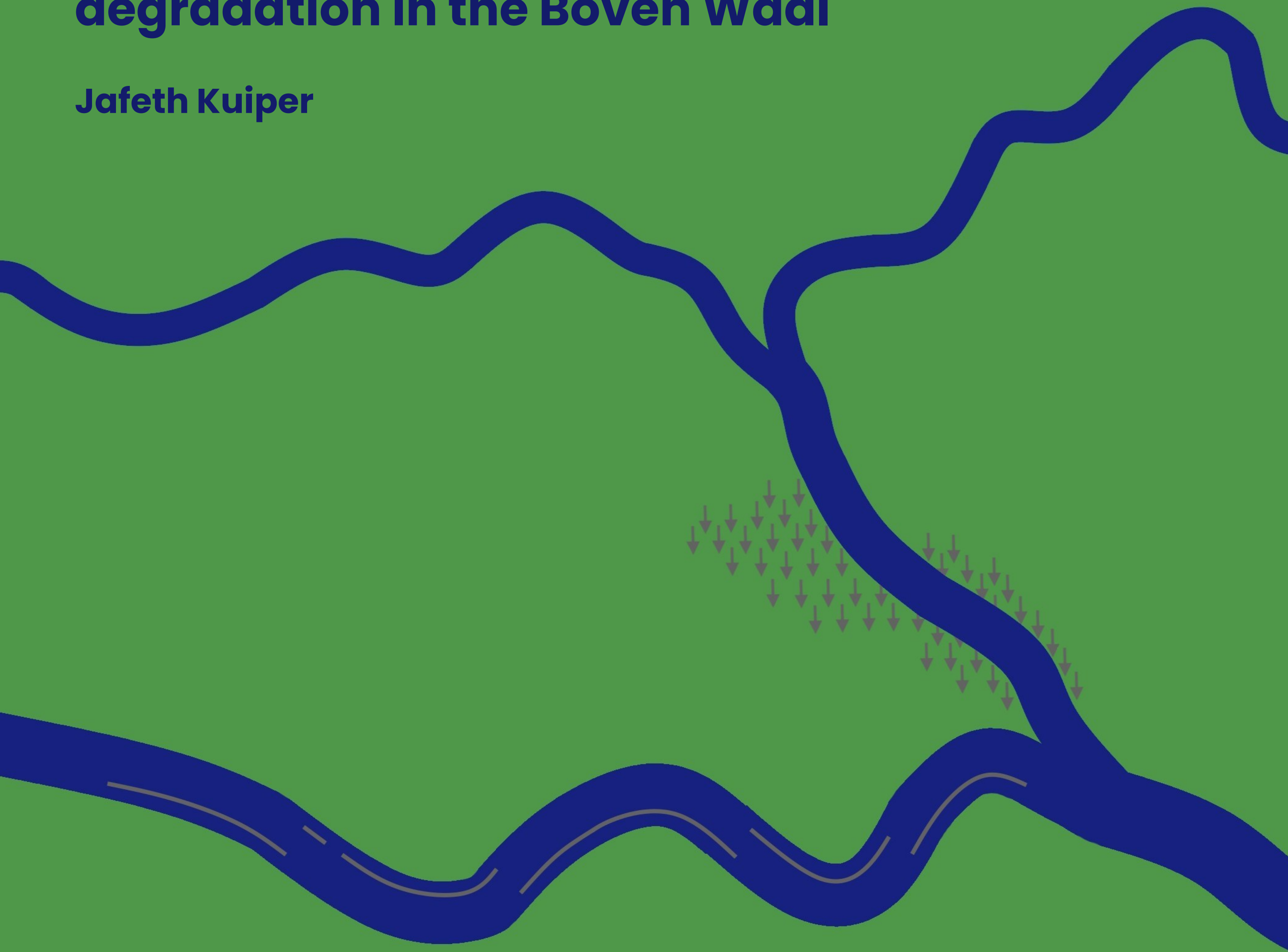
2D modelling of river interventions in the Boven Waal and Pannerdensch Kanaal to restore the low discharge distribution and reduce bed degradation in the Boven Waal

Jafeth Kuiper



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2D modelling of river interventions in the Boven Waal and Pannerdensch Kanaal to restore the low discharge distribution and reduce bed degradation in the Boven Waal.

Master thesis

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Preface

Before you lies my thesis, written as the final part of the Master's program in Civil Engineering & Management at the University of Twente. This thesis marks the end of my academic journey and was developed during my graduation internship at Sweco from March to October 2024.

I am grateful for the guidance and support of several individuals who contributed to this report. First, I would like to thank my daily supervisor at Sweco, Birgit de Lange, for her guidance and useful insights throughout the process. As a sparring partner, we shared a pleasant and informal relationship, and she was always approachable. She helped me stay positive when things became overwhelming, yet also encouraged me to stay critical, often challenging me to take my reasoning one step further. She consistently reminded me of the importance of keeping the bigger picture in mind in relation to my research.

I would also like to thank Roel Velner for his contribution as a supervisor at Sweco and the nice insights and ideas he provided. I am especially grateful for his perseverance in finding powerful computers for my simulations, which eventually led me to Svasek. Additionally, I would like to thank my colleagues at Sweco for the enjoyable time I had working with them.

Furthermore, I would like to express my gratitude to my supervisors at the University of Twente. In particular, Vasileios Kitsikoudis, who served as my daily supervisor. Thank you for your guidance and valuable insights. From our meetings, I learned a great deal about morphology and sediment transport. He was flexible, kind, and provided optimism and clarity when I felt a bit lost. I would also like to thank Denie Augustijn for overseeing the graduation process and ensuring everything progressed smoothly. I want to thank both of them for encouraging me to find a balance between being critical of the model and trusting it, as it is the best tool available.

Moreover, I want to extend my thanks to Saskia van Vuren from Rijkswaterstaat. I really appreciate the nice contact we had, through which she shared valuable insights and provided useful information from her extensive knowledge of the Dutch water system and the Integral River Management programme. Her contribution greatly increased the practical relevance of my study by highlighting the pressing questions in the field related to my topic.

I would also like to express my gratitude to Svasek, particularly to Sam Bom and Bas van Leeuwen, for their assistance. They enabled me to run multiple simulations simultaneously on Svasek's powerful computing systems, which was essential to the success of this thesis. I also appreciate their encouragement to conduct hydraulic simulations before proceeding with morphological ones.

I am also grateful for the support of my friends and family, whose motivation and encouragement helped me stay positive during challenging times. Furthermore, I want to thank the colleagues and external experts in the field who are not explicitly mentioned here but provided assistance and answered my questions throughout the process.

I hope this thesis contributes to finding an approach to restore the low discharge distribution and halt bed degradation in the Waal.

I wish you an enjoyable reading experience.

Jafeth Kuiper
Enschede, October 2024

Summary

Over the past century, bed degradation in the Rhine branches has resulted in an average lowering of the riverbed by 1 to 2 meters, leading to numerous problems across various river functions. Groundwater levels near the river decrease, the stability of structures, cables, and pipelines on the riverbed weakens, and navigation is affected due to varying degradation rates along the river. Additionally, the unequal rates of bed degradation between various Rhine branches have altered and continue to alter the discharge distribution at the bifurcations. The most severe degradation occurs in the Boven Waal, which has resulted in a gradual increase in the discharge partitioning to the Waal over time. This is particularly problematic during low flows, as the required low discharge partitioning to the Pannerdensch Kanaal is currently not being met. This is critical, as the Pannerdensch Kanaal is a key supplier of freshwater to the North(-West) and East of the Netherlands.

Within the Integrated River Management (IRM) programme of Dutch local and national governments, they aim to develop an approach that can both stop degradation in the Boven Waal and restore the low discharge distribution. Bed degradation can be mitigated by reducing the erosivity of the river flow. One promising intervention is the Multiple Channel Approach (in Dutch: meerstroomgeulenconcept), which aims to reduce flow erosivity by creating more space for the river through additional channels. An example of this approach is the use of Longitudinal Training Dams (LTDs). A significant additional benefit of LTDs is their potential to increase the low discharge partitioning to the Pannerdensch Kanaal by narrowing the main channel of the Boven Waal during low flows.

A downside of the LTDs is that by increasing the riverbed capacity during moderate and high discharges, they draw additional discharge to the Waal. This increases both the flow's erosivity and prevents the prescribed discharge partitioning during the design Lobith discharge (in Dutch: "hoogwaterreferentie") from being met, posing a threat to flood safety. This suggests the need for a compensating measure in the Pannerdensch Kanaal when using LTDs.

This study aims to contribute to developing an approach to restore the low discharge distribution and stop bed degradation in the Boven Waal. This is done by investigating interventions designed to simultaneously increase low discharge partitioning to the Pannerdensch Kanaal and reduce bed degradation in the Boven Waal. The following research question is addressed:

"How can varying interventions in the Boven Waal and Pannerdensch Kanaal be used to increase low discharge partitioning to the Pannerdensch Kanaal and reduce the bed degradation in the Boven Waal?"

The study uses the new version of the 2D Delft3D-4 "Duurzame Vaardiepte Rijntakken" (DVR) model, released in April 2024, to simulate the effect of the proposed interventions. The interventions are designed using a systematic approach. First, LTDs are implemented in the Boven Waal. Their configuration is adjusted based on hydraulic simulations to significantly increase the low discharge partitioning to the Pannerdensch Kanaal. Subsequently, the size of the associated riparian channels is adjusted such that the LTDs significantly reduce main channel flow velocities during moderate to high discharges. The effects are then analyzed through morphological simulations. Finally, summerdike removal and floodplain lowering are implemented in the Pannerdensch Kanaal to compensate for the additional discharge drawn to the Waal as a result of the LTDs. The required level of floodplain lowering is first determined using hydraulic simulations, followed by morphological simulations to assess the effect on bed degradation.

It is found that the proposed LTDs significantly increase the initial discharge partitioning to the Pannerdensch Kanaal by 24 to 42 m^3/s during low Lobith discharges ranging from 1020 to 1543 m^3/s. Despite a decrease over time, there is still a notably higher low discharge partitioning to the Pannerdensch Kanaal after a 20-year period compared to the initial observations in the Reference Scenario (+15 to 30 m^3/s). This increase is achieved through a main channel width reduction in the Boven Waal of approximately 65 meters, decreasing the width from 260 meters to 195 meters. The implementation of the proposed LTDs thus leads to considerable progress toward achieving the required low discharge partitioning; the required discharge partitioning to the Pannerdensch Kanaal at a Lobith discharge of 1543 m^3/s is now even met. However, the findings indicate that this main channel width reduction remains insufficient to fully achieve the required low discharge partitioning during Lobith discharges below 1543 m^3/s. Furthermore, there is no room to further reduce the main channel width of the Boven Waal, as the proposed remaining channel width (195 m) already falls below the required width for navigation (230 m).

Additionally, it is found that the proposed LTDs significantly reduce bed degradation in the Boven Waal. This is mainly due to their high effectiveness throughout the moderate to high Lobith discharges (1954 to 7009 m^3/s), during which they cumulatively result in significant reach-averaged sedimentation due to the widening of the main channel. This constitutes a significant step toward stopping bed degradation in the Boven Waal. However, significant bed degradation still occurs because this positive effect is counteracted by several negative effects, predominantly caused by the substantial reduction in the main channel width. This reduction leads to low discharges becoming highly erosive, effectively shifting the erosion problem from moderate to high discharges to low discharges in the Boven Waal. Additionally, severe localized erosion occurs at the transitions between LTDs, where the extreme narrowing due to channel width reductions on both sides leads to the development of significant erosion pits. Therefore, the study indicates that using LTDs for increasing low discharge partitioning to the Pannerdensch Kanaal reduces their effectiveness in reducing bed degradation in the Boven Waal.

The results demonstrate that summerdike removal and floodplain lowering in the Pannerdensch Kanaal cannot simultaneously compensate for the additional discharge drawn to the Waal due to the LTDs across all moderate to extreme discharge levels. Compensating for the changes in discharge partitioning during moderate to high discharges requires very extreme floodplain lowering of 2 to 3 meters. The findings reveal that these interventions are not effective in reducing bed degradation in the Boven Waal, while they do result in a significant increase in erosion in the upstream sections of the Nederrijn and IJssel. On the other hand, the intervention in the Pannerdensch Kanaal, which includes a 0.5 meter floodplain lowering, effectively compensates during a design Lobith discharge of 16,000 m^3/s. Furthermore, this intervention has minimal negative effects on bed degradation in downstream reaches, making it an effective measure in maintaining flood safety when implementing LTDs.

In conclusion, the proposed LTDs lead to substantial improvements toward restoring the low discharge distribution and stopping the bed degradation in the Boven Waal during moderate to high discharges. Therefore, LTDs have the potential to play a significant role in the approach to achieve these objectives. However, the extent of main channel width reduction caused by the proposed LTDs is not optimal, as it introduces substantial erosion during low discharges and does not satisfy navigational requirements. For this reason, recommendations are made to further improve the LTD design and integrate it with other river interventions to guide further research in identifying an effective approach to restore the low discharge distribution and stop bed degradation in the Boven Waal.

Contents

1 Introduction

Over the past century, bed degradation in the Dutch Rhine branches has led to an average lowering of the riverbed by 1 to 2 meters (Klijn et al., 2022). Measurements of bed elevation taken along the Boven Rijn and Waal, illustrated in Figure 1.1, clearly demonstrate the large-scale degradation of the riverbed. The process of bed degradation still continues, though at a decreasing pace, and will remain a persistent issue, worsened by the influence of climate change (Klijn et al., 2022; Ylla Arbós et al., 2023)

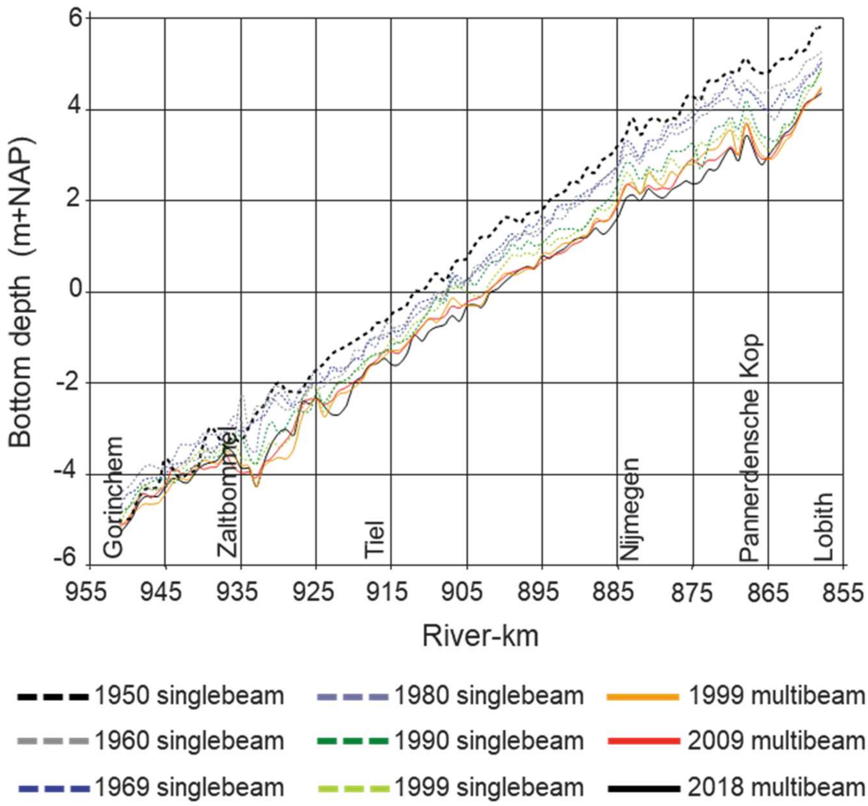

Figure 1.1: Width-averaged bed elevation as measured in the Boven Rijn and Waal between 1950 and 2018. Adapted from Barneveld et al. (2021)

The bed degradation in the Dutch Rhine branches has led to numerous problems across various river functions. It poses a threat to the stability of structures such as dams, locks, and groynes, while also reducing the ground cover over cables and pipelines that cross the river (Blom, 2016; Klijn et al., 2022). Furthermore, the lowering of the riverbed results in decreased water levels, subsequently leading to a decline in groundwater levels. This decline negatively impacts both the ecology and agriculture in the vicinity of the river.

Navigation is another river function significantly affected by bed degradation. The bed degradation exhibits a spatially non-uniform pattern, due to which certain sections of the river experience faster erosion rates than others (Klijn et al., 2022). This variability leads to the formation of local shallows, thereby creating navigational depth issues (Barneveld et al., 2021). Such problems particularly occur in areas where fixed layers have been implemented to mitigate severe erosion in outer bends, such as the fixed layers in the Waal near Nijmegen and the bed groynes near Erlecom (Klijn et al., 2022). These fixed layers remain static while the surrounding bed erodes, making them obstacles to ships.

An important issue related to bed degradation is that it occurs at varying rates among the Rhine branches, which impacts the distribution of discharge at bifurcation points (Blom, 2016; Klijn et al., 2022). The most pronounced bed degradation is observed in the Boven Waal (Sloff, 2019), leading to a gradual increase in discharge partitioning to the Waal at the Pannerdensch bifurcation. This trend is illustrated in Figure 1.2a, which demonstrates that the measured ratio of discharge partitioning to the Waal relative to the discharge at Lobith has been increasing over time (Chowdhury et al., 2023). At the same time, this results in a decrease in discharge to the Pannerdensch Kanaal. This poses a threat to flood safety, as the dikes are designed based on a prescribed discharge partitioning for a Lobith design discharge of 16,000 m^3/s (5835 m^3/s to Pannerdensch Kanaal and 10165 m^3/s to the Waal) (Schropp and Jansen, 2020). Additionally, the decreased partitioning to the Pannerdensh Kanaal makes it increasingly challenging to maintain sufficient freshwater supply to the North(-West) and East of the Netherlands during low flows, as the Pannerdensch Kanaal is a key supplier of freshwater to these regions (Barneveld et al., 2021).

The minimum required discharge partitioning to the Pannerdensch Kanaal, essential for maintaining sufficient freshwater supply, is currently not met for Lobith discharges below 1570 m^3/s. This is illustrated by Figure 1.2b in which the measured discharge of 2024 (solid black line) falls below the minimum required discharge (dashed black line) for Lobith discharges below 1570 m^3/s. According to policy guidelines, for Lobith discharges exceeding 1300 m^3/s, at least 285 m^3/s should be partitioned to the IJssel and 30 m^3/s to the Nederrijn, resulting in a required partitioning of 315 m^3/s to the Pannerdensch Kanaal (Klijn et al., 2022). For Lobith discharges under 1300 m^3/s, no specific partitioning is prescribed. Therefore, this study assumes that for these discharges the same percentage of Lobith discharge should be allocated to the IJssel as for a Lobith discharge of 1300 m^3/s, which is 22%. Including the required 30 m^3/s for the Nederrijn, this results in the required discharge partitioning to the Pannerdensch Kanaal, as illustrated by the dashed black line in Figure 1.2b. The current low discharge partitioning to the Pannerdensch Kanaal needs to increase to meet these standards. For instance, at a Lobith discharge of 1294 m^3/s, an additional 63 m^3/s is needed to achieve the required discharge partitioning to the Pannerdensch Kanaal.

