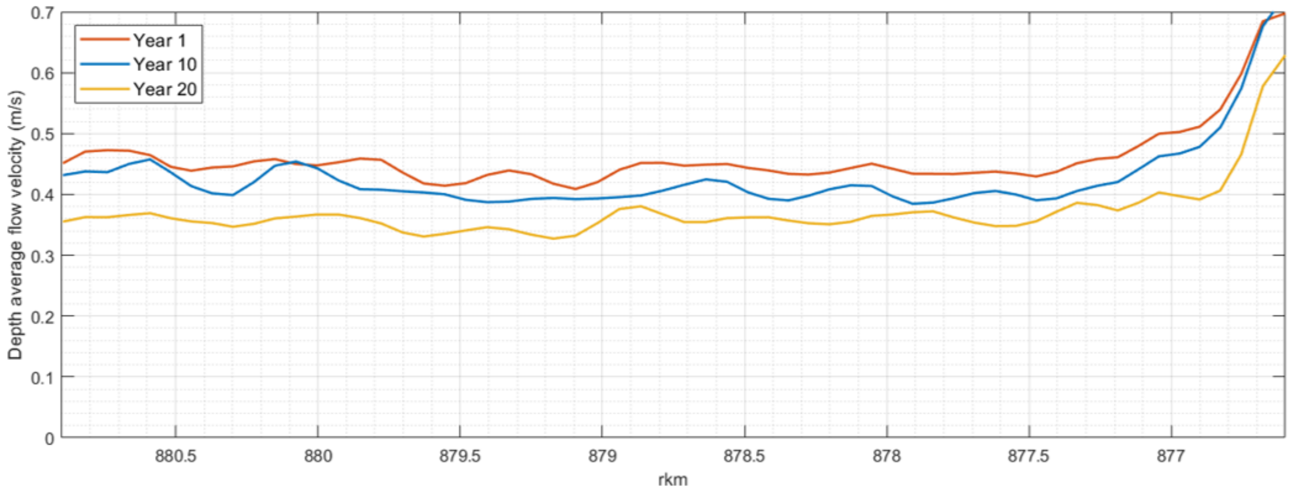

Figure 52: Depth average flow velocities in a riparian channel in the Boven-Waal during a discharge of 1635 m^3/s.

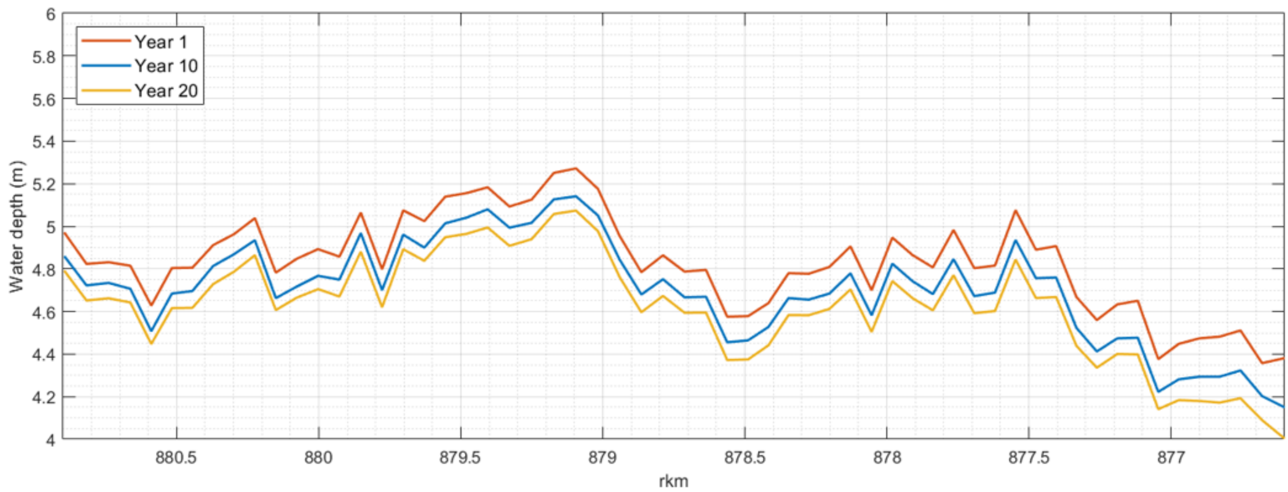

Figure 53: Water depth in a riparian channel in the Boven-Waal during a discharge of 1635 m^3/s.

Figures 54 and 55 show that the riparian channel of the LTD in the Midden-Waal becomes less effective over time. After 10 years of simulation, a reduction in flow velocities of 0.12 m/s and a reduction in water depth of 0.3 m is observed in comparison to the first year of the simulation. This results in a discharge per unit width reduction of 30% after 10 years of simulation. After 20 years of simulation, a reduction in flow velocities of 0.35 m/s and a reduction in water depth of 0.5 m is observed in comparison to the first year of the simulation. This results in a discharge per unit width reduction of 80% after 20 years of simulation.

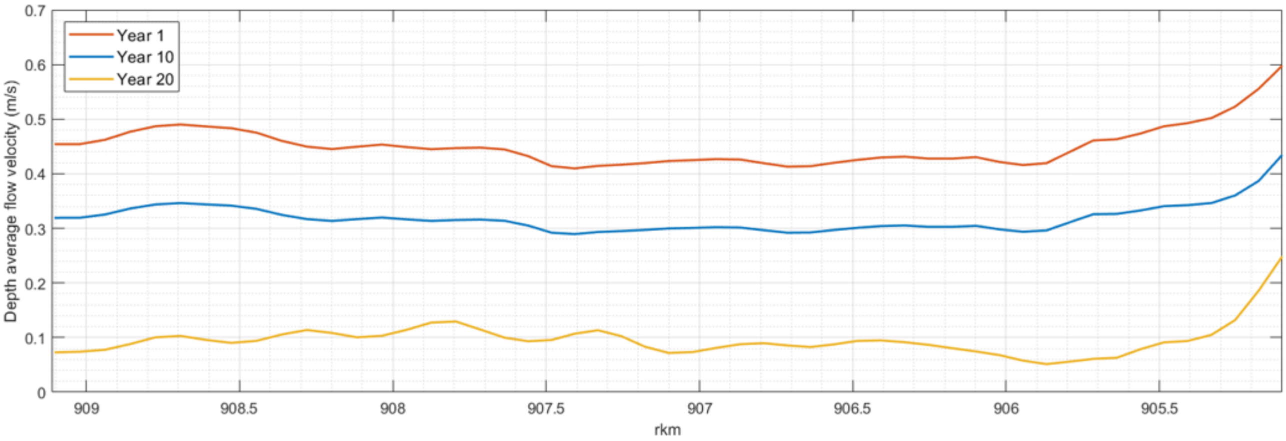

Figure 54: Depth average flow velocities in a riparian channel in the Midden-Waal during a discharge of 1635 m^3/s.