There are three main causes for the bed degradation in the Dutch Rhine branches. The primary cause has been the extensive Rhine training works implemented since the 17th century. These interventions, aimed at improving flood safety and navigability, have resulted in a narrower and shorter river channel. As a consequence, flow velocities have been increased, which in turn increase sediment transport capacities, ultimately leading to bed degradation (Blom, 2016; Ylla Arbós et al., 2021; Klijn et al., 2022; Sloff et al., 2023). The mining of large volumes of sand and gravel from the river bed, alongside intensive dredging operations to improve navigability, has significantly accelerated the bed degradation process (Blom, 2016; Klijn et al., 2022). The third cause of the bed degradation in the Dutch Rhine branches is the reduced sediment supply from the German section of the Rhine (Blom, 2016; Klijn et al., 2022). The canalization of the Oberrhein through weir construction has led to sediment being trapped, resulting in reduced sediment transport to downstream river sections (Klijn et al., 2022). As a result, the flow in the Dutch section of the Rhine is able to pick up more sediment, exacerbating bed degradation.

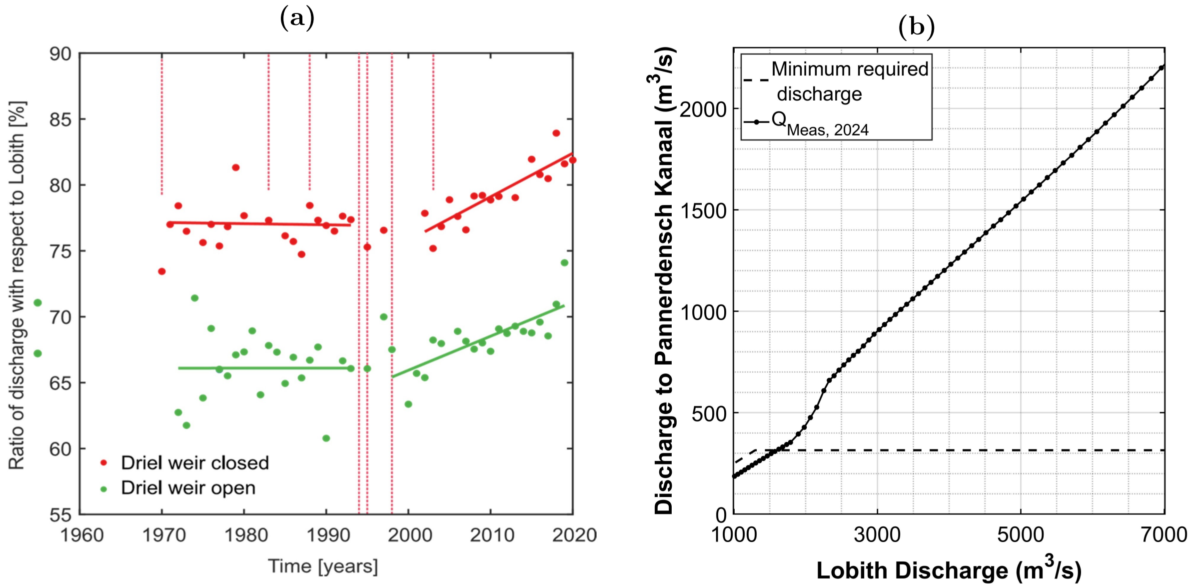

Figure 1.2: (a) Ratio of Waal with respect to Lobith discharge as a function of time, based on measured discharges (Chowdhury et al., 2023). (b) Measured discharge partitioning to the Pannerdensch Kanaal in 2024. The black dashed line represents the required minimum discharge partitioning to the Pannerdensch Kanaal.

Within the Integrated River Management (IRM) program, they aim to develop a strategy that both stops bed degradation in the Boven Waal-where the most severe bed degradation occurs-and restores the low discharge distribution such that it meets the required discharge partitioning to the Pannerdensch Kanaal. This program, initiated in 2019 by local and national governments, aims to enhance the resilience of the Dutch river area to future changes, including those resulting from bed degradation (Klijn et al., 2022; Sloff et al., 2023; Programma Integraal Riviermanagement, 2023). A crucial aspect of this program is its integrated approach in enhancing the different river functions, considering the river system holistically, rather than through isolated sectoral approaches.

Bed degradation can be mitigated by reducing the erosivity of the river flow. One promising intervention is the Multiple Channel Approach (in Dutch: "meerstroomgeulenconcept"), which aims to reduce flow erosivity by creating more space for the river through additional channels. An example of this approach is the implementation of Longitudinal Training Dams (LTDs), as shown in Figure 1.3, which can be constructed using cobble stones or designed in a more nature-friendly manner. They widen the main channel during moderate to high discharges by the implementation of riparian channels. An additional benefit of LTDs is their potential to increase the low discharge partitioning to the Pannerdensch Kanaal by narrowing the main channel of the Boven Waal during low flows.

A downside of LTDs is that by increasing the riverbed capacity during moderate and high discharges, they draw additional discharge to the Waal. This increases both the flow's erosivity and prevents the prescribed discharge partitioning during a design Lobith discharge of 16,000 m^3/s from being met, posing a threat to flood safety. This suggests the need for a compensating measure in the Pannerdensch Kanaal when using LTDs.

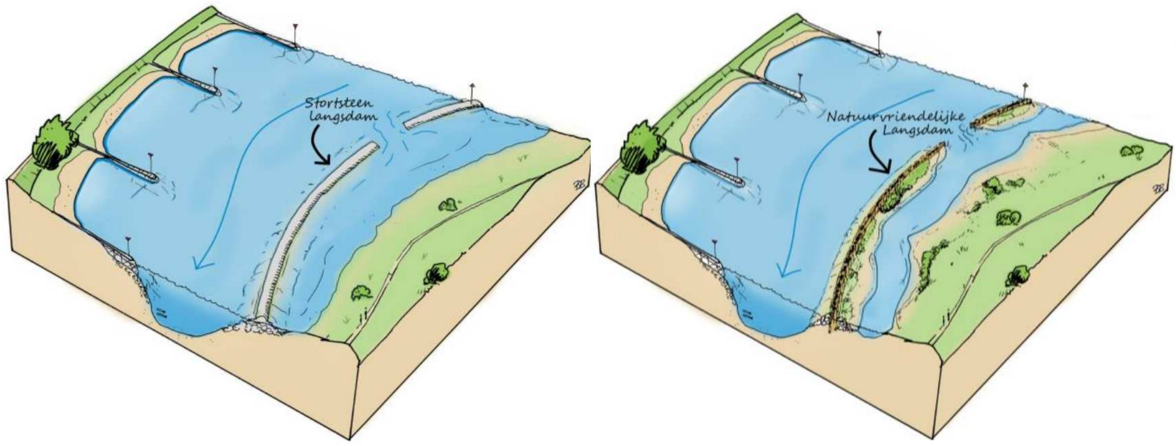

Figure 1.3: Illustration of applications of the Multiple Channel Approach: Longitudinal Training Dams (LTDs) with a cobblestone design on the left and a more nature-friendly design on the right. Adapted from Ouwerkerk et al. (2023)

An important complexity regarding the effects of interventions in the Boven Waal and Pannerdensch Kanaal is their proximity to the Pannerdensch bifurcation. The effects of interventions on morphological development are more complex in bifurcating river systems than in single river channels (Gao et al., 2024). The morphological response to disturbances in one channel-such as changes in river discharges, embankment construction, and dredging activities-can lead to significant morphological responses across all branches of the bifurcating channel network (Van Maren et al., 2023; Chowdhury et al., 2023; Gao et al., 2024). For instance, when a disturbance, such as channel deepening due to dredging and sand mining, increases discharge to the affected branch, this is found to result into sedimentation in the adjacent branch by Gao et al. (2024). Therefore, gaining a better understanding of how interventions in both Rhine branches influence each other is crucial for effective management and intervention planning.

1.1 Problem statement

The bed degradation in the Dutch Rhine branches requires action, especially since the effects of bed degradation become increasingly evident (Klijn et al., 2022). Additionally, if no action is taken, bed degradation in the Dutch Rhine branches could potentially lower the riverbed by an additional meter by the year 2100, partly due to the increasing influence of climate change (Ylla Arbós et al., 2023).

Two pressing issues are the substantial bed degradation occurring in the Boven Waal and the low discharge distribution that fails to meet the minimum required partitioning to the Pannerdensch Kanaal. It is essential to implement interventions that reduce bed degradation in the Boven Waal and increase low discharge partitioning to the Pannerdensch Kanaal.

Numerous studies have explored the effects of various interventions on the bed degradation of the Rhine branches, including side channels (Rorink, 2022; Ten Brink, 2024; Welsch, 2021), sediment nourishments (Becker, 2021; De Lange, 2022; Liptiay, 2023), groyne lowering (Ten Brink, 2024) and LTDs (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024). While these interventions have been shown to significantly reduce bed degradation, they have not been able to fully stop it. Several studies suggest that a combination of interventions is required to achieve this goal. Ten Brink (2024) investigated the combined use of LTDs, side channels, and groyne lowering in the Boven Waal. Although this combination made considerable progress towards stopping bed degradation, it still exacerbated bed degradation in the downstream section of the Boven Waal. The aforementioned studies are discussed in greater detail in the theoretical background (Section 2.1).

Previous studies on interventions in the Dutch Rhine branches have mainly focused on mitigating bed degradation, with less emphasis on addressing the issue of the low discharge distribution. As a result, their impact on increasing the low discharge partitioning to the Pannerdensch Kanaal has been relatively modest. For instance, proposed LTDs are estimated to increase low discharge partitioning by only about 7 m^3/s (Sloff et al., 2024), while sediment nourishments in studies by Becker (2021) and Liptiay (2023) have shown increases of 3-4 m^3/s and 5-10 m^3/s, respectively. These improvements, however, fall significantly short of the required increase in low discharge partitioning to the Pannerdensch Kanaal, which is around 63 m^3/s for a Lobith discharge of 1294 m^3/s.

There is a knowledge gap regarding which interventions are needed to both restore the low discharge distribution and stop bed degradation in the Boven Waal. No research has yet explored interventions specifically designed to make a significant impact on both objectives simultaneously. While the effects of LTDs on bed degradation have been extensively studied, there is limited understanding of their effects when their design is adjusted to also substantially increase low discharge partitioning to the Pannerdensch Kanaal. Furthermore, there is a lack of knowledge whether interventions within the Pannerdensch Kanaal could effectively contribute to achieving these two goals. This study aims to address a part of these knowledge gaps by examining the effects of varying interventions in both the Boven Waal and Pannerdensch Kanaal that are designed to make a significant impact regarding both objectives.

1.2 Research aim and questions

This study contributes to finding an approach to restore the low discharge distribution and stop bed degradation in the Boven Waal. It aims to investigate how interventions in both the Boven Waal and Pannerdensch Kanaal can be used to significantly improve on two goals simultaneously: increasing the low discharge partitioning to the Pannerdensch Kanaal and reducing bed degradation in the Boven Waal. This leads to the following main research question:

"How can varying interventions in the Boven Waal and Pannerdensch Kanaal be used to increase low discharge partitioning to the Pannerdensch Kanaal and reduce the bed degradation in the Boven Waal?"

The main research question will be answered by addressing the two research sub-questions below.

Research sub-question 1: What is the effect of LTDs in the Boven Waal on the low discharge distribution at the Pannerdensch bifurcation and the bed degradation in the Boven Waal and Pannerdensch Kanaal?

Research sub-question 1 focuses specifically on interventions in the Boven Waal. LTDs are considered because they are regarded as one of the most effective measures for mitigating bed degradation. Additionally, LTDs have the potential to increase low discharge partitioning to the Pannerdensch Kanaal by reducing the main channel width of the Boven Waal during low discharges. The initial design principle for the LTDs is to narrow the main channel width of the Boven Waal sufficiently to significantly increase low discharge partitioning to the Pannerdensch Kanaal. Following this, the riparian channel depths are adjusted to reduce flow velocities in the main channel during moderate to high discharges. This adjustment is aimed at mitigating bed degradation, particularly in the Boven Waal.

Research sub-question 2: What is the effect of summerdike removal and varying levels of floodplain lowering in the Pannerdensch Kanaal in addition to LTDs in the Boven Waal on the moderate, high and extreme discharge distribution at the Pannerdensch bifurcation and the bed degradation in both branches?

The LTDs in the Boven Waal lead to additional discharge being drawn to the Waal during moderate, high, and extreme discharge events, as they increase the riverbed capacity under these conditions. This effect enhances the erosivity of the flow in the Boven Waal, reducing the effectivity of the LTDs on reducing bed degradation. Additionally, it causes the prescribed discharge distribution during the Lobith design discharge of 16,000 m^3/s to no longer be met. Interventions in the Pannerdensch Kanaal could compensate for this effect on the discharge distribution during moderate to extreme discharge events. Therefore, research sub-question 2 investigates the effects of interventions in the Pannerdensch Kanaal alongside the implementation of LTDs in the Boven Waal. These interventions include combined summerdike removal and uniform floodplain lowering, as these are useful interventions for influencing the discharge distribution during moderate to extreme discharge events.

2 Theoretical background

This chapter provides an overview of the relevant theoretical background for this research. Section 2.1 begins by summarizing the current state-of-the-art knowledge on the effects of interventions in the Dutch Rhine branches on bed degradation and low discharge distribution. Following that, Section 2.2 explains the theoretical hydrodynamic and morphodynamic response of a bifurcating river system to LTDs, floodplain lowering and summerdike removal.

2.1 Effects of interventions in Dutch Rhine branches

Numerous studies have already been dedicated to the effects of interventions on bed degradation in the Dutch Rhine branches. Some of these studies also consider the impact on the low discharge distribution, though often as a secondary focus. This section provides an overview of the known effects of interventions, as identified in previous research, to summarize what is already understood. This overview is based on the studies displayed in Figure 2.1, where the colors indicate the locations along the Dutch Rhine branches where the interventions have been implemented.

Side channels have the potential to significantly mitigate bed degradation (Rorink, 2022; Ten Brink, 2024). They are secondary channels that are connected to the main river channel and begin to convey a portion of the discharge when the flow in the main channel reaches a certain threshold. This increases the overall riverbed capacity, which reduces flow velocities and, consequently, decreases the sediment transport capacity of the main channel, leading to sedimentation (Rorink, 2022). For a significant impact on bed degradation, side channels must be active as frequently as possible (Rorink, 2022). Side channels that are active nearly 100% of the time (from a Lobith discharge of 1000 m^3/s) could reduce bed degradation by 10-15% in the Waal and 20-25% in the Pannerdensch Kanaal, according to a 1D modeling study by Rorink (2022). Moreover, the combined implementation of side channels in both the Waal and Pannerdensch Kanaal could reduce bed degradation in the Pannerdensch Kanaal by 30-35%. However, the effects of the proposed side channels by Rorink (2022) are still far from sufficient to stop bed degradation, particularly in the Waal.

The discharge threshold at which side channels become active must be carefully selected. If they are active too frequently, excessive local sedimentation can occur, potentially causing navigation issues (Ten Brink, 2024). Conversely, if side channels only become active at higher discharges (from 2601 m^3/s), they can exacerbate erosion significantly. Therefore, it is recommended that side channels be activated during medium discharges (1543–1954 m^3/s), as suggested by the results of a 2D modeling study conducted by Ten Brink (2024).

Sediment nourishments are another intervention that can be used to mitigate bed degradation. They can significantly reduce erosion over a much longer length than the original length of the nourishment itself, as shown in a 1D modeling study performed by De Lange (2022). To effectively mitigate bed degradation, these nourishments should be strategically distributed along the river to prevent additional erosion downstream of the nourishments and consist of a sufficiently large volume of sediment. However, a notable practical limitation is the availability of sediment for nourishments. The 1D modeling study by Liptiay (2023) indicates that even with sediment sourced from actual sources, sediment nourishments can still have a notable positive impact on reducing bed degradation in the Boven Waal. Despite their effectiveness in decreasing erosion, they are still far from sufficient to completely stop bed degradation in the

Waal. Implementing repeated nourishments may enhance their overall effectiveness in reducing bed degradation further (De Lange, 2022; Liptiay, 2023).

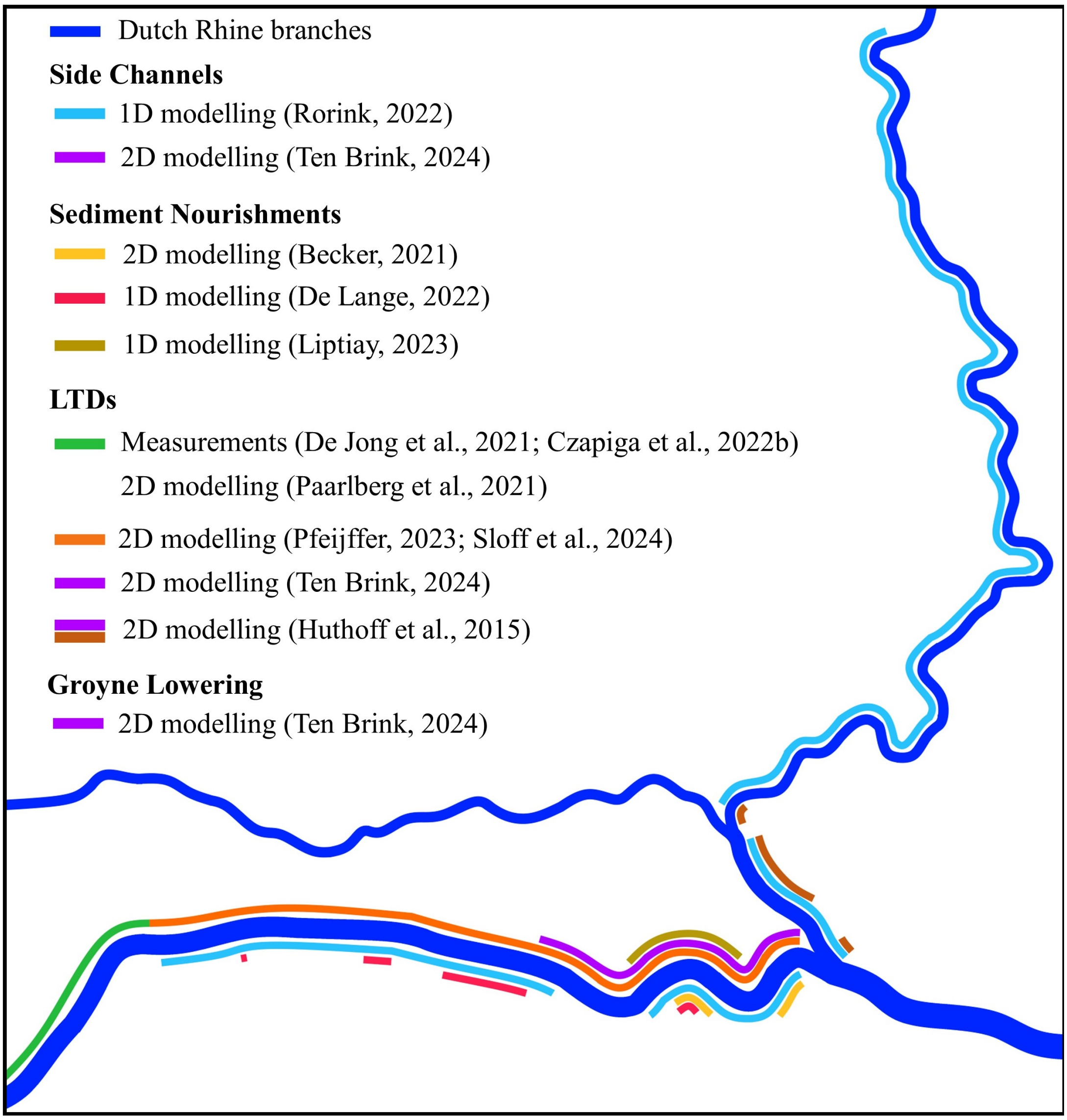

Figure 2.1: Overview of studies investigating the effects of interventions addressing bed degradation in the Dutch Rhine branches and the low discharge distribution at the Pannerdensch bifurcation. The dark blue area represents the majority of the Dutch Rhine branches, including the Boven Rijn, Boven and Midden Waal, Pannerdensch Kanaal, Nederrijn, and IJssel. Other colors indicate the specific locations of the implemented interventions of which the effects are studied.