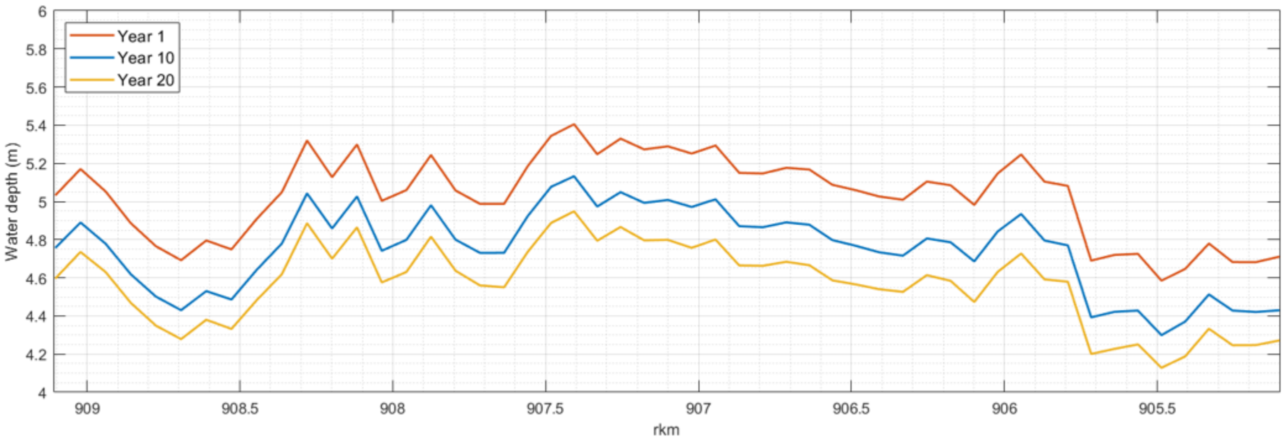

Figure 55: Water depth in a riparian channel in the Midden-Waal during a discharge of 1635 m^3/s.

Over time the riparian channel becomes less effective since the discharge and the depth average flow velocity reduce in the riparian channel, reducing the overall sediment transport in the riparian channel. In the Midden-Waal the effectiveness of the riparian channel reduces more than in the Boven-Waal.

D Discharge scenarios

The yearly repeating hydrograph, used as input for the model, is altered based on the climate scenarios of KNMI'14 (2014). The yearly repeating hydrograph in Figure 56 is based on the historical discharge series of the Rhine at Lobith between 1971 and 2009. Kramer (2016) used time-series of 1901-2015 and moving daily averages of discharges at Lobith of 31 days to project discharge series for two climate change projections (G_l, $W_{H,Dry}$). This method leads to a daily discharge per climate scenario for the whole time series. Kramer (2016) only included the G_l and $W_{H,Dry}$ for 2050 scenarios, thus these scenarios are the only scenarios that are used in this research.

Table 10: Overview of the sequence, discharge level and duration of the steps for the standard hydrograph for morphological studies for RWS (Sloff et al., 2014)

Discharge step	**Discharge at Lobith (m^3/s)**	**Number of days**
1	3053	16
2	3824	8
3	4717	4
4	6151	2
5	8592	2
6	6151	4
7	4717	7
8	3824	12
9	3053	25
10	2250	53
11	1635	70
12	1230	35
13	1020	21
14	1203	23
15	1635	47
16	2250	36
	Total	365

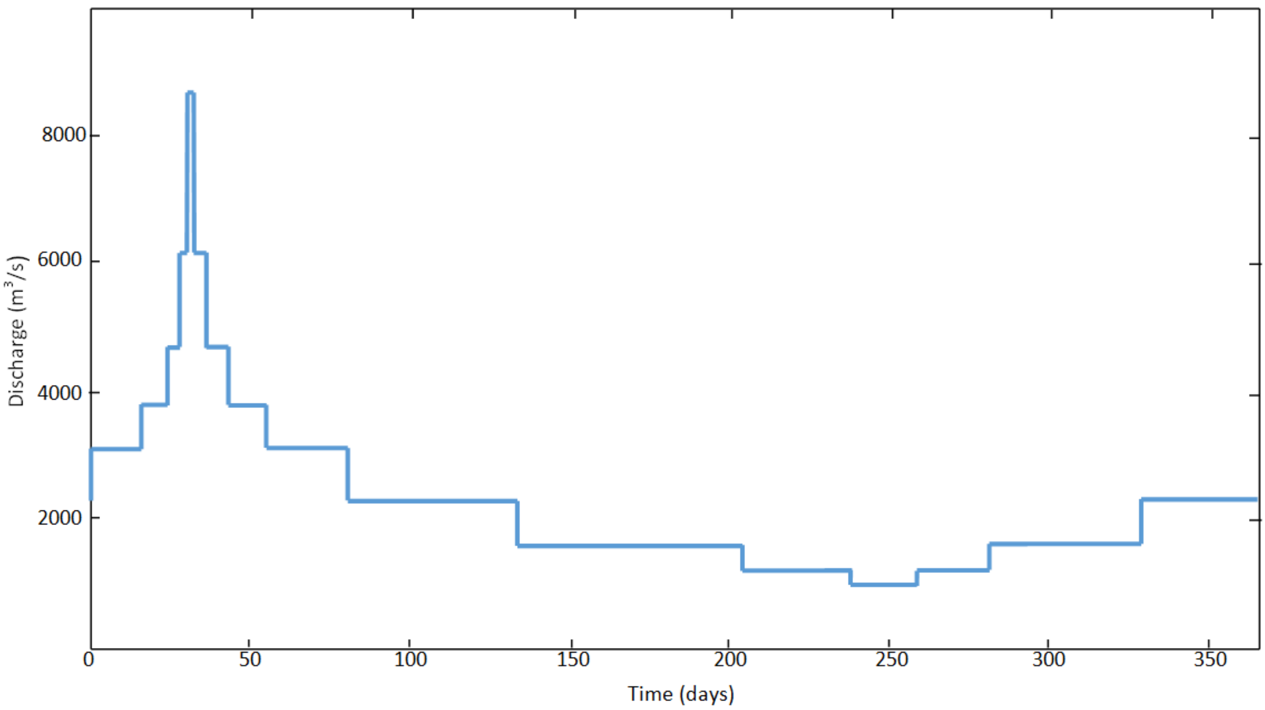

Figure 56: Standard yearly hydrograph used in morphological studies for RWS.

To create a hydrograph from the discharge series, several methods could be used. However, adjusting the standard hydrograph into a hydrograph that represents the climate scenarios is limited to solely adjusting the duration of discharge levels. The height of the discharge levels is not adjusted, since the flow fields for the discharge levels used in the standard hydrograph are part of the model. The essence of the DVR model is that when the discharge level changes towards another value, the model reaches out to the directory of the flow fields to make a quick transition between flow fields. Thus, for discharge levels other than the ones used in the standard hydrograph, the flow fields are unknown. To test which method is the best, the values in the standard hydrograph are compared to values that are calculated using 2 methods. Next to this, 2 methods are applied for two different discharge time series. The first discharge time-series that is used is from the period of 1901 to 2015, which involves the whole dataset. The second discharge time series is from the period of 1971-2009, which is equal to the discharge time series that are used to create the standard hydrograph. To find out which method and which discharge time series to use, the historically measured discharges are used for the selected periods for the two following methods:

Method 1: Discharges of the selected time-series are ranked from large to small. Next, starting from the largest measured discharge, a set of discharges is selected to achieve an average of the set discharge levels as in Figure 56. For example, the average of the largest discharge averaged with discharges until a lower measured discharge needs to average 8592 m^3/s. Afterwards, the largest value outside of the already selected value is the starting point for the second discharge level. This iterative procedure is carried out till all discharge measurements are used and each discharge level is achieved. The amount of discharges per discharge level with respect to the total amount of measured discharges determines the duration of the discharge level per year.