Sediment nourishments in the Waal can also be utilized to increase low discharge partitioning to the Pannerdensch Kanaal (Becker, 2021; Liptiay, 2023). The sediment nourishments proposed by Liptiay (2023) are expected to result in an increase in low discharge partitioning to the Pannerdensch Kanaal of approximately 3-4 m^3/s. This influence on low discharge partitioning can be further amplified by placing the nourishment closer to the Pannerdensch bifurcation

(Becker, 2021). Additionally, a larger sediment volume correlates with a greater increase in low discharge partitioning to the Pannerdensch Kanaal. Specifically, the sediment nourishments proposed by Becker (2021) are initially projected to result in an increase in low discharge partitioning to the Pannerdensch Kanaal of about 5-10 m^3/s. However, over time, this effect reduces as the sediment nourishment erodes.

LTDs reduce bed degradation in the main channel by widening it during moderate to high discharges. Additionally, during low discharges, they narrow the main channel, leading to an increase in water depth during these discharges, which is beneficial for shipping. LTDs have been proven to be effective interventions in reducing bed degradation across numerous modeling studies (Huthoff et al., 2015; Paarlberg et al., 2021; Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024). Measurements at existing LTD locations in the Midden Waal have shown that they also result in channel bed deposition in practice and have a significant short-term local effect on reducing bed degradation (De Jong et al., 2021; Czapiga et al., 2022b). However, the riparian channels associated with the LTDs must be sufficiently large; otherwise, their impact on bed degradation will be minimal (Huthoff et al., 2015).

Extending the existing LTDs to cover the entire Midden and Boven Waal significantly reduces bed degradation in the upstream section of the Boven Waal (river kilometers 867.3-882) (Pfeijffer, 2023; Sloff et al., 2024). However, this extension considerably exacerbates bed degradation more downstream, particularly in the Midden Waal. The upstream LTDs significantly reduce sediment transport capacities, thereby 'trapping' sediment and ensuring that the downstream LTDs are not effective in achieving their goal of reducing bed degradation. Therefore, it is suggested that the dimensions of the riparian channels of the LTDs should increase in the downstream direction, thereby establishing a sediment transport gradient that continues to result in reduced erosion or even sedimentation downstream.

The discussed interventions all have a reducing effect on bed degradation; however, none are sufficient to completely stop it. This necessitates an approach that combines various interventions, particularly in the Boven Waal, where bed degradation is most severe. Consequently, the combination of groyne lowering, side channels, and LTDs in the Boven Waal has been investigated by Ten Brink (2024). This approach results in a significant reduction in bed degradation, particularly in the upstream section of the Boven Waal (river kilometers 867.3-882), where significant reach-averaged sedimentation occurs. However, a substantial exacerbation of erosion is observed in the downstream section of the Boven Waal (river kilometers 882-891), similar to the findings in the studies by Pfeijffer (2023) and Sloff et al. (2024). The side channels investigated in the study of Ten Brink (2024) do not significantly mitigate bed degradation in the Boven Waal because they only become active at a relatively high Lobith discharge of 2601 m^3/s. While groyne lowering does contribute to a reduction in bed degradation, the effect is minor. The LTDs, which have a similar configuration to those in the studies by Pfeijffer (2023) and Sloff et al. (2024), are the most effective intervention in this study for reducing bed degradation in the Boven Waal.

In addition to reducing bed degradation, LTDs in the Boven Waal can also be used to increase the low discharge partitioning to the Pannerdensch Kanaal. By causing a decrease in the main channel width during low discharges, the LTDs lead to an increase in water level, which, due to backwater effects, extends to the Pannerdensch bifurcation. This results in a redistribution of flow, leading to a higher low discharge partitioning to the Pannerdensch Kanaal. Specifically, when LTDs decrease the main channel width of the Boven Waal by approximately 20 meters, as seen in the studies by Pfeijffer (2023), Sloff et al. (2024) and Ten Brink (2024), the discharge partitioning to the Pannerdensch Kanaal increases by about 7 m^3/s during a Lobith discharge of 1294 m^3/s. However, this increase is still relatively small compared to the 63 m^3/s needed to meet the required discharge partitioning at this Lobith discharge.

2.2 Initial hydrodynamic and morphodynamic response to interventions in a bifurcating river

This section qualitatively describes the initial hydrodynamic and morphodynamic response of the Boven Rijn, Waal, and Pannerdensch Kanaal to the proposed interventions. Given the mild bed slope of the Dutch Rhine branches, the flow is subcritical, meaning that interventions not only affect flow at the intervention location but also upstream, due to backwater effects. The response to LTDs in the Boven Waal is discussed first (Section 2.2.1), followed by their combined effects with summerdike removal and floodplain lowering in the Pannerdensch Kanaal (Section 2.2.2).

2.2.1 Effect of LTDs in the Boven Waal

The initial hydrodynamic and morphodynamic response to LTDs differs between low and high discharges. The following two sections will outline the theoretical response of the Rhine branches under both of these discharge ranges. The simulation results, presented later in this study, will clarify which response is most dominant regarding the overall bed level changes.

Effect during low discharges
The LTDs cause the main channel of the Boven Waal to narrow during low discharges, as illustrated by the schematic overview in Figure 2.2. This narrowing leads to an increase in initial water levels along the LTD section, compared to the reference situation without LTDs. Additionally, the main channel discharge now flows through a smaller cross-sectional area. By conservation of mass, this leads to increased initial flow velocities in the main channel along the LTD section compared to the reference situation.

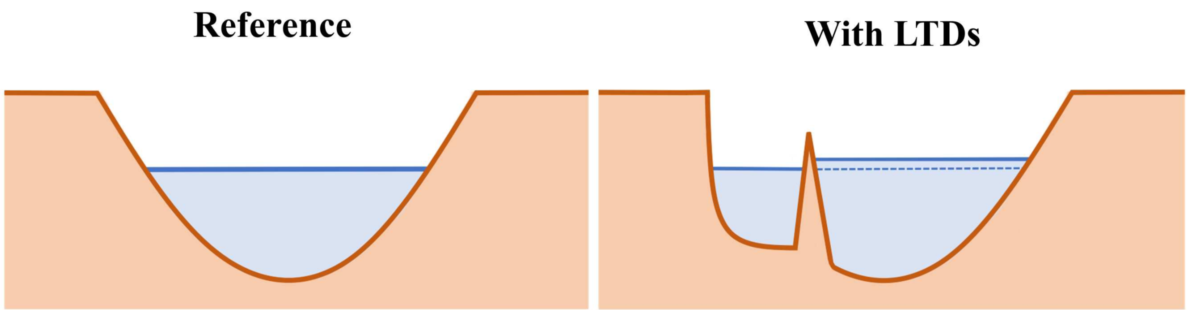

Figure 2.2: Schematic river cross-sections illustrating the initial hydrodynamic response of a river with (right) and without (left) LTDs during low discharges.

The LTDs cause an increase in upstream water levels during low discharges due to the formation of backwater curves. This initial hydrodynamic response is illustrated in Figure 2.3. The increase in water levels propagates to the Pannerdensch bifurcation, resulting in a redistribution of flow: more flow is directed toward the Pannerdensch Kanaal (indicated by the upward light blue arrow), while less flow is directed to the Waal (indicated by the downward light blue arrow).

Consequently, this leads to increased water levels in the Pannerdensch Kanaal and decreased water levels downstream of the LTDs in the Midden Waal.

The initial morphodynamic response to LTDs during low discharges is shown in Figure 2.3. This response is characterized by the formation of erosion pits and sedimentation humps at locations where there are abrupt changes in sediment transport capacity. Over time, these will expand downstream. Additionally, gradual sedimentation and erosion occur along sections where sediment transport capacity increases or decreases steadily due to backwater effects from downstream. The subsequent paragraphs will detail this response from an upstream to downstream order. The response in the Waal is discussed before the response in the Pannerdensch Kanaal.

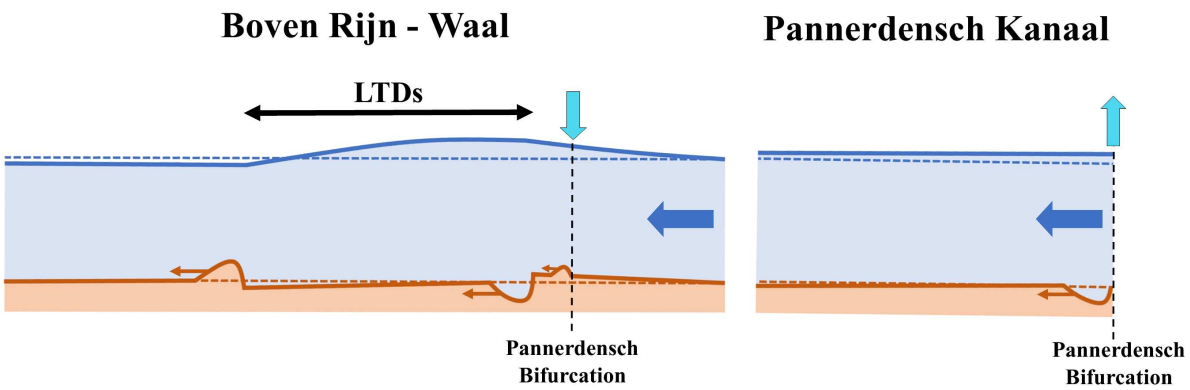

Figure 2.3: Initial hydrodynamic and morphodynamic response to LTDs in the Boven Waal for both the Boven Rijn and Waal (left) and Pannerdensch Kanaal (right) during low discharges. The dark blue arrow represents the flow direction. The light blue arrow indicates a decrease (downward arrow) or an increase (upward arrow) in discharge partitioning to the respective branch.

Upstream of the Pannerdensch bifurcation (Boven Rijn), initially gradual sedimentation occurs during low discharges in response to the LTDs (Figure 2.3). The increased water levels mean that the same discharge flows through a larger cross-sectional area. According to the principle of conservation of mass, this results in an increase in flow velocity in the downstream direction. Since flow velocity scales nonlinearly with sediment transport capacity, this leads to a sediment transport capacity that also increases in downstream direction, leading to gradual sedimentation in this area.

Directly downstream of the Pannerdensch bifurcation in the Boven Waal, a sedimentation hump forms in response to the LTDs during low discharges (Figure 2.3). This occurs due to a reduction in discharge partitioning to the Waal compared to the reference situation. As a result, there is a sudden decrease in flow velocity and, consequently, sediment transport capacity at this location, which leads to sedimentation.

Along the LTD section, an erosion pit forms at the upstream end, which will expand downstream over time (Figure 2.3). This erosion occurs because the LTDs increase the main channel flow velocities during low discharges compared to the reference situation. This leads to a sudden increase in sediment transport capacity of the flow at the upstream end of the LTD section, leading to erosion. Towards the downstream end of the LTD section, gradual erosion occurs

(Figure 2.3). This happens because of the backwater effects from downstream the LTDs. This causes the cross-sectional flow area to decrease in the downstream direction, which in turn increases flow velocities by conservation of mass. This leads to a sediment transport capacity that is increasing in downstream direction, leading to gradual erosion.

Downstream of the LTDs (Midden Waal), the initial morphodynamic response of the main channel riverbed during low discharges is characterized by the formation of a sedimentation hump, which will expand downstream over time (Figure 2.3). In this area, the absence of LTDs means that flow velocities are no longer increased compared to the reference situation. As a result, there is a sudden decrease in sediment transport capacity directly downstream of the LTDs, leading to the formation of a sedimentation hump.

In the Pannerdensch Kanaal, an erosion pit develops at the upstream end in response to the LTDs during low discharges, which will expand downstream over time (Figure 2.3). The increased discharge partitioning during low discharges results in higher flow velocities in the Pannerdensch Kanaal. Consequently, this leads to a sudden increase in sediment transport capacity at the upstream end, causing the formation of the erosion pit.

In summary, during low discharges, the LTDs initially cause sedimentation in the Boven Rijn, erosion along the LTD section in the Boven Waal, sedimentation in the Midden Waal, and erosion in the Pannerdensch Kanaal.

Effect during high discharges
The LTDs induce a widening of the main channel in the Boven Waal during high discharges, as illustrated by the schematic overview in Figure 2.4. This widening results in a reduction of initial water levels along the LTD section compared to the reference scenario without LTDs. Furthermore, the main channel's discharge now flows through a larger cross-sectional area compared to the reference situation. According to the principle of conservation of mass, this causes a decrease in initial flow velocities in the main channel along the LTD section.

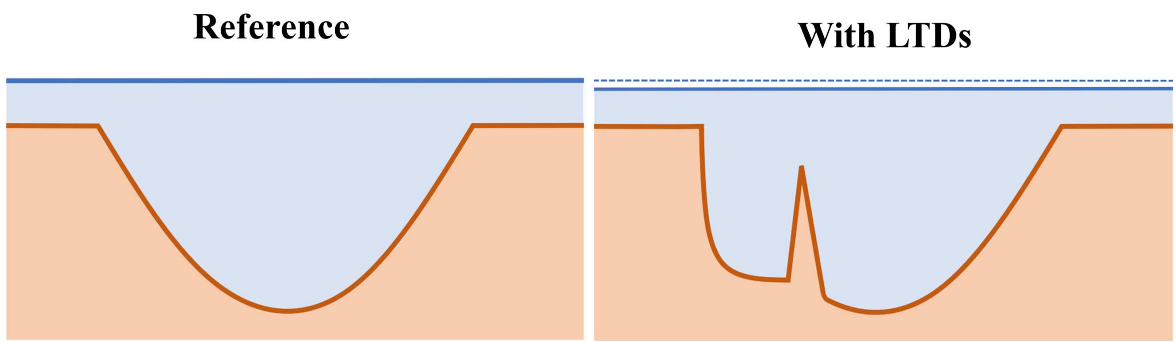

Figure 2.4: Schematic river cross-sections illustrating the initial hydrodynamic response of a river with (right) and without (left) LTDs during high discharges.

The LTDs lead to a reduction in upstream water levels during high discharges due to the development of backwater curves. This initial hydrodynamic response is illustrated in Figure 2.5. The decline in water levels travels upstream to the Pannerdensch bifurcation, resulting in a redistribution of flow: less flow is directed toward the Pannerdensch Kanaal (shown by the downward light blue arrow), while more flow is partitioned to the Waal (indicated by the upward light blue arrow). As a result, water levels in the Pannerdensch Kanaal decrease, while they rise downstream of the LTDs in the Midden Waal.

The initial morphodynamic response to LTDs during high discharges is shown in Figure 2.5. This response is exactly the opposite of the response during low discharges. The explanation for the morphodynamic response during high discharges follows the same reasoning as outlined in the previous section regarding the response during low discharges. The only distinction is that the underlying physical processes are opposite. Therefore, a detailed explanation is not provided in this section.

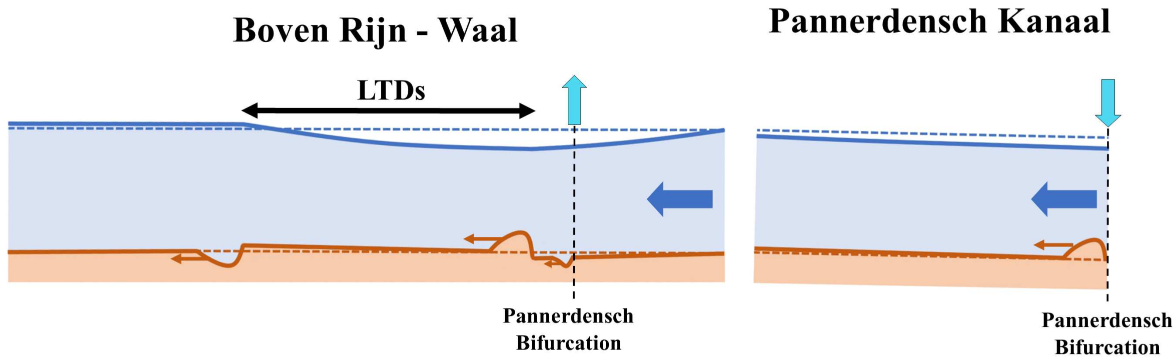

Figure 2.5: Initial hydrodynamic and morphodynamic response to LTDs in the Boven Waal for both the Boven Rijn and Waal (left) and Pannerdensch Kanaal (right) during high discharges. The dark blue arrow represents the flow direction. The light blue arrow indicates a decrease (downward arrow) or an increase (upward arrow) in discharge partitioning to the respective branch.

In short, erosion occurs in the Boven Rijn due to backwater effects from the LTDs, which lead to higher flow velocities. In the Boven Waal, sedimentation takes place along the LTD section as a consequence of the decreased flow velocities caused by the LTDs. Downstream of the LTDs (Midden Waal), erosion occurs because the absence of LTDs leads to a sudden increase in sediment transport capacity. Meanwhile, sedimentation happens in the Pannerdensch Kanaal, as reduced discharge partitioning to this branch results in lower flow velocities.

2.2.2 Effect of interventions in both the Boven Waal and Pannerdensch Kanaal

Summerdike removal and floodplain lowering are implemented in the Pannerdensch Kanaal to address the increased discharge partitioning to the Waal during high discharges. They do not have an impact during low discharges. By enlarging the riverbed capacity in the Pannerdensch Kanaal, these interventions lead to a significant decrease in initial water levels during high discharges, as illustrated in Figure 2.6. This reduction in water levels propagates upstream to the Pannerdensch bifurcation as a result of backwater curves (Figure 2.7), resulting in a redistribution of flow. This section assumes that the intervention is designed to precisely compensate the additional discharge diverted to the Waal by the LTDs, thereby restoring the high discharge partitioning to levels comparable to those in the reference situation.

The initial morphodynamic response to the combination of the interventions in the Boven Waal and Pannerdensch kanaal during high discharges is shown in Figure 2.7. The morphodynamic response in the Waal closely resembles the response when only implementing LTDs (Figure 2.5). The key difference is that erosion no longer occurs due to the increased discharge partitioning to the Waal.

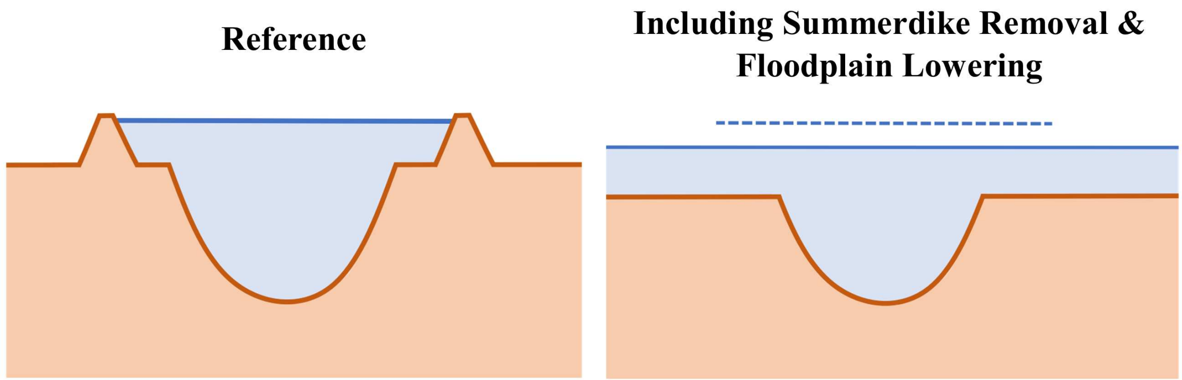

Figure 2.6: Schematic river cross-sections illustrating the initial hydrodynamic response of a river with (right) and without (left) summerdike removal and floodplain lowering during high discharges.

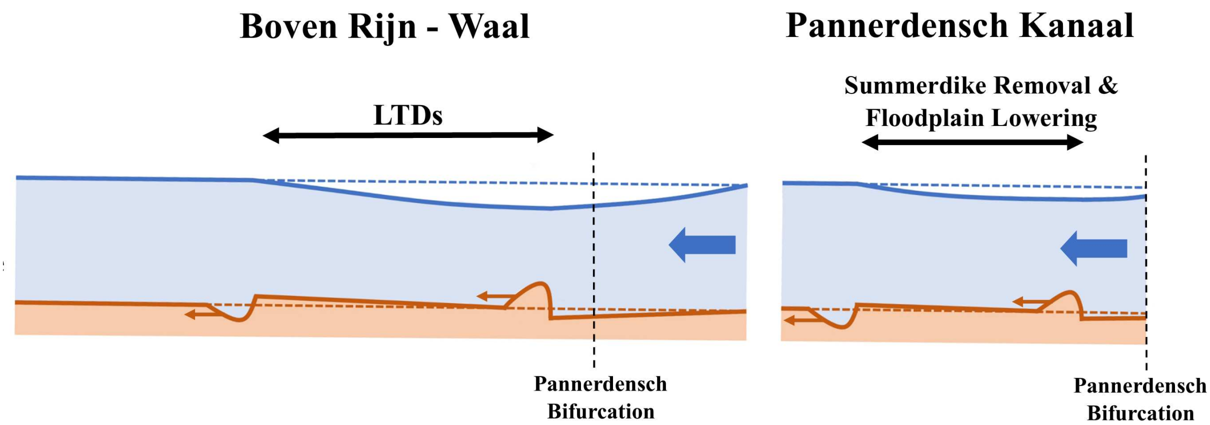

Figure 2.7: Initial hydrodynamic and morphodynamic response to LTDs in the Boven Waal and summerdike removal and floodplain lowering in the Pannerdensch Kanaal for both the Boven Rijn and Waal (left) and Pannerdensch Kanaal (right) during high discharges. The dark blue arrow represents the flow direction.

In contrast, the initial erosion upstream of the Pannerdensch bifurcation in the Boven Rijn is more pronounced compared to the scenario involving only LTDs. This increase is attributed to the fact that interventions in both Rhine branches lead to reduced water levels in the Boven Rijn as a result of their backwater effects. Consequently, this results in a greater decrease in the cross-sectional area for the same flow, which in turn elevates flow velocities and, consequently, sediment transport capacities.

The initial morphodynamic response in the Pannerdensch Kanaal to the combination of interventions during high discharges (Figure 2.7) differs significantly from the response when solely implementing LTDs (Figure 2.5). The summerdike removal and floodplain lowering significantly increase the cross-sectional area of flow along their section in the Pannerdensch Kanaal (Figure 2.6). Consequently, the same discharge passing through a larger cross-sectional area leads to reduced flow velocities because of conservation of mass. This results in a sudden increase in sediment transport capacity at the upstream end of the intervention section, causing the formation of a sedimentation hump.

Towards the downstream end of the summerdike removal and floodplain lowering section, gradual sedimentation occurs. This is attributed to the increasing water levels in the downstream direction, which arise from the backwater curve generated by the water levels downstream of the intervention section. This rise in water levels leads to an increase in the cross-sectional area, ultimately resulting in a decrease in sediment transport capacity in downstream direction along the intervention section. This explains the gradual sedimentation that occurs in this area.

Upstream of the summerdike removal and floodplain lowering, there occurs initial erosion due to backwater effects from the interventions that lead to higher flow velocities. Downstream of the interventions, an erosion pit develops that expands in downstream direction over time. This initial morphodynamic response is caused by the absence of an intervention in that area, due to which a sudden increase in sediment transport capacity occurs.

3 Methodology

3.1 DVR Model

This study uses the new version of the Delft3D-4 "Duurzame Vaardiepte Rijntakken" (DVR) model (version delft3d_4-rijn-j18-v1, released in April 2024) for simulating the effect of the interventions (Sloff et al., 2024). This is a state-of-the-art 2DH morphological model of the Dutch Rhine branches, regarded as the most advanced tool available for studying the morphology of these branches. It was initially developed to evaluate proposed construction and sediment management interventions in the Rhine delta (Van Vuren et al., 2015). However, in light of the Integrated River Management (IRM) program, the model was updated in 2024 (Sloff et al., 2024), as the previous version was outdated and struggled to accurately predict large-scale morphological trends, particularly overestimating erosion in the Waal (Sloff et al., 2023). The new version significantly improved on predicting these morphological trends. Section 3.1.4 provides further details on the differences between the old and new version.

A 2D model is selected for this study since there is a strong focus on the development of the discharge distribution at the bifurcations and how this is impacted by interventions. Unlike 1D models, which rely on simplified nodal relationships, a 2D model simulates these bifurcations based on physical processes, including secondary flow. Additionally, 2D models allow for a more detailed schematization of interventions and include important two-dimensional effects such as bend sorting and transverse bed slope.

The DVR model is developed for assessing long-term, large-scale morphological development in the Rhine branches and assessing the effects of interventions on this morphological development (Sloff et al., 2024). For this purpose, the hydraulics in the model have been optimized specifically for morphological simulations, with a focus on accurately representing flow velocities and the discharge distribution at the Pannerdensch and IJssel bifurcation. To achieve this, a constant Chézy roughness coefficient of 50 $m^{1/2}/s$ has been applied, which leads to the overestimation of absolute water levels (up to 20 cm) (Sloff et al., 2024; Ten Brink, 2024).

The DVR model operates on the computational core of Delft3D-FLOW and solves the unsteady shallow water equations numerically in two dimensions: the longitudinal and transverse direction of the river. Given that the horizontal length and time scales are significantly larger than the vertical scales of the Rhine branches, the use of a depth-averaged model is valid (see depth-averaged equations Equations 1 and 2).

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial z_w}{\partial x} = -g\frac{u\sqrt{u^2+v^2}}{hC^2} \tag{1}$$

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

In Equations 1 and 2, u [m/s] is the depth-averaged velocity in the longitudinal direction along distance x [m]. v [m/s] is the depth-averaged velocity in the transverse direction along distance y [m]. t [s] is time, g [m/s^2] is the gravitational acceleration, z_w [m] is the water level, h [m] is the water depth and C [$m^{1/2}/s$] is the Chézy roughness coefficient.

The model couples the hydrodynamics to a morphological module. This module computes the sediment transport with the MMeyer-Peter and Müller (1948) (MPM) equation (see Equation

3). The sediment transport gradients resulting from the MPM equation are then translated into bed level changes using the Exner equation (Equation 4). The sediment consists of eleven sediment fractions ranging from 6.3×10^{-5} to 0.125 meter. The DVR model applies different calibration parameter values (α) for the MPM equation across the various Rhine branches (Table 3.1), as this is necessary to accurately replicate the observed large-scale morphological trends within each branch (Sloff et al., 2024). The MPM equation is originally developed for coarse bed load transport (Meyer-Peter and Müller, 1948) but is used in the DVR model to simulate both bed load and suspended load. The model developers also explored combining the Engelund and Hansen equation for sand transport (particles <2 mm) with the MPM equation for gravel (particles >2 mm), but this approach yielded less satisfactory results and did not perform as effectively (Sloff et al., 2024).

$$S = \alpha B D^{3/2} \sqrt{g\Delta} \left(\frac{\mu u^2}{C^2 \Delta D} - \xi \theta_{cr} \right)^{3/2} \tag{3}$$

S is the sediment transport per unit width (without pores) [m^2/s], α [-] represents a calibration coefficient, B [m] is the alluvial width of the river, D [m] is the grain diameter, Δ [-] is the relative density, μ [-] is the ripple factor (= 1), u [m/s] is the depth-averaged flow velocity, ξ [-] is the hiding and exposure factor, which contains a correction formulated by Parker et al. (1982) and θ_{cr} [-] is the critical Shields stress.

$$(1-\epsilon)\frac{\partial z_b}{\partial t} + \bigtriangledown q_s = 0 \tag{4}$$

ϵ [-] represents the bed porosity, z_b [m] is the bed level and $\bigtriangledown q_s$ is the divergence of the bed-material load sediment flux (q_s [m^2/s]) per unit width.

Table 3.1: Calibration coefficients of the Meyer-Peter and Müller (1948) sediment transport equation per Rhine branche applied in the DVR model.

Branche	**Calibration Coefficient α (-)**
Niederrhein/Bovenrijn	0.3
Waal	0.25
Pannerdensch Kanaal	0.75
Nederrijn	0.6
IJssel	0.2

3.1.1 Model domain

The model domain of the DVR model consists of 9 subdomains and has four boundary conditions (Figure 3.1). The upstream boundary condition at the German Niederrhein is a discharge hydrograph (see Figure 3.2), while the downstream boundary conditions at the Beneden Waal, Nederrijn and Beneden IJssel are Q-h relations. The downstream boundary conditions are determined based on rating curves (in Dutch: ”Betrekkingslijnen”).

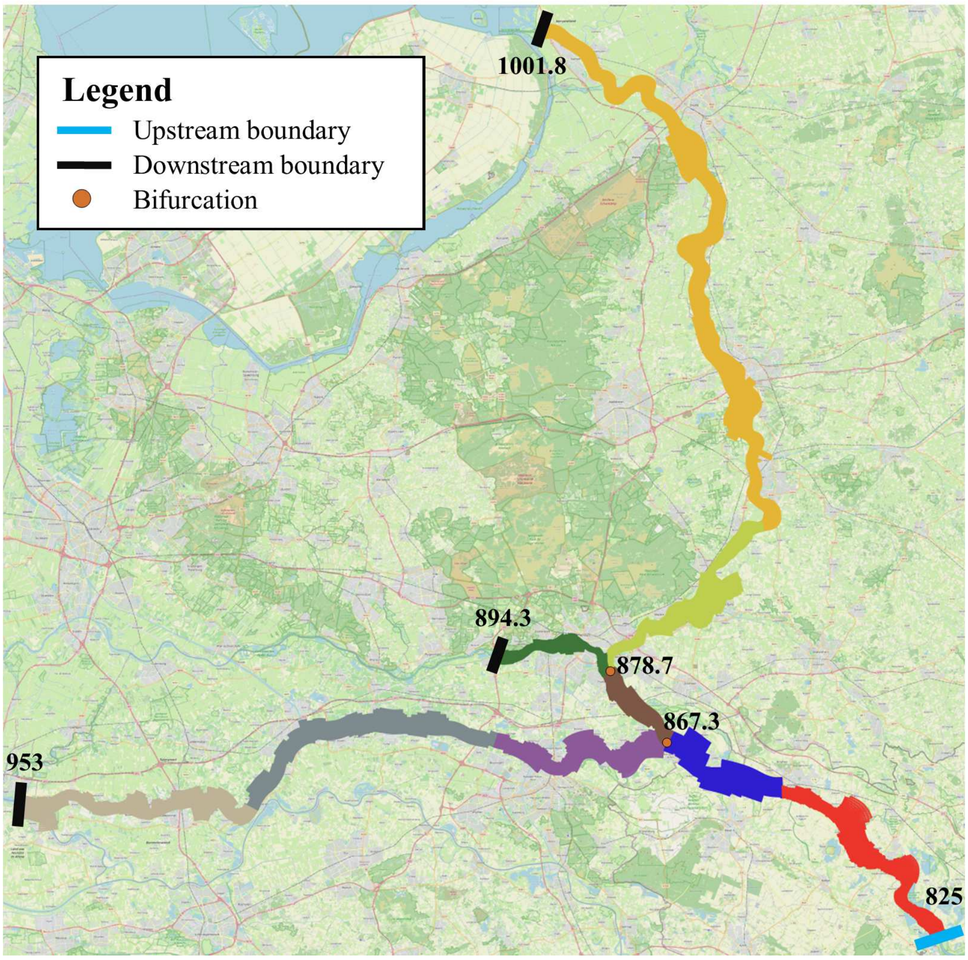

Figure 3.1: The model domain of the DVR model. The different colours illustrate the different model subdomains. The blue and black lines illustrate the upstream and downstream boundary conditions. The brown dots represent the bifurcations. The numbers in black are the river kilometers of the boundary conditions and bifurcations.

3.1.2 Hydrograph and morphological acceleration factor

The DVR model makes use of a schematized hydrograph to increase computational speed (Sloff, 2011) (see Figure 3.2). A Simulation Management Tool (SMT) controls the simulations, ensuring that the flow fields for each discharge are stored at the end of each discharge step and reused the next time the same discharge occurs. The SMT manages the computational core of Delft3D-FLOW for each discharge individually. Before the morphological simulation of each discharge, a 720-minute hydrodynamic simulation is conducted to allow the hydraulic parameters to spin up to their new equilibrium values. During this spin-up period, no bed level changes are applied. The hydrodynamic spin-up should be at least 1440 minutes in the initial year when interventions are implemented (Sloff et al., 2024).

Furthermore, the SMT enhances computational speed by employing morphological acceleration factors (as shown in Table 3.2) (Sloff et al., 2024). This allows the model to run for a short period (the hydrodynamic calculation time in Table 3.2), after which the bed level changes are multiplied by a morphological acceleration factor, estimating what the bed level changes would be for the full morphological calculation time. The accuracy of this estimation decreases with larger bed level developments, as significant changes in the bed impact the flow dynamics over time, causing the morphological development to change. Consequently, in the DVR model, higher discharges are assigned relatively low morphological acceleration factors, while lower discharges, where less bed level development is expected, are assigned higher morphological acceleration factors (Sloff et al., 2024).

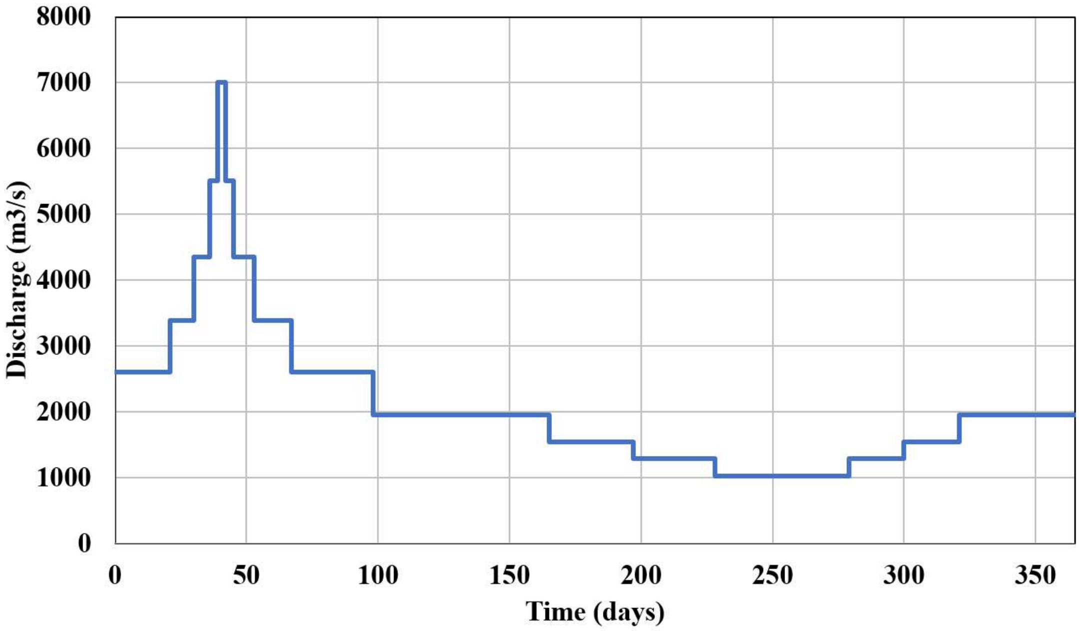

Figure 3.2: Hydrograph representing the upstream boundary condition of the DVR model.

Table 3.2: Morphological calculation time, morphological acceleration factor and hydrodynamic calculation time for each discharge.

Discharge (m3/s)	**Morphological calculation time (days)**	**Morphological acceleration factor (-)**	**Hydrodynamic calculation time (min)**
1020	51	1440	51
1294	52	1440	52
1543	53	720	106
1954	111	720	222
2601	52	240	312
3384	23	240	138
4353	14	120	168
5506	6	120	72
7009	3	120	36

3.1.3 Morphological spin-up

The initial bed composition and level determine the initial morphological reaction of the riverbed. These initial effects induced by the model can be excluded by including a spin-up period. This study uses the spin-up method as prescribed by Sloff et al. (2024), which consists of two steps.

The first step of the spin-up method involves a local spin-up for fixed layers located near Nijmegen (rkm 883-885.2), Erlecom (rkm 873.5-875.5), and St. Andries (rkm 925-927). These fixed layers do not contain sediment within the model schematization, making them non-erodible. This results in significant initial downstream erosion, with effects that persist longer than typical initial riverbed changes. To address this, a two-year localized spin-up is performed in these areas. After this step, only the sediment thickness and composition at the fixed layers and the zones directly downstream (1 km) are retained for the next spin-up stage. The bed level at the start of the second spin-up step is similar to the original bed level.

The second spin-up step is a two-year spin-up for the entire model domain, which simultaneously spins up both the bed level and bed composition. During the spin-up period, the hydrodynamic spin-up per discharge step should be set to 1440 minutes to ensure proper stabilization of flow parameters (Sloff et al., 2024). Although the model uses width-averaged bed composition values as input, no additional step is incorporated in the prescribed approach to spin up the bed composition separately before bed level variations are introduced (Sloff et al., 2024). This choice influences the bed level development, especially in areas where significant sorting effects, such as bends, occur.

3.1.4 Difference between the old and new version of the DVR Model

Significant improvements have been made to the new version of the DVR model compared to the previous version (Sloff et al., 2024). First of all, the grid, geometry and grain size distribution have been updated. Additionally, in the new version, all Rhine branches are modeled with non-uniform sediment, whereas the previous version utilized uniform sediment for some areas. Also the fixed layers are more accurately represented by incorporating a local spin-up step, as described in the previous section.

One of the key improvements in the new version is the more accurate simulation of bed level trends. The old version failed to simulate these trends accurately, which was one of the main reasons to update the DVR model. The new version reduces excessive erosion in the Midden Waal while increasing it in the Boven Waal. This is more realistic based on measured data (Sloff et al., 2024). Achieving this required the use of distinct calibration parameters in the Meyer-Peter and Müller sediment transport equation for each branch (Table 3.1). In contrast, the old version employed a uniform calibration parameter (0.625) across all branches.