Method 2: Discharges of the selected period are ranked from large to small. Next, the average values between discharge levels are determined. Discharge levels thus have an upper boundary and a lower boundary. Each discharge of the discharge time series that falls within this interval is designated to the corresponding discharge level. For example, the discharge level of 6151 m^3/s has boundaries between discharge level 8151 m^3/s and 4717 m^3/s of 7371.5 m^3/s and 5434 m^3/s. Thus, all discharges in the time series that fall in between 7371.5 m^3/s and 5434 m^3/s are designated to the discharge level of 6151 m^3/s. The amount of discharges that are designated to each discharge level is counted, and the amount of counted discharges per discharge level is compared to the total measured discharges and this determines the number of days per year for this discharge level.

Table 11: Applying method 1 and method 2 using discharge measurements from 1901 until 2050

Discharge level (m3/s)	**Number of days**	**Number of days method 1**	**Absolute difference**	**Difference in %**	**Number of days method 2**	**Absolute difference**	**Difference in %**
8592	2	1,5	0,5	25,0	1,5	0,5	25,0
6151	6	7,5	1,5	25,0	7	1,0	16,7
4717	11	13	2	18,2	12,5	1,5	13,6
3824	20	17,5	2,5	12,5	20	0,0	0,0
3053	41	39,5	1,5	3,7	45,5	4,5	11,0
2250	89	119	30	33,7	99	10,0	11,2
1635	117	94	23	19,7	100	17,0	14,5
1203	58	58	0	0,0	49,5	8,5	14,7
1020	21	15	6	28,57142857	30	9	42,9
			Sum: 67,0	**Mean: 17,5**		**Sum: 52,0**	**Mean: 16,6**

Table 12: Applying method 1 and method 2 using discharge measurements from 1971 until 2009

Discharge level (m3/s)	**Number of days**	**Number of days method 1**	**Absolute difference**	**Difference in %**	**Number of days method 2**	**Absolute difference**	**Difference in %**
8592	2	2	0	0,0	2	0,0	0,0
6151	6	7	1	16,7	7	1,0	16,7
4717	11	14	3	27,3	13	2,0	18,2
3824	20	18,5	1,5	7,5	22	2,0	10,0
3053	41	42	1	2,4	46	5,0	12,2
2250	89	108,5	19,5	21,9	92	3,0	3,4
1635	117	103	14	12,0	103,5	13,5	11,5
1203	58	58	0	0,0	54,5	3,5	6,0
1020	21	12	9	42,85714286	25	4	19,0
			Sum: 49,0	**Mean: 14,5**		**Sum: 34,0**	**Mean: 10,8**

As can be concluded from Table 11 and Table 12, method 2 using the data set of 1971-2009 gives the best results, which means that method 2 using the data set of 1971-2009 will mimic the reference hydrograph the best. Method 2 for the data set of 1971-2009 had the lowest differences in absolute values and percentage numbers in comparison to the reference hydrograph which is shown in Figure 56. Thus, this method and data set are used to calculate the values needed to create the hydrographs for the different climate projections and thus discharge scenarios. The values for the hydrographs for the different climate scenarios can be seen in Table 13.

Table 13: Overview of the sequence, discharge level and curation of the steps for the reference hydrograph and the climate scenarios

Discharge step	**Discharge level**	**Number of days reference scenario**	**Number of days scenario G_l**	**Number of days scenario $W_{H,Dry}$**
1	3053	16	22	15,5
2	3824	8	11	9
3	4717	4	6,5	5,5
4	6151	2	4	3
5	8592	2	5	3
6	6151	4	8	6
7	4717	7	12	9,5
8	3824	12	16	13,5
9	3053	25	34,5	24
10	2250	53	57	41
11	1635	70	56,5	50
12	1203	35	25	38
13	1020	21	14,5	61
14	1203	23	16,5	25
15	1635	47	38	33,5
16	2250	36	38,5	27,5
Total		365	365	365

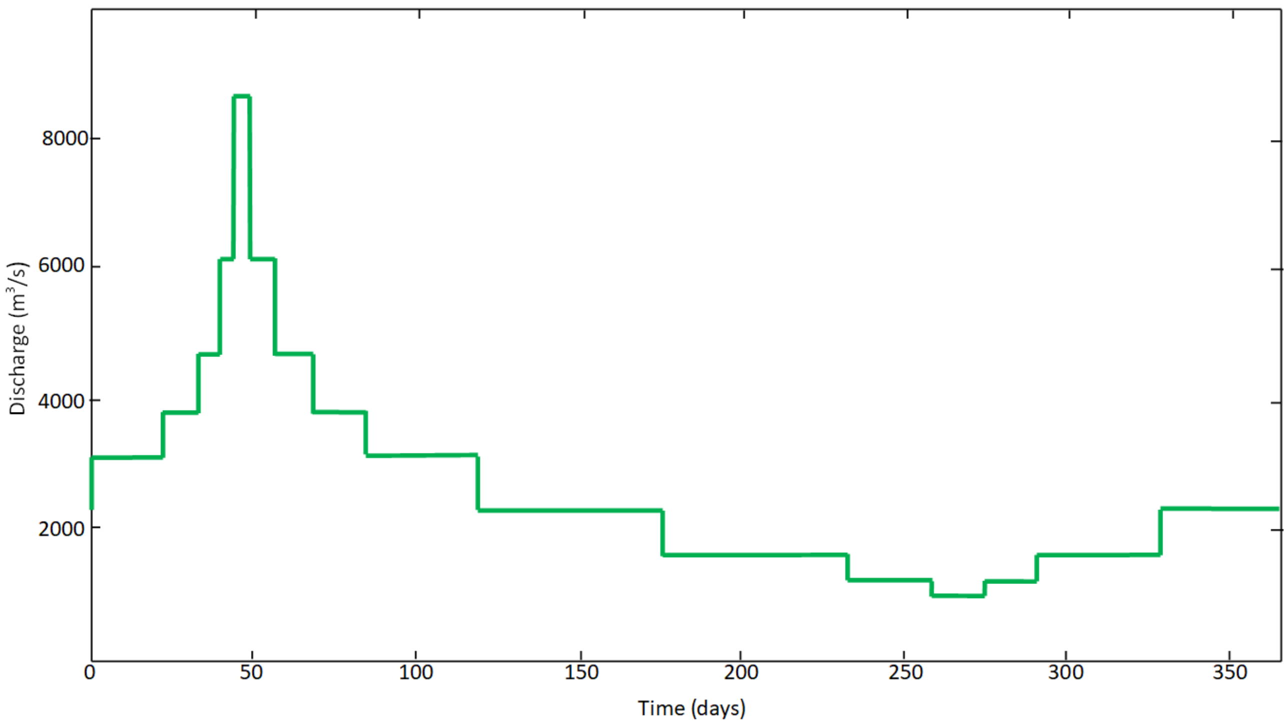

Figure 57: Hydrograph for climate projection G_l.

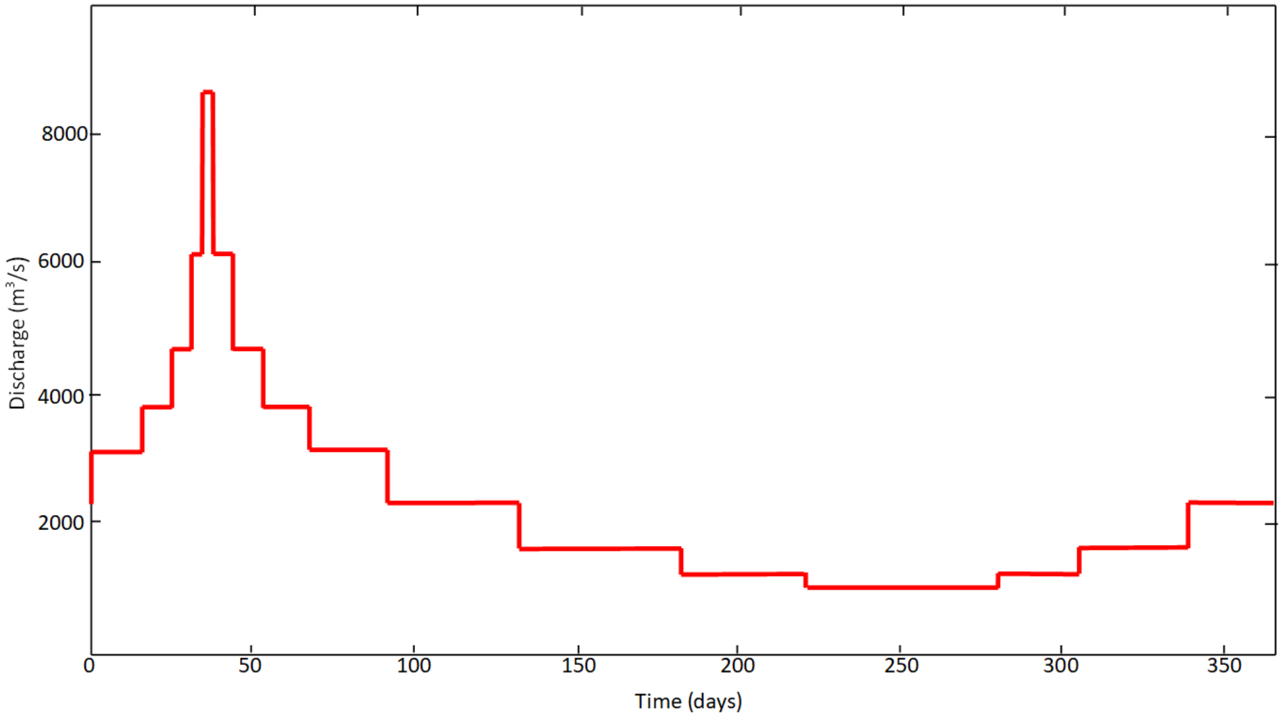

Figure 58: Hydrograph for climate projection $W_{H,Dry}$.

E Domain averaged bed level changes

Table 14: Average change in bed level with respect to the initial situation in the main channel after 10 years of morphological development

	S_{actual}	S_{LTDs}	S_1	S_2	S_3
Boven-Waal	-0.25 m	-0.01 m	0.03 m	-0.04 m	-0.02 m
Midden-Waal	-0.26 m	-0.52 m	-0.59 m	-0.51 m	-0.51 m
Beneden-Waal	0.12 m	0.02 m	0.02 m	0.01 m	0.01 m

Table 15: Average change in bed level with respect to the intial situation, with main channel and riparian channel included, after 10 years of morphological development

	S_{actual}	S_{LTDs}	S_1	S_2	S_3
Boven-Waal	-0.21 m	0.01 m	0.02 m	-0.08 m	0.00 m
Midden-Waal	-0.20 m	-0.23 m	-0.25 m	-0.22 m	-0.23 m
Beneden-Waal	0.12 m	0.02 m	0.02 m	0.01 m	0.01 m

Table 16: Average change in bed level with respect to the initial situation in the main channel after 20 years of morphological development

	S_{actual}	S_{LTDs}	S_1	S_2	S_3
Boven-Waal	-0.44 m	-0.16 m	-0.11 m	-0.20 m	-0.17 m
Midden-Waal	-0.40 m	-0.87 m	-1.04 m	-0.82 m	-0.84 m
Beneden-Waal	0.16 m	-0.10 m	-0.08 m	-0.12 m	-0.12 m

Table 17: Average change in bed level with respect to the initial situation, with main channel and riparian channel included, after 20 years of morphological development

	S_{actual}	S_{LTDs}	S_1	S_2	S_3
Boven-Waal	-0.44 m	-0.06 m	-0.04 m	-0.08 m	-0.07 m
Midden-Waal	-0.40 m	-0.40 m	-0.43 m	-0.37 m	-0.38 m
Beneden-Waal	0.16 m	-0.10 m	-0.08 m	-0.12 m	-0.12 m

Table 18: Average change in bed level with respect to the initial situation in the main channel after 10 years of morphological development for different climate change projections

	S_{actual}	$S_{actual,Gl}$	$S_{actual,WHDry}$	S_1	$S_{1,Gl}$	$S_{1,WHDry}$
Boven-Waal	-0.25 m	-0.25 m	-0.24 m	0.03 m	0.13 m	0.06 m
Midden-Waal	-0.26 m	-0.29 m	-0.26 m	-0.59 m	-0.66 m	-0.58 m
Beneden-Waal	0.12 m	0.04 m	0.08 m	-0.02 m	-0.12 m	-0.04 m

Table 19: Average change in bed level with respect to the initial situation, with main channel and riparian channel included, after 10 years of morphological development for different climate change projections

	S_{actual}	$S_{actual,Gl}$	$S_{actual,WHDry}$	S_1	$S_{1,Gl}$	$S_{1,WHDry}$
Boven-Waal	-0.21 m	-0.21 m	-0.19 m	0.01 m	0.10 m	0.06 m
Midden-Waal	-0.20 m	-0.23 m	-0.20 m	-0.23 m	-0.49 m	-0.42 m
Beneden-Waal	0.12 m	0.04 m	0.08 m	-0.02 m	-0.12 m	-0.04 m

Table 20: Average change in bed level with respect to the initial situation in the main channel after 20 years of morphological development for different climate change projections

	S_{actual}	$S_{actual,Gl}$	$S_{actual,WHDry}$	S_1	$S_{1,Gl}$	$S_{1,WHDry}$
Boven-Waal	-0.44 m	-0.55 m	-0.51 m	-0.16 m	0.00 m	-0.05 m
Midden-Waal	-0.40 m	-0.55 m	-0.49 m	-0.87 m	-1.16 m	-1.04 m
Beneden-Waal	0.16 m	0.01 m	0.11 m	-0.08 m	-0.34 m	-0.19 m

Table 21: Average change in bed level with respect to the initial situation, with main channel and riparian channel included, after 20 years of morphological development for different climate change projections