As a result of the improvements, the new version of the DVR model enhances the accuracy of sediment transport gradient. Unlike the old version, the new model does not produce large, unrealistic sediment transport gradients. The is due to a combination of improvements, including the use of an updated geometry, a constant hydraulic roughness, a new bed composition featuring non-uniform sediment across all branches, and the calibrated sediment transport model.

Additionally, the new version features a constant active layer thickness of 1 meter for all domains, whereas previous studies based this thickness on water depth. According to Sloff et al. (2024), utilizing a constant active layer thickness simplifies the model without compromising quality.

3.2 Simulations

This study uses a systematic approach to design interventions in the Boven Waal and Pannerdensch Kanaal aiming to both significantly increase low discharge partitioning to the Pannerdensch Kanaal and reduce bed degradation in the Boven Waal. This approach is illustrated schematically in Figure 3.3. Table 3.3 provides an overview of the simulations following from this approach, including a Reference Scenario for comparison with the intervention scenarios.

Research Question 1 focuses on the implementation of LTDs with associated ripraian channels in the Boven Waal. The first step is to reduce the main channel width of the Boven Waal during low Lobith discharges (1020 to 1543 m^3/s) using LTDs to significantly increase the low discharge partitioning to the Pannerdensch Kanaal. Subsequently, the riparian channel depths are adjusted to sufficiently widen the main channel of the Boven Waal during during moderate to high Lobith discharges (1954 to 7009 m^3/s) such that flow velocities during these discharges are significantly reduced. This adjustment is aimed at reducing bed degradation in the Boven Waal. These steps are carried out through performing various hydraulic simulations. Three LTD Scenarios with varying riparian channel depths are designed for which the morphological development is simulated with the DVR model (see Table 3.3). Section 3.2.1 provides further details on the choices, assumptions, and development of these scenarios.

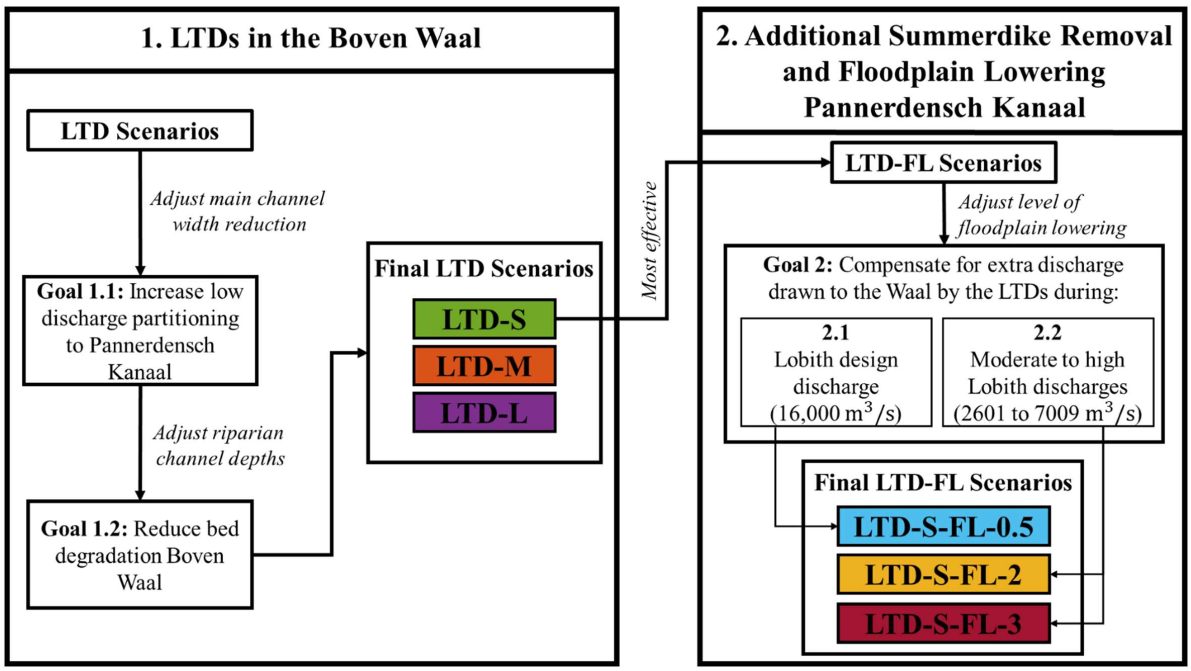

Figure 3.3: Systematic approach to designing interventions in the Boven Waal and Pannerdensch Kanaal.

Research Question 2 proceeds with the LTD Scenario that is most effective concerning both the low discharge distribution and bed degradation. This scenario is identified as Scenario LTD-S, which will be clarified later in this study. Additionally, interventions are explored in the Pannerdensch Kanaal to compensate for the increased discharge drawn into the Waal by the LTDs. First, compensation is needed during the Lobith design discharge (16,000 m^3/s) to maintain the prescribed discharge distribution (5835 m^3/s to Pannerdensch Kanaal and 10165

m^3/s to the Waal) (Schropp and Jansen, 2020). The second aim is to also compensate during moderate to high Lobith discharges (1954 to 7009 m^3/s) to further reduce bed degradation in the Boven Waal, beyond what is achieved with LTDs alone.

The interventions in the Pannerdensch Kanaal are focused on the floodplains, as there is limited space within the main channel, and to avoid negatively impacting the low discharge distribution. The objective here is not to design an optimal intervention, but rather to evaluate the potential effects of these kind of compensatory measures. Therefore, for simplicity, the interventions involve summerdike removal for all LTD-FL Scenario, along with varying levels of uniform floodplain lowering. These interventions are implemented over an approximate length of 7.5 kilometer. To avoid an overly complex design process, one LTD-FL Scenario including a 0.5-meter floodplain lowering is designed to maintain the discharge distribution during the Lobith design discharge. Additionally, two LTD-FL Scenarios with 2-meter and 3-meter floodplain lowering are designed to address compensation during moderate to high Lobith discharges (see Table 3.3).

Table 3.3: Overview of Performed Simulations

	Scenario	**Abbreviation**	**Description**
0	Reference Scenario	Ref	Reference Simulation
RQ1	**LTDs in the Boven Waal**		
1.1	LTD Scenario Small	LTD-S	Least deep riparian channels
1.2	LTD Scenario Medium	LTD-M	Moderately deep riparian channels
1.3	LTD Scenario Large	LTD-L	Deepest riparian channels
RQ2	**LTDs in the Boven Waal and summerdike removal and floodplain lowering in the Pannerdensch Kanaal**		
2.1	LTD-FL Scenario 0.5m	LTD-S-FL-0.5	0.5-meter floodplain lowering
2.2	LTD-FL Scenario 2m	LTD-S-FL-2	2-meter floodplain lowering
2.3	LTD-FL Scenario 3m	LTD-S-FL-3	3-meter floodplain lowering

3.2.1 LTDs in the Boven Waal

The simulations of the LTDs in the Boven Waal involve three LTD Scenarios (see Table 3.3), each consisting of six LTDs with corresponding riparian channels spanning almost the entire length of the Boven Waal (Figure 3.4). Their placement is based on the "Globaal Ontwerp Langsdammen" (Huthoff et al., 2015), a design which is also used in previous studies of LTDs in the Boven Waal (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024). A small interruption exists between LTDs 4 and 5 to accommodate the outflow point of the Spiegelwaal. The LTDs are positioned on the inner bend of the river to prevent rapid sedimentation and closure of the channels, which would occur if they were located at the bend apex or curvature crossover (Czapiga et al., 2022b). As a result, there is a necessary shift in the downstream direction from LTDs on the left and right sides of the main channel. This design leads to the need for six separate LTDs rather than one continuous body.

The LTDs are positioned three grid cells (~65 m) further into the main channel compared to the ends of the current groynes, thereby reducing the original main channel width of the Boven Waal (260 meters) by approximately 65 meters. Previous studies regarding LTDs reduced the

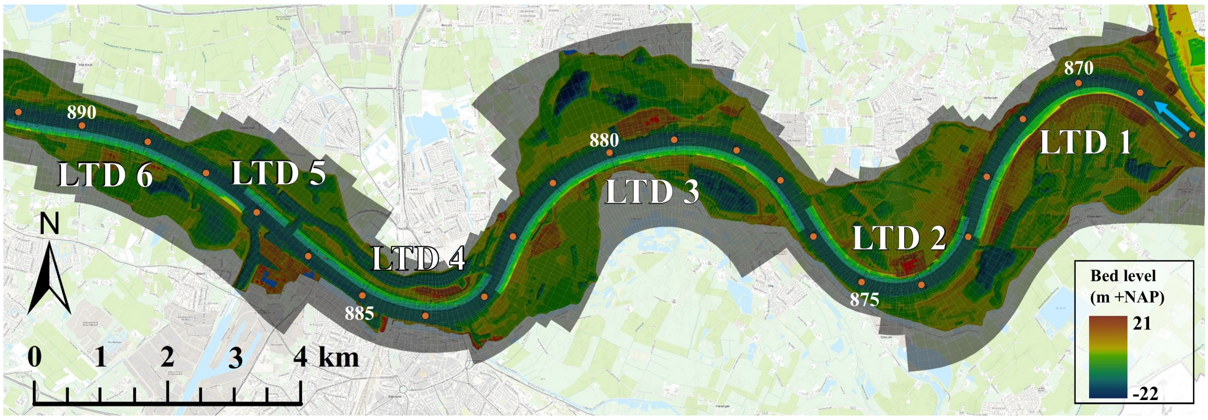

Figure 3.4: The location of the riparian channels for the six LTDs in the Boven Waal (rkm 867.3-891) displayed on top of the DVR model grid and the original riverbed depth before the introduction of LTDs. Transparent grid cells represent the riparian channels, while darker cells indicate unchanged areas. The light blue arrow represents the flow direction. The brown dots represent river kilometers.

main channel width relative to the ends of the groynes by only one grid cell (~20 meters), which resulted in a minimal increase in low discharge partitioning to the Pannerdensch Kanaal (~7 m^3/s) (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024). Therefore, this study has investigated the effect of reducing the main channel width by two (~40 m) and three grid cells (~65 m) on the initial low discharge partitioning to the Pannerdensch Kanaal by doing some hydraulic trial runs. Due to the coarse resolution of the grid, intermediate reductions could not be modeled. The three grid cell reduction is selected because it resulted in the highest increase in low discharge partitioning to the Pannerdensch Kanaal.

The current LTD design results in a main channel width of 195 meters. Although this is below the policy-required width of 230 meters (comprising 150 meters for navigation, 20 meters for future expansion, and two 30-meter safety margins) (Klijn et al., 2022), it remains reasonably close to the required dimensions. Given that the focus of this study is on evaluating the effects of significant channel reduction rather than achieving a fully realistic design, this difference is considered acceptable.

At the LTD transition zones, the main channel width narrows to approximately 131 meters due to the shift in LTD placement from one side of the river to the other. This width is well below the required 230 meters and, in practice, would necessitate greater spacing between LTDs to avoid such a drastic reduction. However, the transition zones are left unchanged in this study for the same reason as mentioned in the previous paragraph.

The total width of the riparian channels is designed to be five grid cells (approximately 125 meters), which includes three cells from the original main channel and two cells from the previous groyne areas. However, in specific sections, the riparian channel of LTD 1 (rkm 868.1 to 870.4) and LTD 2 (rkm 873.7 to 874.4) are narrower, spanning only four grid cells (~95 m). For LTD 1, this narrower section is due to the presence of a summerdike further inland, which is intentionally left unaffected to preserve the local dynamics of the floodplain. For LTD 2, the narrower width is a result of buildings in the floodplain, which are also intentionally left unaffected.

The LTDs are schematized by removing the groynes and lowering the bed level within the riparian channels (Figure 3.5). The LTD crest and inlet sill are modeled as a weir. A weir, being a fixed, non-movable structure, introduces energy losses due to flow constriction. This approach is necessary because the width of the LTD crest (~2 meters) is considerably smaller than the grid cell width (~25 meters). Assigning the entire grid cell the height of the LTD would overly reduce the cross-sectional area. Instead, the outermost grid cell of the riparian channel, closest to the main channel, is slightly raised relative to the rest of the riparian channel bed level to compensate for the reduction in cross-sectional area caused by the LTD body (see Figure 3.5c). Appendix A provides additional technical details on how the LTD schematization is included into the DVR model input files.

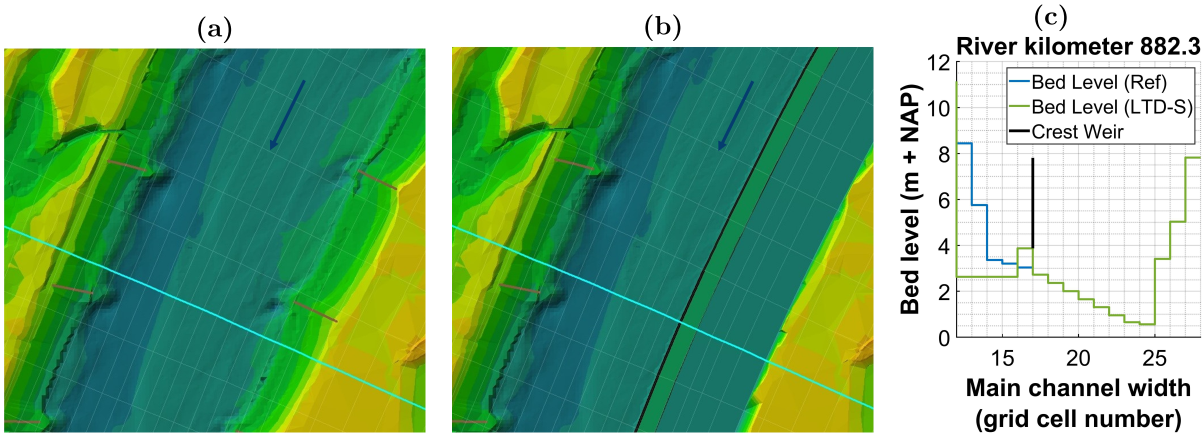

Figure 3.5: (a) Top view of the original main channel (Reference) in the Boven Waal around river kilometer 882.3 (blue line). Brown lines represent groynes. (b) Top view of the main channel after implementation of LTD 4. The black line represents the LTD body. The dark blue arrow represents the flow direction. (c) Schematized cross-sectional bed level of the main channel at river kilometer 882.3 for the Reference Scenario and Scenario LTD-S. The black line represents the LTD crest weir.

At the downstream end of the LTD body, the riparian channel extends for an additional two grid cells (~160 m) to ensure smooth water flow out of the riparian channel without excessive obstruction from the elevated groyne area (Figure 3.6). Another schematization choice involves to include no initial sediment in the riparian channels, making them non-erodible at the start of the simulation. However, sediment deposited during the simulation can be eroded. This approach aligns with previous studies on LTDs in the Boven Waal (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024) and is supported by observations from the LTD pilot project in the Midden Waal (Eerden, 2022), where no significant erosion occurred in the riparian channels.

The Nikuradse roughness height at the location of the LTD body and riparian channels has been adjusted to account for the presence of the LTDs and the associated changes in flow resistance. A value of 0.2 is used for the riparian channels, while the outer riparian channel cells, closest to the main channel, have a slightly increased roughness value of approximately 0.23. This increase is because these grid cells are partially covered by the LTD body, which has a roughness height of 0.4. The roughness for these cells is calculated by averaging the roughness values based on the proportion of the cell area covered by the LTD body and the riparian channels.

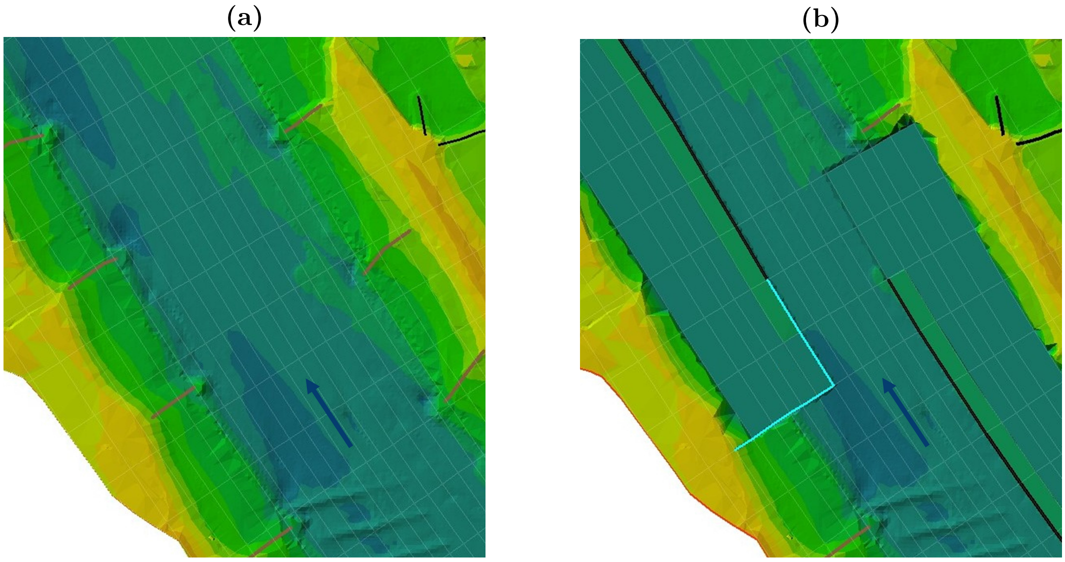

Figure 3.6: (a) Top view of the original main channel (Reference) in the Boven Waal around river kilometer 876.2. Brown lines represent groynes. (b) Top view of the main channel after implementation of LTDs 3 and 4. The black line represents the LTD crest, the light blue line represents the LTD inlet, which is at a lower level than the crest. The dark blue arrow represents the flow direction.

The crest levels of the LTDs are set at OLR + 2 meters, where OLR ("Overeengekomen Lage Rivierstand") represents the water level during a Lobith discharge of 1020 m^3/s. This approach aligns with previous LTD studies (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024). On the contrary, in this study, the inlet heights of the LTDs (Table 3.4) differ from those in the previous studies, which used OLR + 0.5 meters. The higher reduction in main channel width caused by the LTDs in this study leads to higher water levels during low Lobith discharges (1020 to 1543 m^3/s) compared to the other studies. Consequently, higher inlet heights are required to minimize flow extraction from the main channel during low discharges. This is especially crucial for the upstream LTDs 1-3, which significantly affect the low discharge distribution due to their proximity to the Pannerdensch bifurcation. Therefore, the inlet heights are higher relative to OLR for LTDs closer to the Pannerdensch bifurcation (see Table 3.4). In contrast, the inlet heights of the downstream LTDs 5 and 6 are set lower relative to OLR, because these LTDs have a less significant impact on the low discharge distribution. The lower inlet height causes main channel flow velocities to further reduce during discharges of 1543 and 1954 m^3/s along those LTDs.

The riparian channel depths are varied among the LTD Scenarios because hydraulic trial runs showed that this parameter has the most significant impact on reducing flow velocities in the main channel during during moderate to high Lobith discharges (1954 to 7009 m^3/s), compared to the Reference Scenario. Table 3.4 shows the average bed level of the riparian channels in each of the LTD Scenarios. Deeper riparian channels result in higher flow extraction from the main channel during these discharges, which leads to a more substantial reduction in main channel flow velocities. Apart from the width of the riparian channels, which is fixed after the initial design step, other LTD parameters, such as inlet height, inlet length, and crest height, influence initial flow velocities only during discharges at which the water levels just exceed the inlet or crest height, as observed from the trial runs.