	S_{actual}	$S_{actual,Gl}$	$S_{actual,WHDry}$	S_1	$S_{1,Gl}$	$S_{1,WHDry}$
Boven-Waal	-0.28 m	-0.45 m	-0.41 m	-0.04 m	0.01 m	-0.02 m
Midden-Waal	-0.25 m	-0.43 m	-0.38 m	-0.43 m	-0.81 m	-0.71 m
Beneden-Waal	0.16 m	0.01 m	0.11 m	-0.08 m	-0.34 m	-0.19 m

F Changes in bed level after 20 years of morphological changes of all simulations

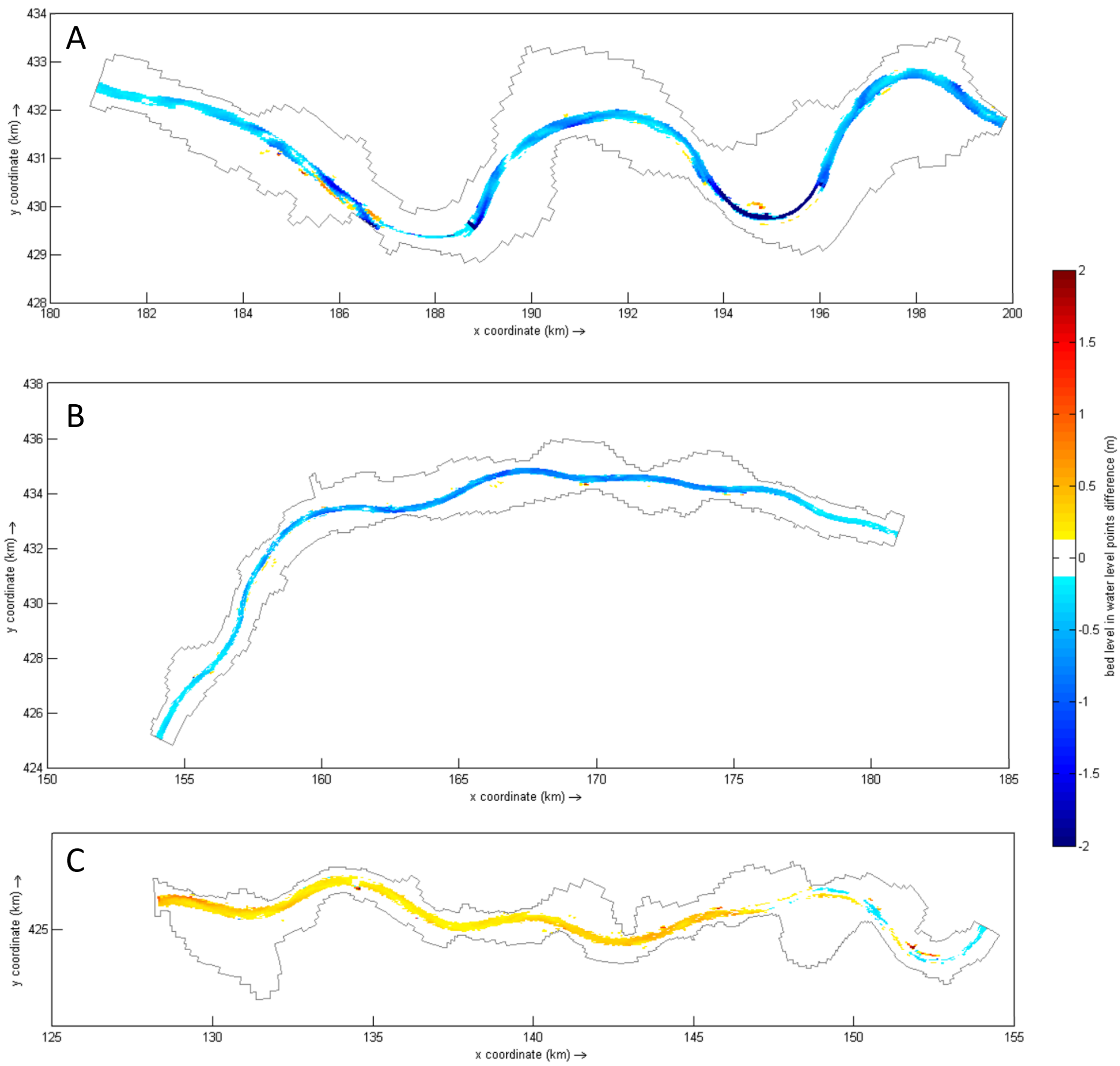

Figure 59: Changes in bed level after 20 years of morphological development in the Boven-Waal (A), Midden-Waal (B) and Beneden-Waal (C) for no taken measures (S_{actual}).

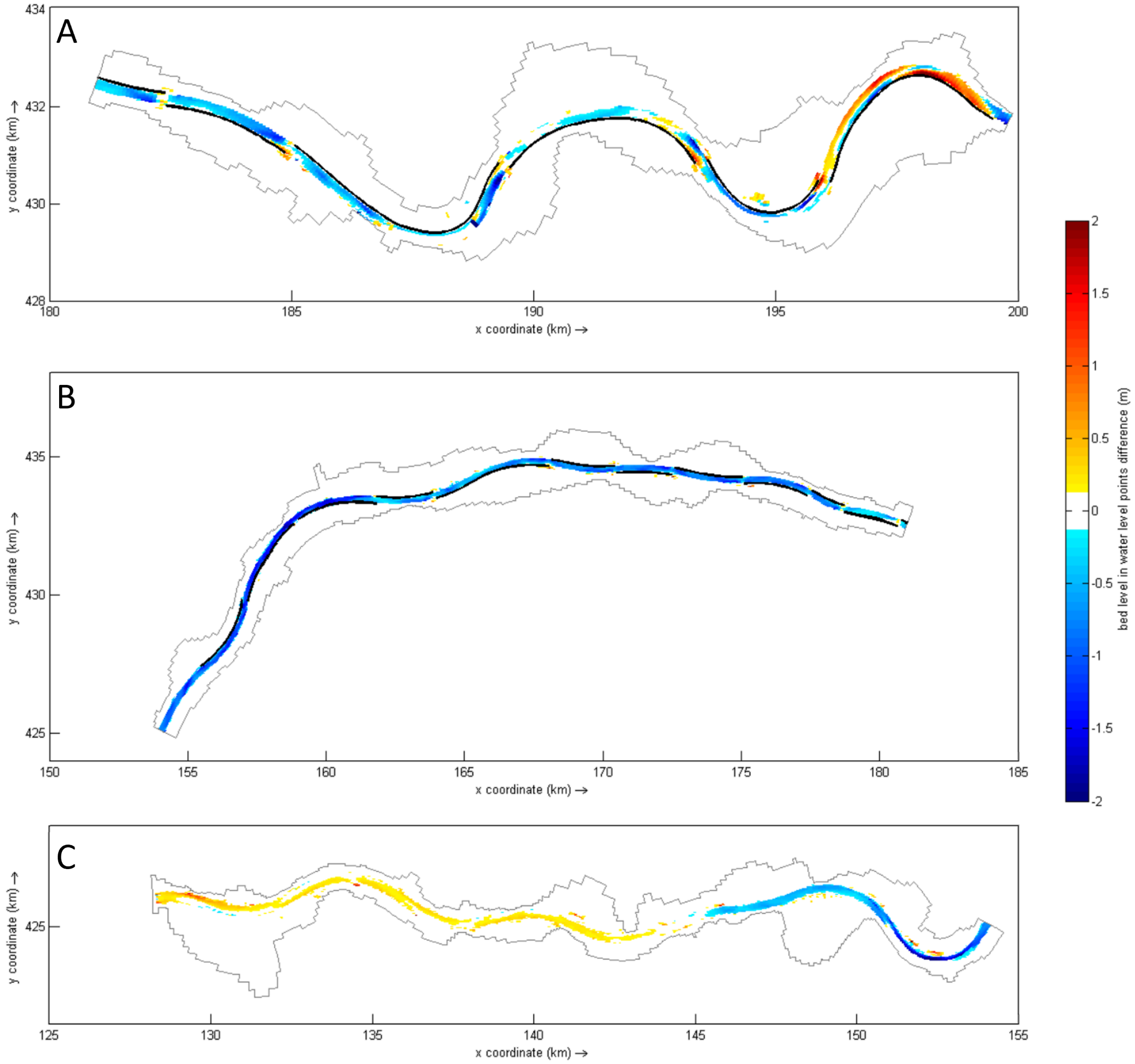

Figure 60: Changes in bed level after 20 years of morphological development in the Boven-Waal (A), Midden-Waal (B) and Beneden-Waal (C) for the reference situation with LTDs (S_{LTDs}) in the Boven-Waal and Midden-Waal.

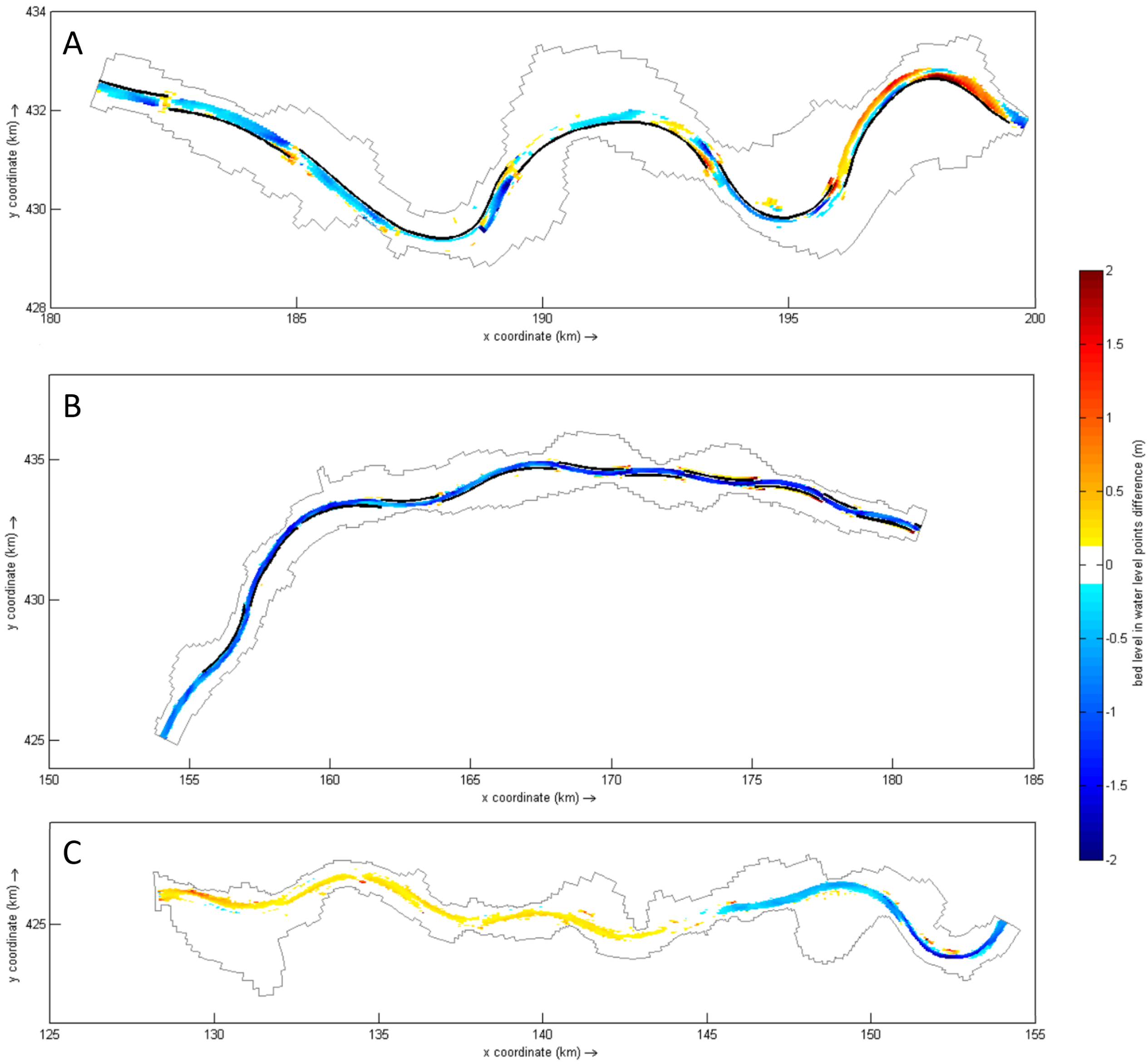

Figure 61: Changes in bed level after 20 years of morphological development in the Boven-Waal (A), Midden-Waal (B) and Beneden-Waal (C) for the simulation with widened riparian channels (S_1) in the Midden-Waal.