The bed level of the upstream riparian channels is set higher relative to the main channel bed level than that of the downstream riparian channels (see Table 3.4). As a result, downstream LTDs cause a more significant reduction in flow velocities relative to the Reference Scenario during moderate to high discharges (1954 to 7009 m^3/s) than upstream LTDs. This approach aims to create a gradient in sediment transport capacity along the Boven Waal, as recommended by previous studies (Sloff et al., 2024; Ten Brink, 2024). These studies, which did not include such a gradient, found that the downstream LTDs were less effective at reducing erosion and even exacerbated erosion compared to the Reference Scenario.

Table 3.4: Dimensions of the LTDs in the LTD Scenarios: length, inlet heights and average bed level of the riparian channels. OLR ("Overeengekomen Lage Rivierstand") represents the water level during a Lobith discharge of 1020 m^3/s ("Overeengekomen Lage Afvoer").

Id	Rkm	Length (km)	Inlet height (m + NAP)		Average bed level (m + NAP)			
					Riparian channel			Main channel
			Relative	Absolute	LTD-S	LTD-M	LTD-L	
LTD 1	868.1-872.9	4.8	OLR + 0.9	7.98	4.81	4.61	4.11	2.50
LTD 2	872.7-876.3	3.6	OLR + 0.7	7.39	4.02	3.82	3.22	2.27
LTD 3	876.2-882.6	6.4	OLR + 0.6	6.92	2.75	2.40	2.05	1.73
LTD 4	882.5-886.2	3.7	OLR + 0.5	6.27	2.65	2.15	1.95	1.60
LTD 5	886.5-887.2	0.7	OLR + 0.3	5.58	0.97	0.35	0.15	1.09
LTD 6	887.0-891.1	4.1	OLR + 0.3	5.54	0.85	-0.05	-0.05	0.84

3.2.2 Summerdike removal and floodplain lowering in the Pannerdensch Kanaal

This study adopts a relatively simple design involving summerdike removal and floodplain lowering in the Pannerdensch Kanaal, as the focus is on assessing the effects of floodplain expansion rather than identifying an optimal design. For example, this design does not account for areas that cannot be lowered due to existing structures, such as buildings. Thereby, potential changes in floodplain roughness values resulting from floodplain lowering have not been considered in the design.

The summerdike removal consists of the removal of the summerdikes at the locations indicated by the red lines in Figure 3.7a. This removal is consistent across all three floodplain lowering scenarios and is essential to allow water to inundate the floodplains. The floodplain lowering entails a uniform reduction by either 0.5m, 2m, or 3m, depending on the scenario, across the floodplains of the Pannerdensch Kanaal at the location of the darker areas shown in Figure 3.7a. These values are determined by the use of hydraulic trial runs. A key decision in the design is that floodplain lowering cannot reduce the floodplain below 8 m + NAP (Figure 3.7b), as this would begin to affect the low discharge conditions (1020 to 1543 m^3/s), which is not desired. Additionally, groynes remain unchanged to avoid impacting these discharges.

The interventions in the Pannerdensch Kanaal are implemented in the DVR model by first removing the summerdikes. This involves removing the associated weirs from the input files and lowering the elevation of the summerdikes in the bathymetry file to match the elevation of the surrounding floodplain. Following this, a uniform floodplain lowering is applied across the entire floodplain area. As a result, the total floodplain reduction exceeds the uniform level of lowering at locations where summerdikes have been removed. This is illustrated in Figure 3.7b, where the bed level of Scenario LTD-S-FL-3 (red) is approximately 6.4 meters lower than that of the Reference Scenario (blue). Note that the summerdike on the right side of the floodplain has not been removed at this location. Appendix A.2 further elaborates on the technical implementation of the interventions in the DVR model.

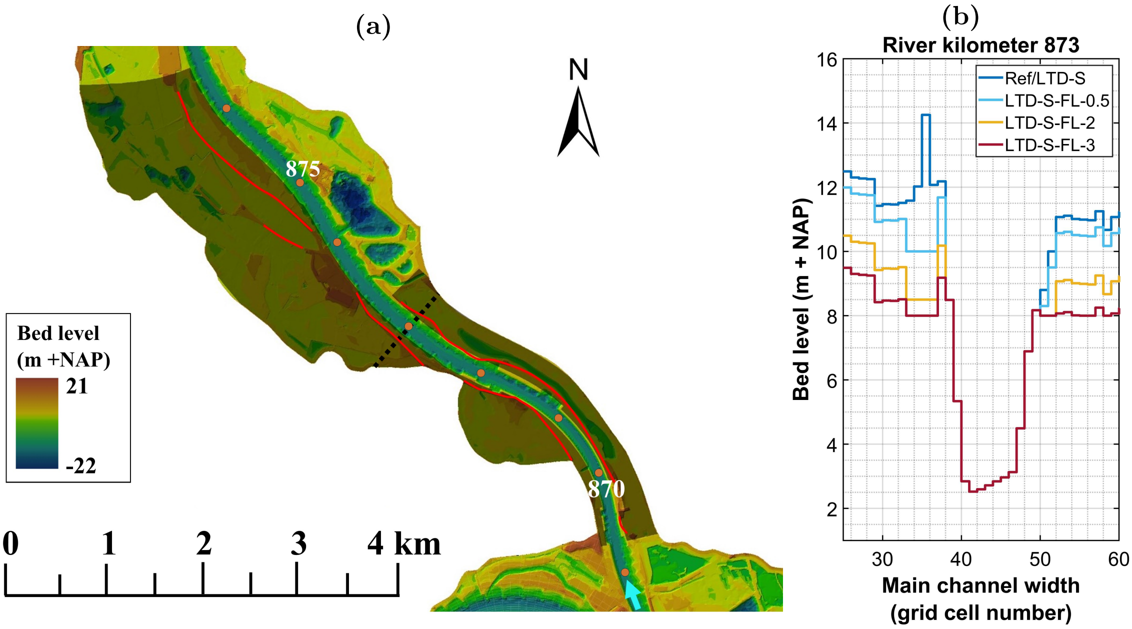

Figure 3.7: (a) Location of the floodplain lowering (darker areas) and the summerdikes (red lines) that have been removed in the Pannerdensch Kanaal. The brown dots represent river kilometers. The light blue arrow indicates the flow direction. The black dotted line shows the location of the cross-section at river kilometer 873. (b) Schematized cross-sectional bed level of the Pannerdensch Kanaal at river kilometer 873, viewed in flow direction.

The provided DVR model is not yet capable of simulating the Lobith design discharge of 16,000 m^3/s. To enable this, additional boundary conditions must be defined. This study adopts a similar approach to that used by the model developers for the discharges already incorporated into the model (Sloff et al., 2024). The upstream boundary condition at the Niederrhein is set equal to the Lobith discharge (16,000 m^3/s). The three downstream boundary conditions are the corresponding water levels for this Lobith discharge, determined using rating curves (in Dutch: "Betrekkingslijnen") (Sloff et al., 2024). Further details on the technical implementation of this discharge within the DVR model can be found in Appendix B.

4 Results

This section presents and analyses the results of the simulations as outlined in the methodology. Section 4.1 examines the development of the discharge partitioning to the Pannerdensch Kanaal and the bed level development in the Boven Waal during the Reference Scenario. Section 4.2 then analyses the main effects of the LTDs in the Boven Waal on both the low discharge partitioning to the Pannerdensch Kanaal and the bed degradation in the Boven Waal, as well as in other affected reaches. Finally, Section 4.3 discusses the combined effects of LTDs in the Boven Waal with summerdike removal and floodplain lowering in the Pannerdensch Kanaal, focusing on the discharge distribution and bed degradation in the Boven Waal and other affected reaches.

4.1 Analysis of the Reference Scenario

The Reference Scenario (abbreviated as 'Ref') simulates the morphological development of the Rhine branches as represented in the DVR model, without any additional interventions. This scenario serves as a baseline for comparing the intervention scenarios against, enabling the investigation of the relative effects of those interventions. The following sections discuss the development of discharge partitioning to the Pannerdensch Kanaal and the bed level changes in the Boven Waal, as these are the critical focus points of this study.

4.1.1 Development of discharge partitioning to the Pannerdensch Kanaal

The discharge partitioning to the Pannerdensch Kanaal measured in 2024 does not meet the required values for Lobith discharges below 1570 m^3/s. This is evident in Figure 4.1a, where the black line falls below the black dashed line at these discharges. The simulated low discharge partitioning to the Pannerdensch Kanaal at the start of the Reference Scenario (blue in Figure 4.1a) closely aligns with the measured low discharge partitioning. To meet the required partitioning, the discharge to the Pannerdensch Kanaal must increase by 14 m^3/s at a Lobith discharge of 1543 m^3/s, by 61 m^3/s at 1020 m^3/s, and by 63 m^3/s at 1294 m^3/s.

The discharge partitioning to the Pannerdensch Kanaal decreases over time due to ongoing erosion in the Waal, which leads to more discharge being directed towards the Waal. This can be seen by the negative values of the blue dashed line in Figure 4.1b. This erosion, which is discussed further in the next section, results in an additional 20 m^3/s reduction in discharge partitioning to the Pannerdensch Kanaal during low discharges (1020 to 1543 m^3/s), further moving the required discharge partitioning out of reach. A significantly larger decrease in discharge partitioning is noted at a Lobith discharge of 2601 m^3/s compared to other discharges. This likely originates from the behavior of the weir at Driel, which acts as the downstream boundary of the Nederrijn, as it transitions to free-flowing conditions at this discharge in the DVR model. The specific cause of this anomaly is not examined further, as it is not essential to the core focus of this study.

Overall, the discharge partitioning to the Pannerdensch Kanaal, as initially simulated by the DVR model, closely resembles the measured discharge partitioning (Figure 4.1a). The largest deviation is observed at a Lobith discharge of 7009 m^3/s, at which the DVR model overestimates the discharge partitioning to the Pannerdensch Kanaal by approximately 48 m^3/s. This indicates that the model is less accurate in simulating discharge distribution during high discharges.

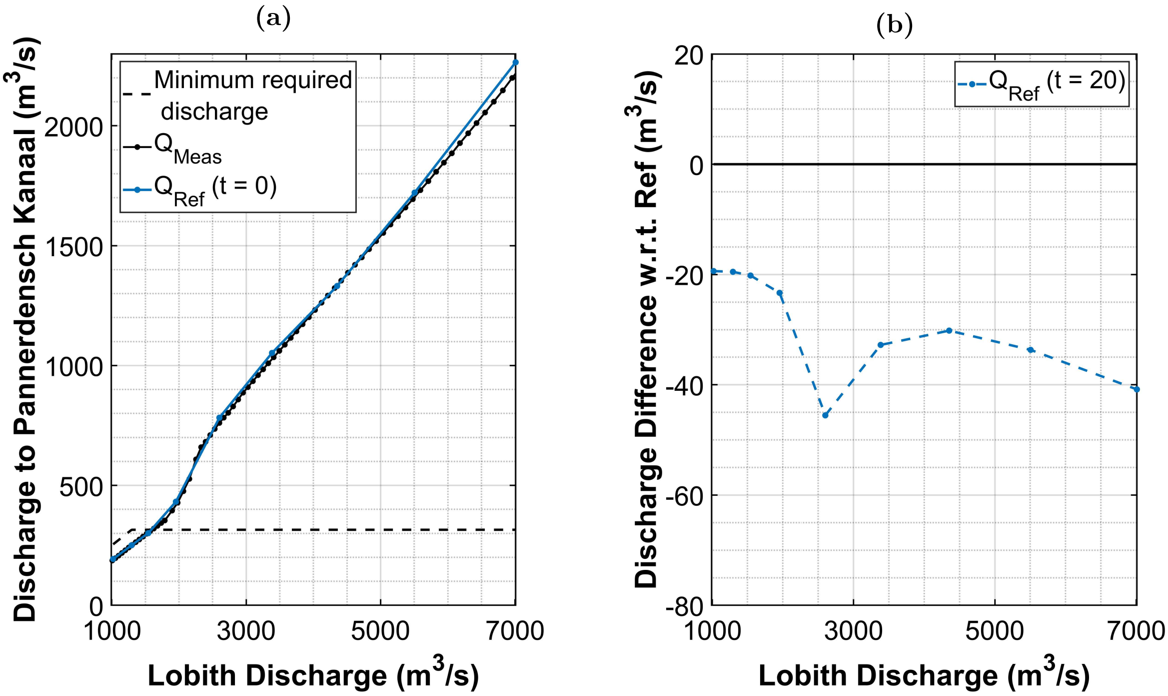

Figure 4.1: Discharge partitioning to the Pannerdensch Kanaal in the Reference Scenario at the start (t = 0), the measured discharge in 2024 and the minimum required discharge to the Pannerdensch Kanaal. (b) Difference in discharge partitioning to the Pannerdensch Kanaal between year 20 and year 0 in the Reference Scenario. Negative values mean a decrease in discharge partitioning.

4.1.2 Bed level development in the Boven Waal

Significant erosion occurs in the main channel of the Boven Waal over a 20-year period during the Reference Scenario. This is evident from the extensive red areas in the main channel shown in Figure 4.2 and the width-averaged bed level development of the main channel of the Boven Waal over time illustrated in Figure 4.3a. Remarkably, substantial erosion takes place in the inner bends alongside the fixed layers at Nijmegen and Erlecom, while the bed level at the fixed layers themselves does not change significantly. This is illustrated by the red areas on the inner side of the bends around x-coordinates 195,000 m (Erlecom) and 188,000 m (Nijmegen) in Figure 4.2, as well as by the change in cross-sectional bed level at river kilometer 884, which is in the bend containing the fixed layer at Nijmegen (see Figure 4.3b). This phenomenon can be primarily attributed to limited sediment availability over the fixed layer and the differing Chézy coefficients—40 $m^{1/2}/s$ for the fixed layer compared to 50 $m^{1/2}/s$ for the rest of the riverbed, including the inner bends alongside the fixed layers. A higher Chézy coefficient leads to higher flow velocities, creating a sediment transport gradient between the fixed layer and the inner bend, which leads to erosion in the inner bend.

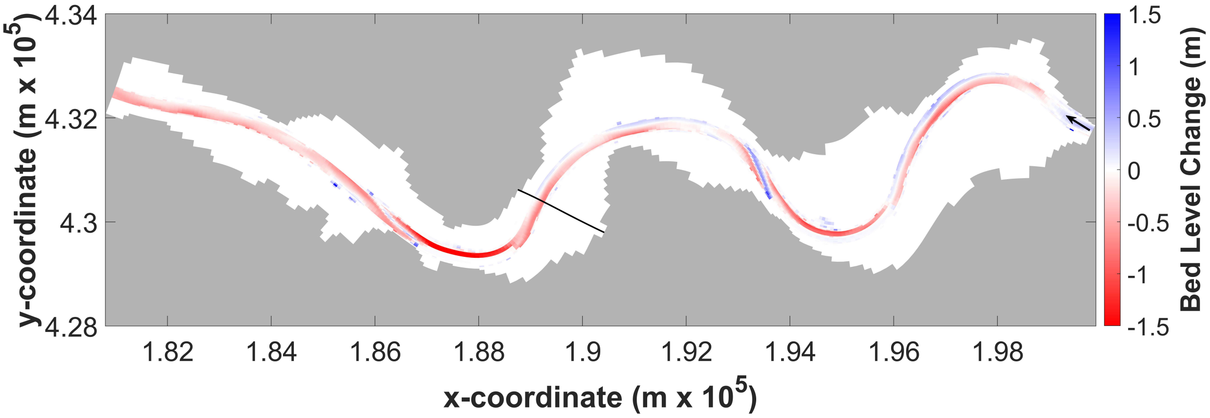

Figure 4.2: Bed level change in the Boven Waal over 20 years of morphological development during the Reference Scenario. Blue areas indicate sedimentation, while red areas indicate erosion. The black line represents the boundary between the upstream (rkm 867.3-882) and downstream section (rkm 882-891) of the Boven Waal. The black arrow shows the flow direction.

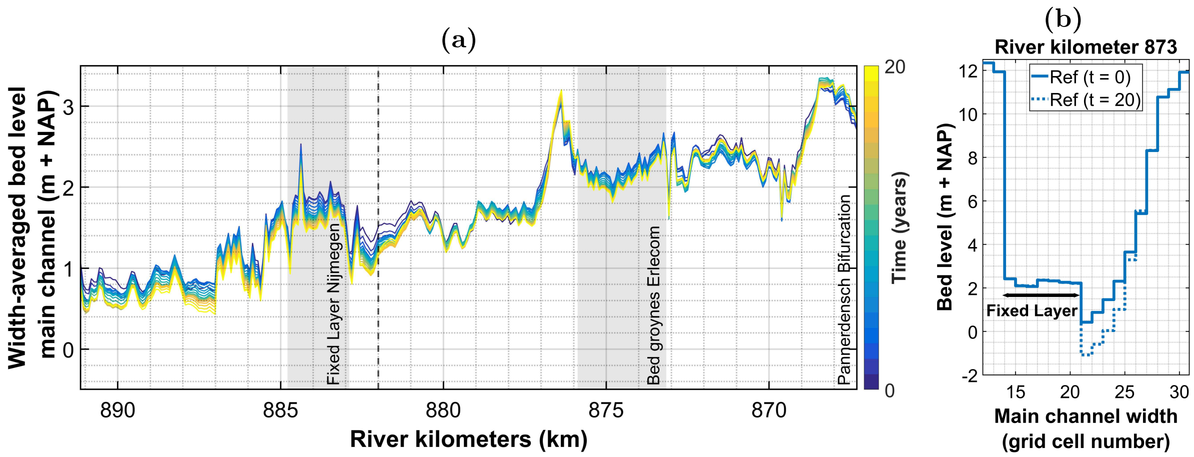

Figure 4.3: (a) Width-averaged bed level development of the main channel in the Boven Waal during the Reference Scenario for every year of the simulation. The grey areas represent the fixed layers. The dashed line at river kilometer 882 marks the boundary between the upstream (BW-1; rkm 867.3-882) and downstream section (BW-2; rkm 882-891) of the Boven Waal. (b) Cross-sectional bed level for the Reference Scenario at the start (t = 0) and end (t = 20) of the simulation at river kilometer 884, viewed in the flow direction.

Significantly more erosion occurs in the downstream section of the Boven Waal (BW-2; rkm 882-891) compared to the upstream section (BW-1; rkm 867.3-882). This is illustrated by the significant difference in reach-averaged bed level change shown in Figure 4.4a. Until year 3, the reach-averaged bed level changes in both sections remain relatively similar; however, a change in trend occurs afterward. This moment corresponds to the start of erosion in the Boven Rijn after an initial period of sedimentation (discussed in the later results section 4.2.4), leading to increased sediment transport to the Boven Waal. As a result, the bed level in the upstream section of the Boven Waal experiences less erosion compared to the downstream section.

Erosion in the main channel of the Boven Waal primarily occurs during Lobith discharges ranging from 3384 to 7009 m^3/s. This is demonstrated by the negative accumulated bed level change over a 20-year period during these discharges, shown in Figure 4.4b. It highlights the need to reduce the erosivity of the flow during these discharges. Conversely, reach-averaged sedimentation takes place during Lobith discharges between 1020 and 2601 m^3/s, which mitigates the bed degradation in the Boven Waal.