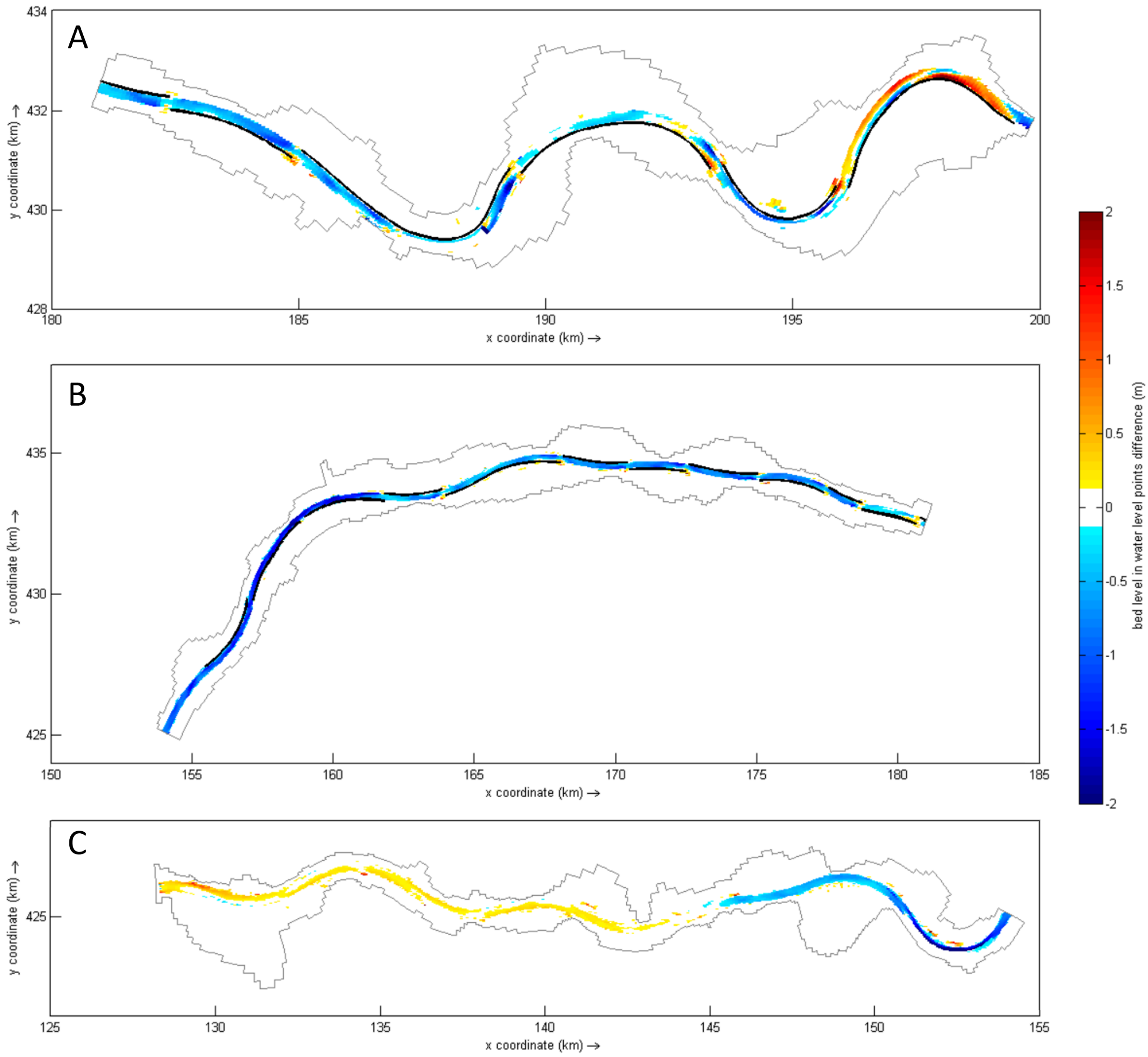

Figure 62: Changes in bed level after 20 years of morphological development in the Boven-Waal (A), Midden-Waal (B) and Beneden-Waal (C) for the simulation with lowered sill heights (S_2) in the Midden-Waal.

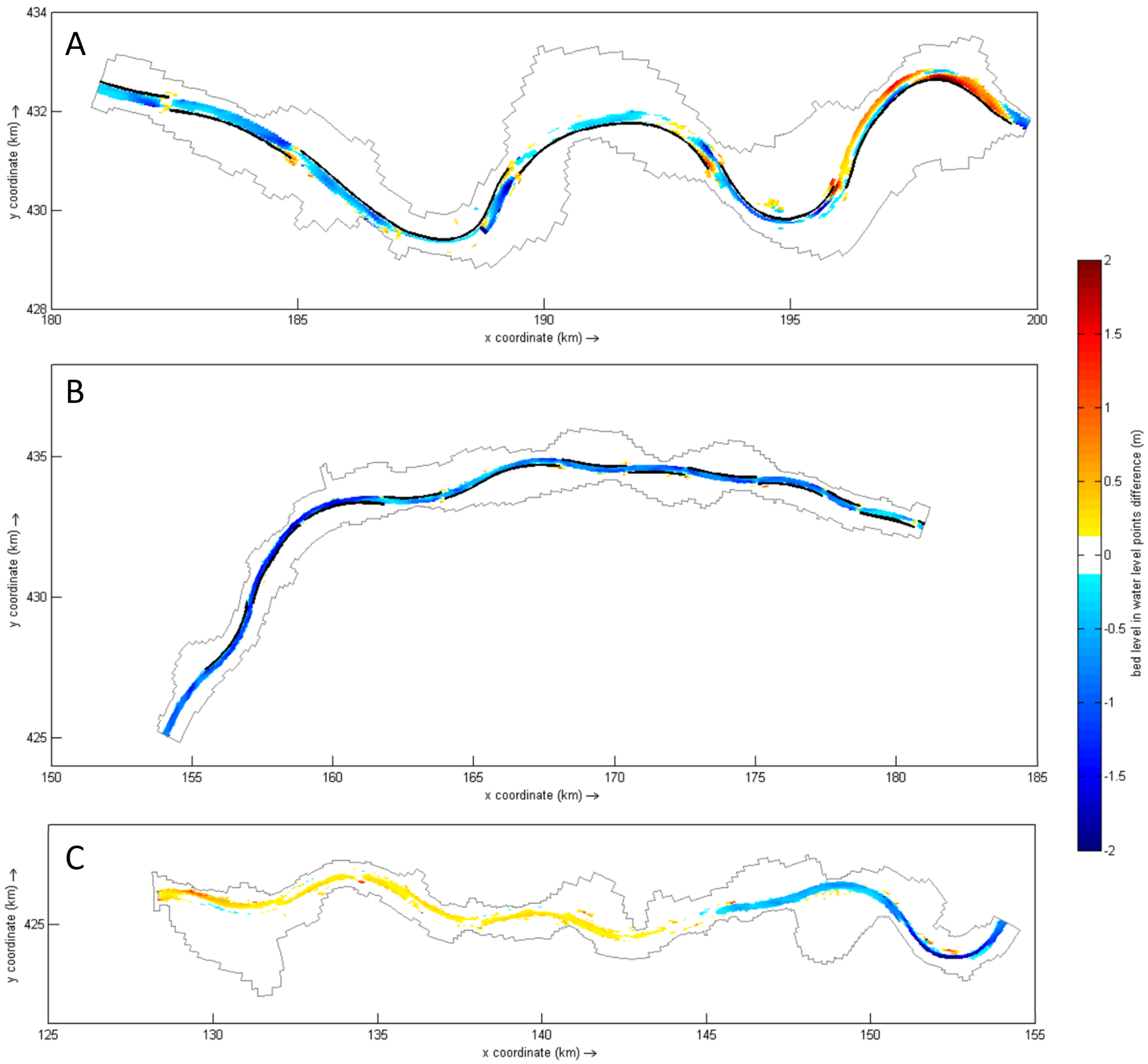

Figure 63: Changes in bed level after 20 years of morphological development in the Boven-Waal (A), Midden-Waal (B) and Beneden-Waal (C) for the simulation with lowered crest heights (S_3) in the Midden-Waal.

G Sufficient local water depth in the Boven-Waal

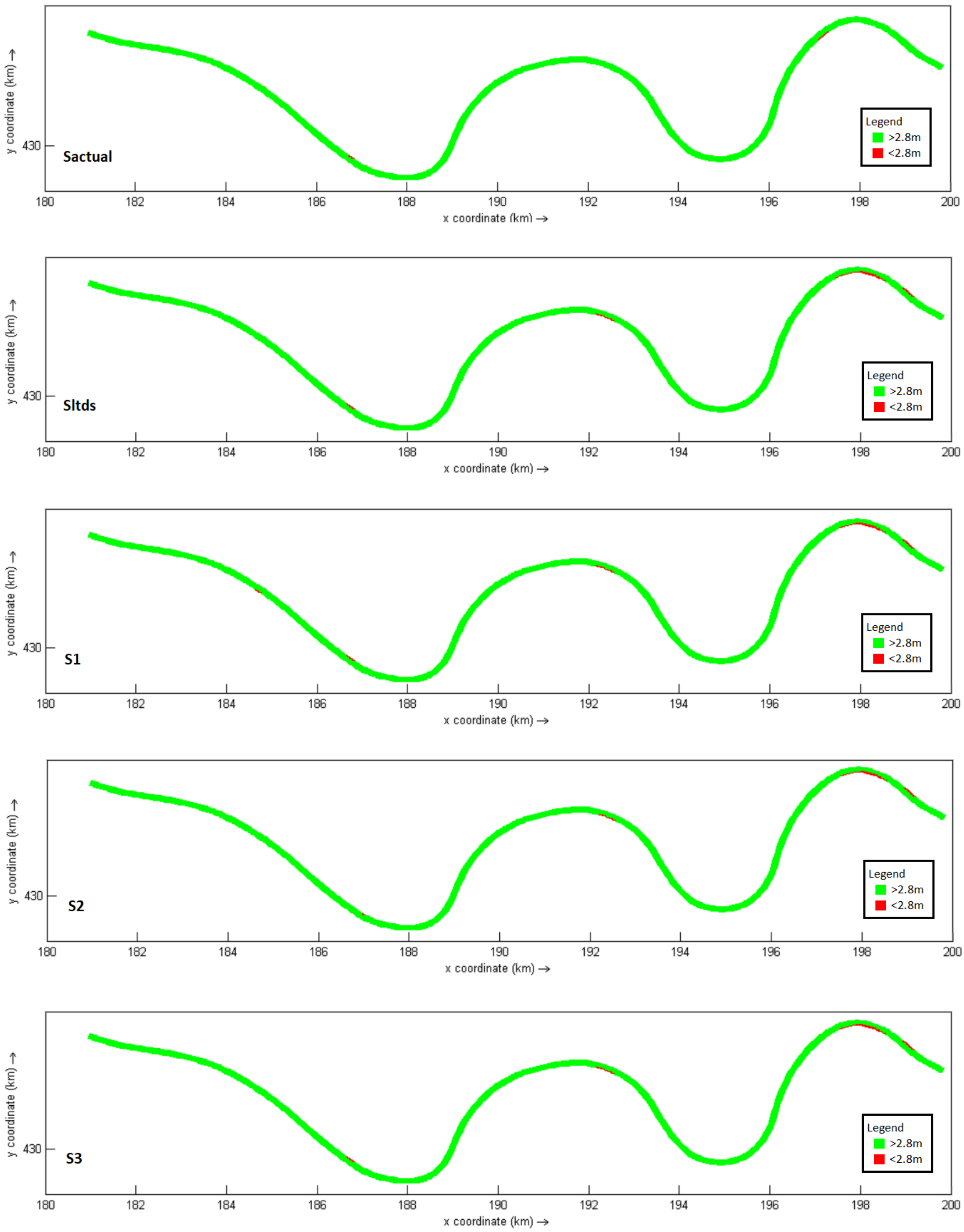

Figure 64: Schematisation of adequate local water depth in the Boven-Waal; green signifies sufficient water depth and red signifies insufficient water depth.

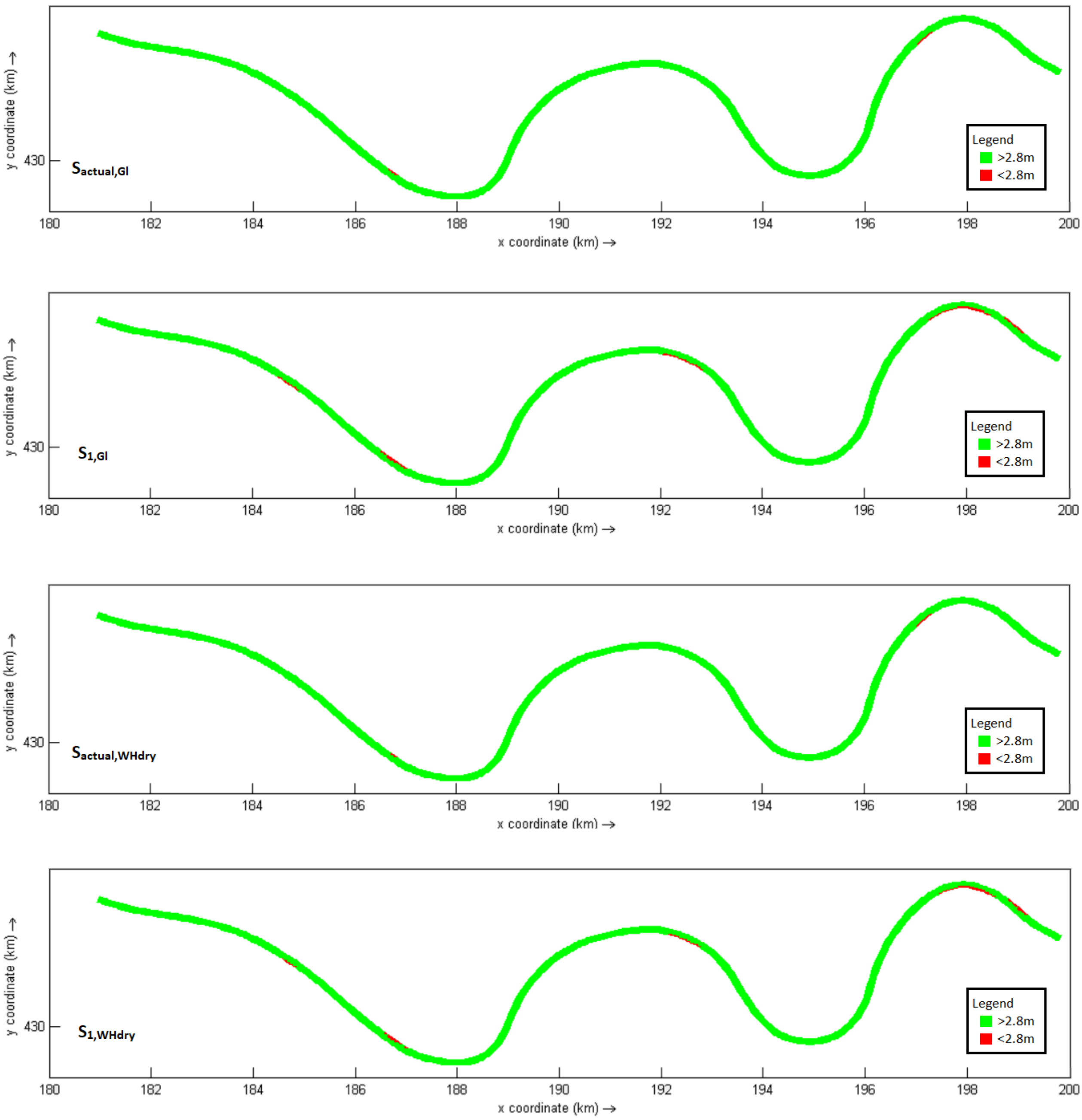

Figure 65: Schematisation of adequate local water depth in the Boven-Waal after 20 years of morphological development, green signifies sufficient water depth and red signifies insufficient water depth.