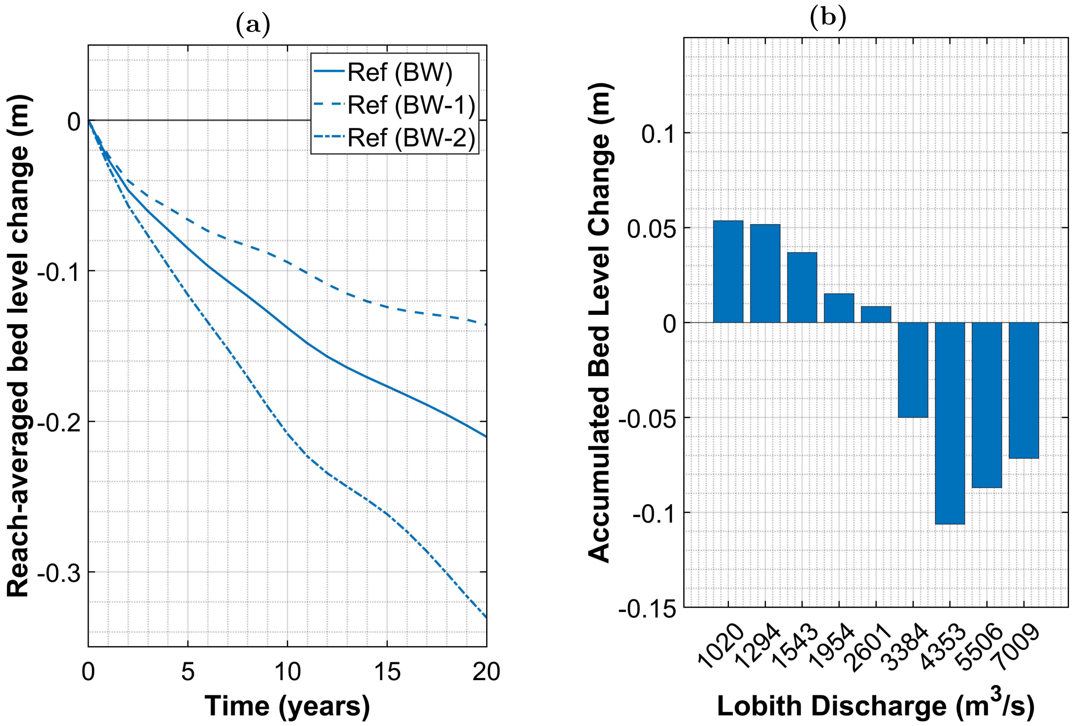

Figure 4.4: (a) Reach-averaged bed level change in the main channel of the Boven Waal over time relative to t = 0 for the Reference Scenario. A distinction is made between the entire Boven Waal (BW; rkm 867.3-891), and the upstream (BW-1; rkm 867.3-882) and downstream section (BW-2; rkm 882-891) of the Boven Waal. (b) Accumulated reach-averaged bed level change (m) per Lobith discharge during 20 years of morphological development for the Reference Scenario.

4.2 Effects of the LTDs

This section presents the main effects of the LTDs in the Boven Waal regarding the low discharge distribution at the Pannerdensch bifurcation and bed degradation in the Boven Waal. Additionally, the impact on bed degradation in other significantly affected branches is also discussed. This follows from the simulation of the three LTD Scenarios, described in Section 3.2, which are referred to as LTD-S (small), LTD-M (medium) and LTD-L (large). The primary difference between these scenarios lies in the depth of the riparian channels, with Scenario LTD-L having the deepest riparian channels. The riparian channels become active at a Lobith discharge of 1294 m^3/s; however, significant flow extraction that reduces main channel flow velocities relative to the Reference Scenario begins to occur from a discharge of 1954 m^3/s.

The physical processes underlying the effects of the LTDs have been qualitatively explained in detail in the theoretical background (Section 2.2). This section will primarily concentrate on discussing the most significant quantitative effects of the LTDs regarding the discharge distribution and bed degradation.

4.2.1 Effect on the discharge distribution

The implementation of the LTDs initially results in a significantly increased discharge partitioning to the Pannerdensch Kanaal during low Lobith discharges (1020 to 1543 m^3/s), compared to the Reference Scenario (+24-42 m^3/s) (Figure 4.5). This represents substantial progress in achieving the minimum required discharge towards the Pannerdensch Kanaal, with the target discharge at a Lobith discharge of 1543 m^3/s now being met (required: 315 m^3/s, achieved: 325 m^3/s). The increase in discharge partitioning is attributed to the reduction in main channel width in the Boven Waal caused by the LTDs during these low discharge conditions, which leads to increased water levels compared to the Reference Scenario. The resulting backwater effects propagate upstream to the Pannerdensch bifurcation, leading to a redistribution of flow due to which more discharge is directed towards the Pannerdensch Kanaal.

Over time, the LTD Scenarios lead to a smaller decrease in low discharge partitioning to the Pannerdensch Kanaal than the Reference Scenario (Figure 4.5b). The decrease in discharge partitioning can be attributed to bed degradation in the Boven Waal. As the bed level of the Boven Waal declines, the water levels in this section also decrease. The resulting backwater effects lead to an increased discharge partitioning to the Waal and a corresponding reduction in flow to the Pannerdensch Kanaal. The LTDs cause reduced erosion in the Boven Waal (to be discussed in more detail in the next section), resulting in a less pronounced decrease in discharge partitioning to the Pannerdensch Kanaal over time in the LTD Scenarios.

The reduction in low discharge partitioning to the Pannerdensch Kanaal over a 20-year period during the LTD Scenarios is less significant than the initial increase in low discharge partitioning to the Pannerdensch Kanaal resulting from the LTDs (Figure 4.5a). Consequently, after 20 years, there remains a significantly higher level of low discharge partitioning to the Pannerdensch Kanaal than what was initially observed in the Reference Scenario (+15-30 m^3/s; see Figure 4.5a).

During Lobith discharges ranging from 2601 to 7009 m^3/s, the LTDs result in a significant reduction in discharge partitioning towards the Pannerdensch Kanaal compared to the Reference Scenario (Figure 4.5). This reduction occurs because, at these discharge levels, the riparian channels extract a significant volume of flow from the main channel, effectively widening it compared to the Reference Scenario. As a result, the water levels decrease, and consequently, the flow at the Pannerdensch bifurcation is redistributed through backwater effects, leading to a greater discharge partitioning to the Waal and a reduced flow to the Pannerdensch Kanaal.

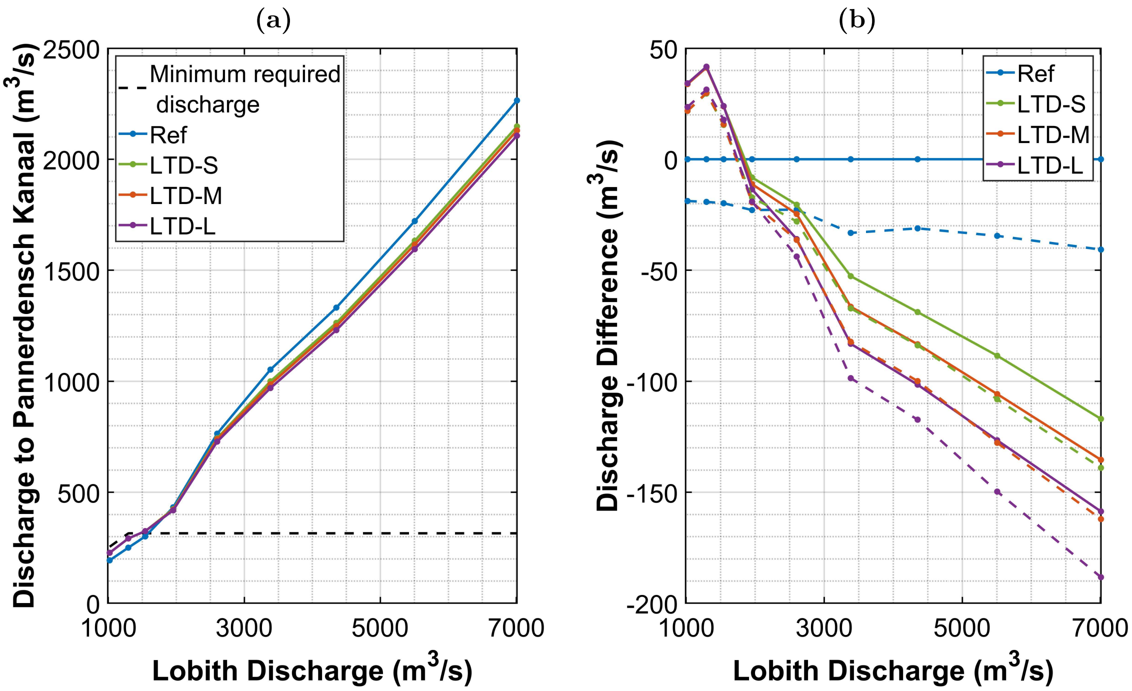

Figure 4.5: (a) Discharge partitioning to the Pannerdensch Kanaal at t = 0. The dashed black line represents the minimum required discharge to the Pannerdensch Kanaal. (b) Difference in discharge partitioning to the Pannerdensch Kanaal with respect to the discharge distribution of the Reference Scenario at t = 0. The solid lines represent the discharge partitioning at t = 0, the dashed lines represent the discharge partitioning at t = 20.

To conclude, the LTDs significantly enhance low discharge partitioning to the Pannerdensch Kanaal compared to the Reference Scenario. Initially, they increase low discharge partitioning by 24 to 42 m^3/s, and after 20 years, the low discharge partitioning to the Pannerdensch Kanaal remains higher than initially observed in the Reference Scenario, with an increase of 15-30 m^3/s. As a result, the required discharge partitioning to the Pannerdensch Kanaal at a Lobith discharge of 1543 m^3/s is achieved both at the beginning and the end of the 20-year period.

4.2.2 Effect on the bed degradation in the Boven Waal

The LTDs lead to a significant reduction in bed degradation in the main channel of the Boven Waal (Figure 4.6a). In this figure, it can be seen that the bed level change is less for all the LTD scenarios compared to the Reference Scenario starting from year 9, indicating a reduction in bed degradation from that point onward. The reach-averaged bed level of the main channel in the Boven Waal declines by approximately 8 cm over a 20-year period in the LTD Scenarios, compared to a decline of approximately 15 cm in the Reference Scenario.

Significant erosion persists in the LTD Scenarios, predominantly occurring in the downstream section of the Boven Waal (BW-2), ranging from river kilometers 882 to 891 (Figure 4.6b). This figure illustrates that the bed level change caused by the LTDs in the downstream section of the Boven Waal is greater than in the Reference Scenario right from the beginning, meaning an increase in bed degradation in this section. In contrast, the upstream section of the Boven Waal (rkm 867.3 to 882) exhibits overall sedimentation in the LTD scenarios, indicated by the positive bed level change in Figure 4.6b.

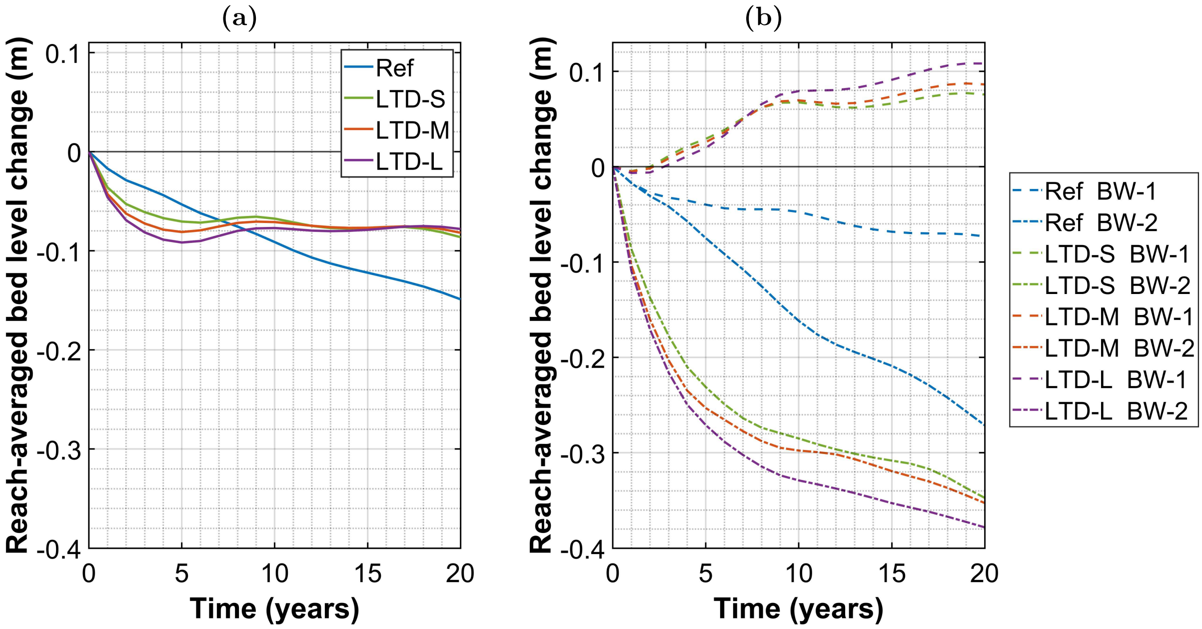

Figure 4.6: Reach-averaged bed level change of the main channel over time relative to t = 0 for the Reference Scenario and LTD Scenarios. (a) the reach-averaged bed level change for the entire Boven Waal (rkm 867.3-891), and (b) for the upstream part (BW-1; rkm 867.3-882) and the downstream part (BW-2; rkm 882-891km) of the Boven Waal.

The differing trend in bed level change between the upstream and downstream section of the Boven Waal is also evident in the map of bed level changes in the Boven Waal during Scenario LTD-S (Figure 4.7). This figure illustrates predominantly sedimentation (blue) in the upstream section and primarily erosion (red) in the downstream section. Additional impacts of the LTDs apparent in this map include substantial erosion at the LTD transition zones and sedimentation within the riparian channels, particularly in the downstream section. The bed level change during Scenarios LTD-M and LTD-L shows similar effects.

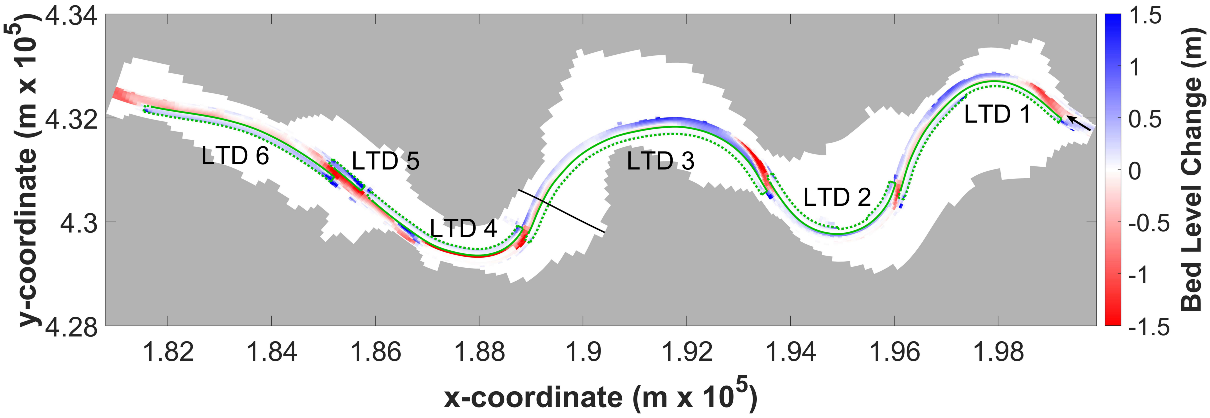

Figure 4.7: Bed level change in the Boven Waal over 20 years of morphological development during Scenario LTD-S. Blue areas indicate sedimentation, while red areas indicate erosion. Solid green lines depict LTD bodies, whereas the combination of solid and dotted green lines outlines the boundaries of the riparian channels. The black line marks the boundary between the upstream (rkm 867.3-882) and downstream section (rkm 882-891) of the Boven Waal. The black arrow shows the flow direction.

The LTDs result in an overall reduction in bed degradation in the main channel of the Boven Waal compared to the Reference Scenario. This overall impact is primarily attributable to four specific effects of the LTDs. Figure 4.8 provides a schematic overview of how these specific effects contribute to the overall impact on bed degradation. The significantly reduced erosion during moderate and high Lobith discharges (1954 to 7009 m^3/s) is the main intended effect of the LTDs on reducing bed degradation in the Boven Waal (Effect 1). However, this positive effect is counteracted by three unintended effects of the LTDs (Figure 4.8). The subsequent sections will discuss the four effects in detail, one by one.

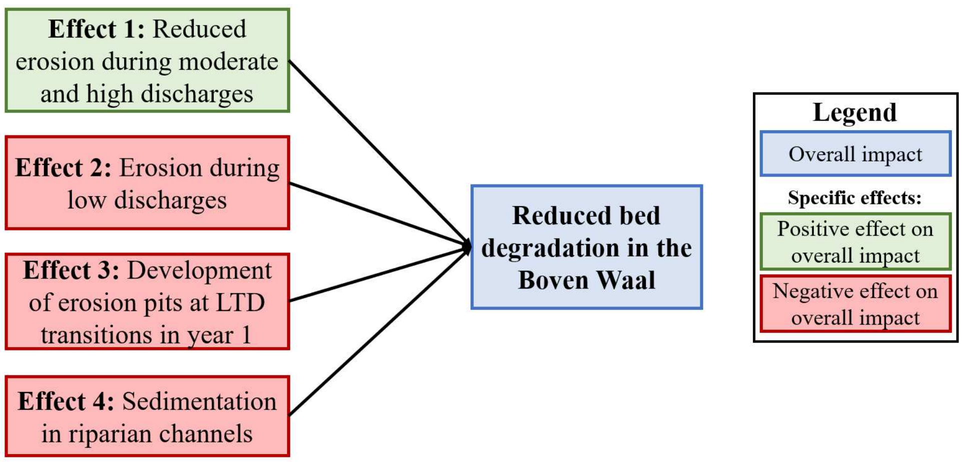

Figure 4.8: Schematic overview of how specific effects of the LTDs contribute to overall reduced bed degradation in the Boven Waal.

Reduced erosion during moderate and high discharges
The LTDs significantly reduce erosion during moderate and high Lobith discharges (1954 to 7009 m^3/s). From a reach-averaged perspective, significant sedimentation even occurs during these discharges in the main channel of the Boven Waal (Figure 4.9a). The reach-averaged accumulated sedimentation during these discharges is approximately 0.46 meters, whereas the Reference Scenario exhibits overall erosion of approximately 0.29 meters during the same discharge conditions. This contrast can be attributed to the fact that the LTDs significantly decrease flow velocities during moderate to high discharges compared to the Reference Scenario, as illustrated by the initial flow velocity differences shown in Figure 4.10b. A reduction in flow velocities results in reduced sediment transport capacities, thereby creating a less erosive flow.

The influence of the LTDs on bed level development during moderate to high Lobith discharges (1954 to 7009 m^3/s) is less pronounced in the downstream section of the Boven Waal (BW-2) compared to the upstream section (BW-1) (Figures 4.9b and 4.9c). This phenomenon is primarily due to two processes. The first process is that the LTDs in the upstream section significantly reduce sediment transport capacities during these discharges. The design of the LTDs creates a velocity gradient in the upstream section of the Boven Waal (Figure 4.10a), causing the flow to gradually lose its erosivity in the downstream direction. However, the LTDs in the downstream section are less effective in reducing flow velocity beyond the influence of LTD 3 (Figure 4.10), thereby limiting sedimentation potential in the downstream section and even resulting in significant erosion during the high discharges (4353 to 7009 m^3/s; see Figure 4.9c). Second, significantly more sedimentation occurs in the downstream riparian channels compared to the upstream riparian channels, which reduces the availability of sediment for deposition in the main channel of the downstream section. This phenomenon will be discussed in greater detail in the section concerning sedimentation in the riparian channels (Effect 4).

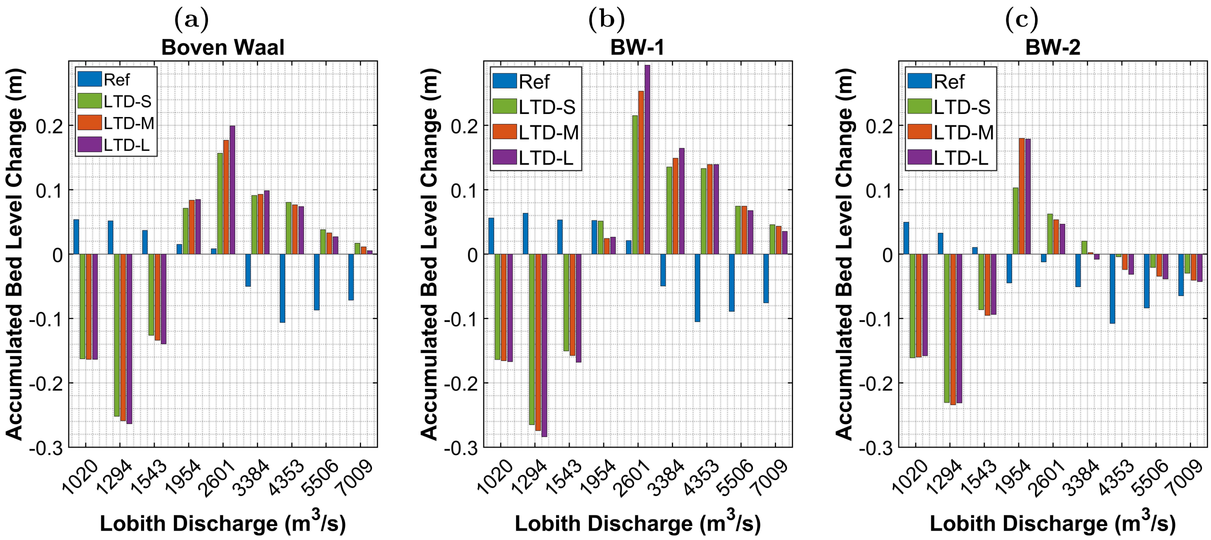

Figure 4.9: Accumulated reach-averaged bed level change (m) per Lobith discharge during 20 years of morphological development for the Reference Scenario and the LTD Scenarios. For (a) the entire Boven Waal (rkm 867.3-891), (b) the upstream part of the Boven Waal (BW-1; rkm 867.3-882), and (c) the downstream part of the Boven Waal (BW-2; rkm 882-891).

It is important to note that Figure 4.9 presents the total accumulated bed level changes over a 20-year period for each Lobith discharge separately. Consequently, the duration of the discharges during a model simulation year plays a significant role in the amount of accumulated bed level change they induce. For instance, this mainly explains why the accumulated bed level change during a discharge of 2601 m^3/s (which occurs 52 days per year) is significantly greater than that induced by higher discharges, which occur much shorter (e.g., 7009 m^3/s occurs for only 3 days per year).

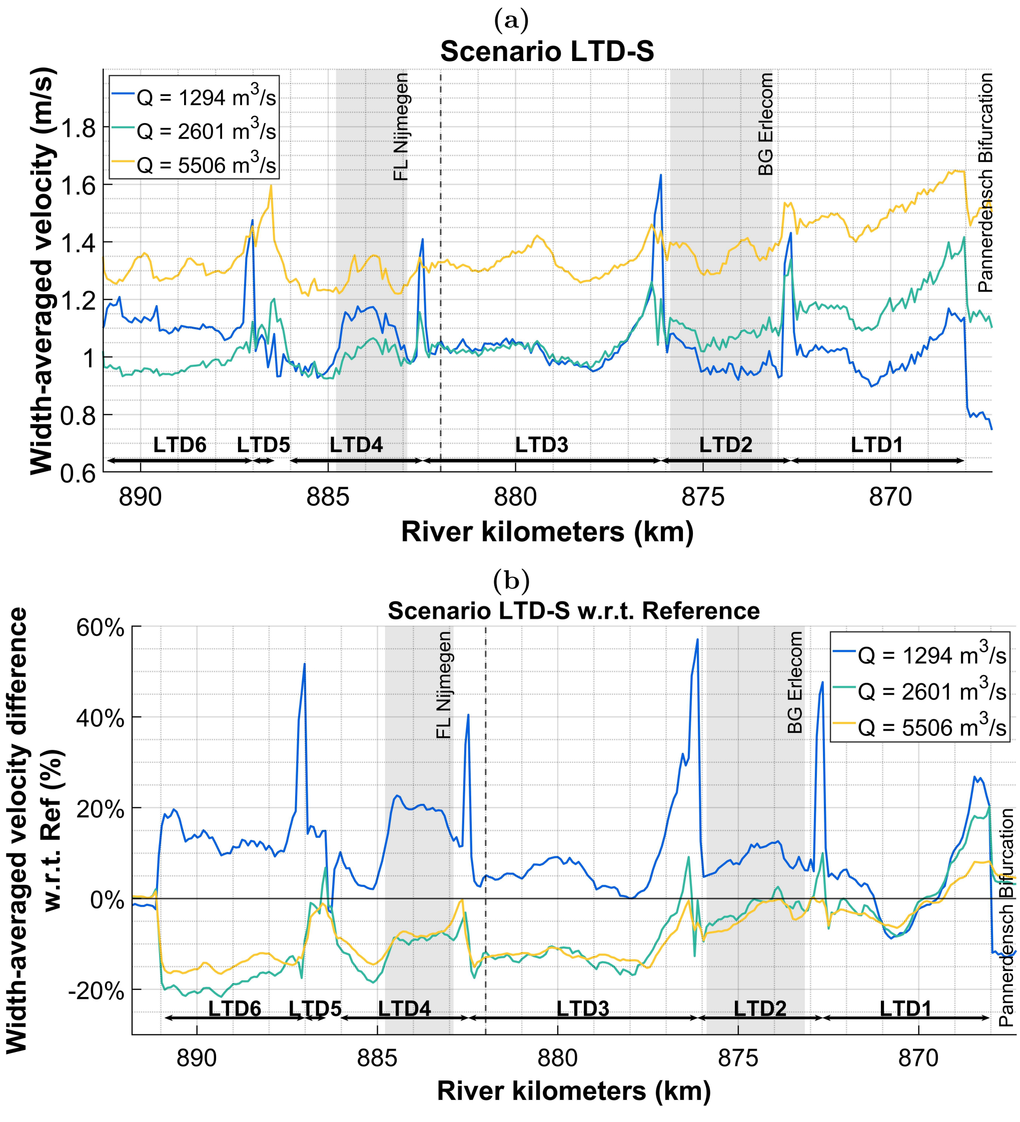

Figure 4.10: (a) Width-averaged flow velocities in the main channel of the Boven Waal for three representative Lobith discharges at the start of Scenario LTD-S (t=0). (b) Percentage difference in width-averaged flow velocities between Scenario LTD-S and the Reference Scenario. The grey areas represent the fixed layers at Nijmegen and Erlecom, the black arrows represent the LTDs. The dashed black line marks the boundary between the upstream section (BW-1; rkm 867.3-882) and the downstream section of the Boven Waal (BW-2; rkm 882-891).

Erosion during low discharges
The LTDs induce significant erosion in the Boven Waal during low Lobith discharges (1020 to 1543 m^3/s) (Figure 4.9). Cumulatively, these discharges result in approximately 0.54 meters of reach-averaged erosion in the LTD Scenarios, which exceeds the positive effects observed during moderate to high discharges (~0.46 m sedimentation; Figure 4.9a). This presents an opposite pattern compared to the Reference Scenario, where low discharges lead to a cumulative sedimentation of 0.14 meters. Although unintended, this effect of the LTDs counteracts the objective of reducing bed degradation in the Boven Waal. The cause of this effect lies in the significant reduction of the main channel width induced by the LTDs during low discharges (Figure 4.12a). As a result, the flow must pass through a smaller cross-sectional area, and, by the principle of mass conservation, this leads to increased flow velocities compared to the Reference Scenario, as illustrated by the initial flow velocity differences in Figure 4.10b. Higher flow velocities increase sediment transport capacity, consequently leading to enhanced erosion.

Development of erosion pits at LTD transitions in year 1
The erosion pits that develop in the LTD Scenarios at the upstream end of LTD 1 and at the transitions between the various LTDs account for a large part of the erosion observed in the longitudinal bed level change of the Boven Waal (Figures 4.11a and 4.11b). These erosion pits rapidly form within the first year of the simulation (Figure 4.11c) due to localized increases in sediment transport capacity resulting from significantly enhanced flow velocities in the main channel at these locations, particularly during low discharges (1020 to 1543 m^3/s; Figure 4.10). Most erosion pits occur at the transitions between successive LTDs on opposite sides of the main channel, where a substantially narrower passage occurs (see Figures 4.7 and 4.12b). According to the principle of mass conservation, this narrowing leads to a significant increase in flow velocity. There are three erosion pits that do not occur at such transitions; the increase in sediment transport capacity at these locations, which leads to erosion, is explained by a different mechanism, as outlined in Table 4.1.

Table 4.1: Explanation for the local increase in sediment transport capacity occurring at three particular erosion pits.

Erosion pit	Explanation for local increase in sediment transport capacity
Start of LTD 1	The local cross-sectional geometry results in the LTDs reducing the main channel's cross-sectional area more than they expand it (across all discharges) (Figure 4.12a), thereby significantly increasing flow velocities compared to upstream (Figure 4.10).
Section between LTD 4 and 5	No LTD is present here to reduce flow velocities during moderate to high discharges, because of the outflow point of the Spiegelwaal. This leads to a significant increase in flow velocities during these discharges compared to upstream (Figure 4.10).
Along LTD 5	This LTD does not extract sufficient flow from the main channel to significantly reduce flow velocities during moderate to high discharges compared to the Reference Scenario. At the same time, the LTD does cause a significant increase in flow velocity during low discharges (Figure 4.10).

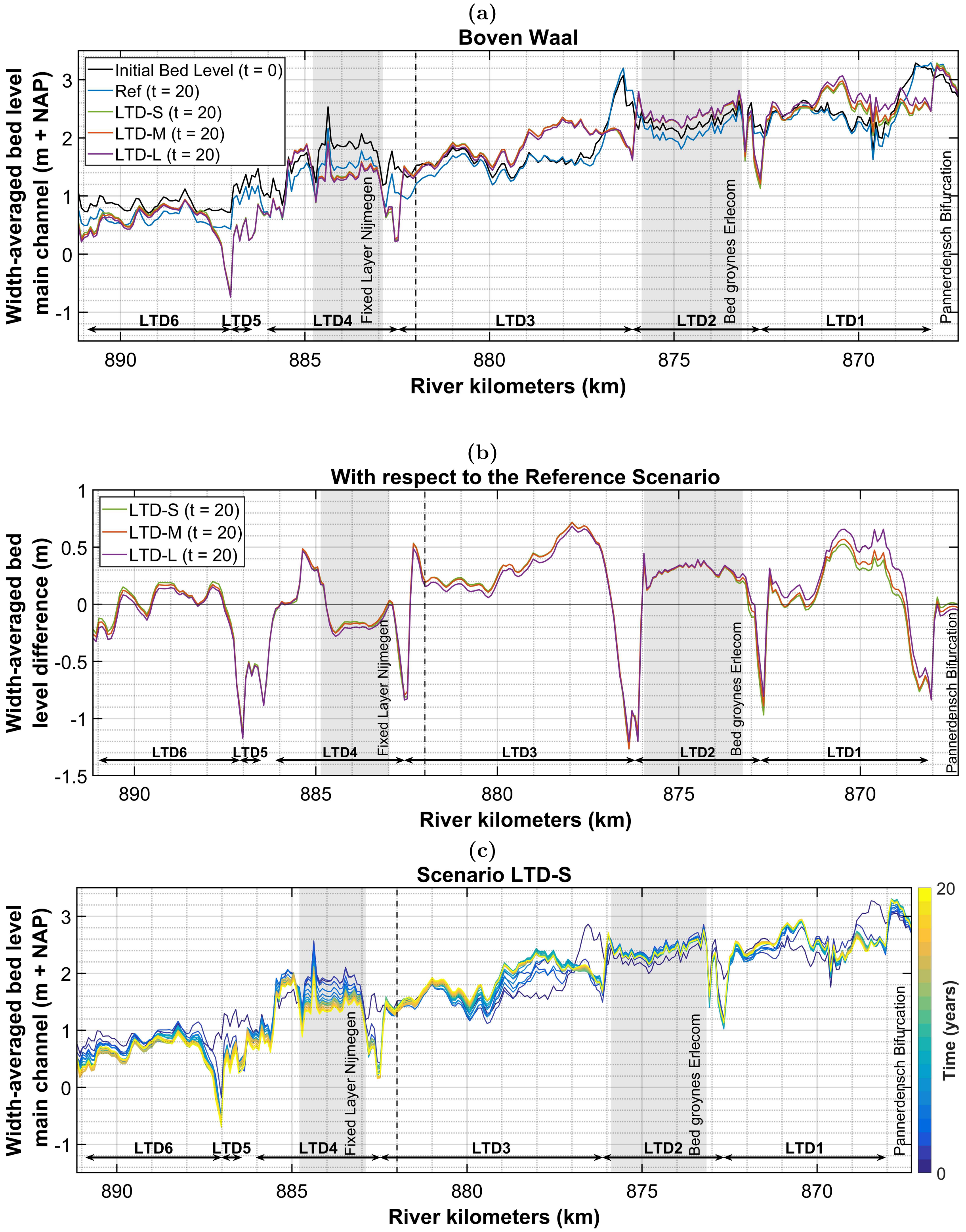

Figure 4.11: (a) Width-averaged bed level of the main channel in the Boven Waal after 20 years of bed level development, and (b) the difference compared to the Reference Scenario. (c) Width-averaged bed level development of the main channel during Scenario LTD-S for every year of the simulation. The grey areas represent the fixed layers, the black arrows represent the LTDs. The dashed line at rkm 882 marks the boundary between the upstream and downstream section of the Boven Waal.

The bed level of the main channel in the Boven Waal responds to the sharp increase in sediment transport capacity at the LTD transitions by experiencing significant erosion, which subsequently creates additional cross-sectional space for the flow (Figures 4.12a and 4.12b). As water levels remain relatively stable during the first year, flow velocities at these locations significantly decrease (conservation of mass). Consequently, the erosion pits do not expand significantly beyond the first year.

From a reach-averaged perspective, the development of the erosion pits significantly contributes to overall erosion in the Boven Waal (approximately 4 cm; Figure 4.6a). However, this impact is relatively minor compared to the substantial effects of the LTDs during low (Effect 2) and moderate to high Lobith discharges (Effect 1) (Figure 4.9a). This limited impact is because a significant portion of the eroded sediment is subsequently deposited downstream within the Boven Waal, reducing the net effect on bed degradation from a reach-averaged perspective. This is particularly evident for the sediment eroded from the pits at the upstream ends of LTDs 1 to 3, due to which substantial sedimentation occurs in the main channel along these LTDs in the first year (Figure 4.11c).

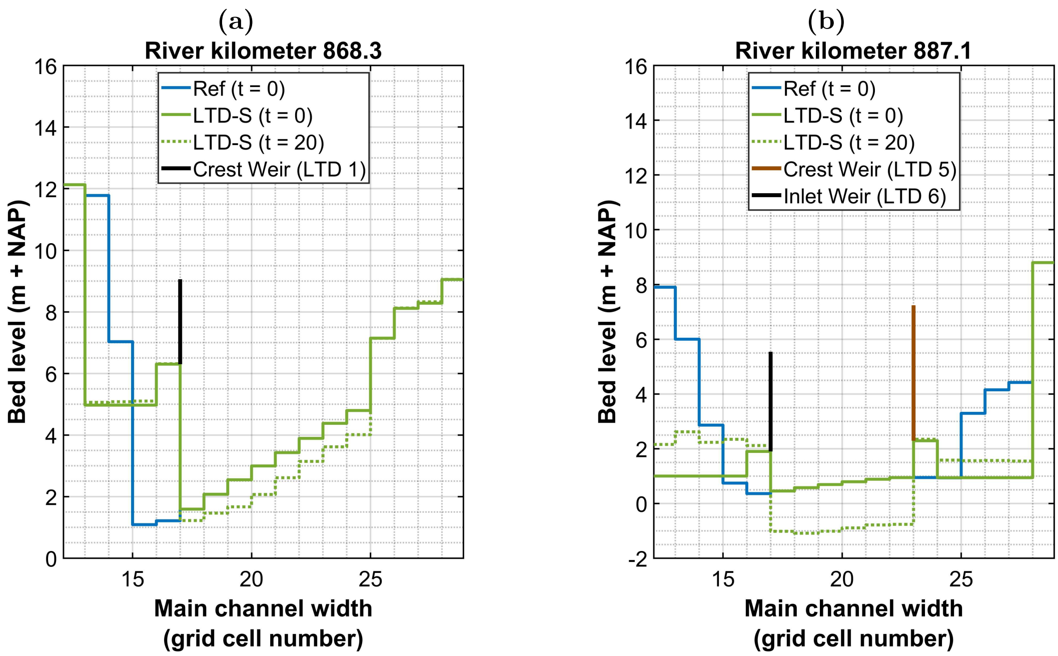

Figure 4.12: Cross-sectional bed level for the Reference Scenario (t = 0) and Scenario LTD-S (t = 0 and t = 20) at river kilometers (a) 868.3 and (b) 887.1, viewed in the flow direction.

The development of the erosion pits during the first year influences the reach-averaged bed level of the Boven Waal because, in the downstream section (BW-2), a large portion of the eroded sediment from the erosion pits is deposited in the riparian channels (Figure 4.13c). Consequently, less sediment remains available for deposition downstream along the LTDs within the main channel, due to which reach-averaged erosion occurs in this section of the Boven Waal in year 1 (Figures 4.6b and 4.14c). Therefore, the impact of the development of the erosion pits (Effect 3) on reduced bed degradation in the Boven Waal cannot be considered independently from the sedimentation occurring in the riparian channels (Effect 4). Without significant sedimentation in the riparian channels, the development of the erosion pits would not have a significant impact on the reach-averaged erosion, which is the case for the upstream section of the Boven Waal (Figure 4.14b).

In conclusion, the development of the erosion pits at the LTD transitions (Effect 3) particularly exerts a substantial influence on local bed degradation within the main channel of the Boven Waal. It also affects reach-averaged bed degradation when considered together with the associated sedimentation occurring in the riparian channels. Nevertheless, this reach-averaged effect is considerably less pronounced compared to the reduced erosion during moderate to high discharges (Effect 1) and the erosion during low discharges (Effect 2).

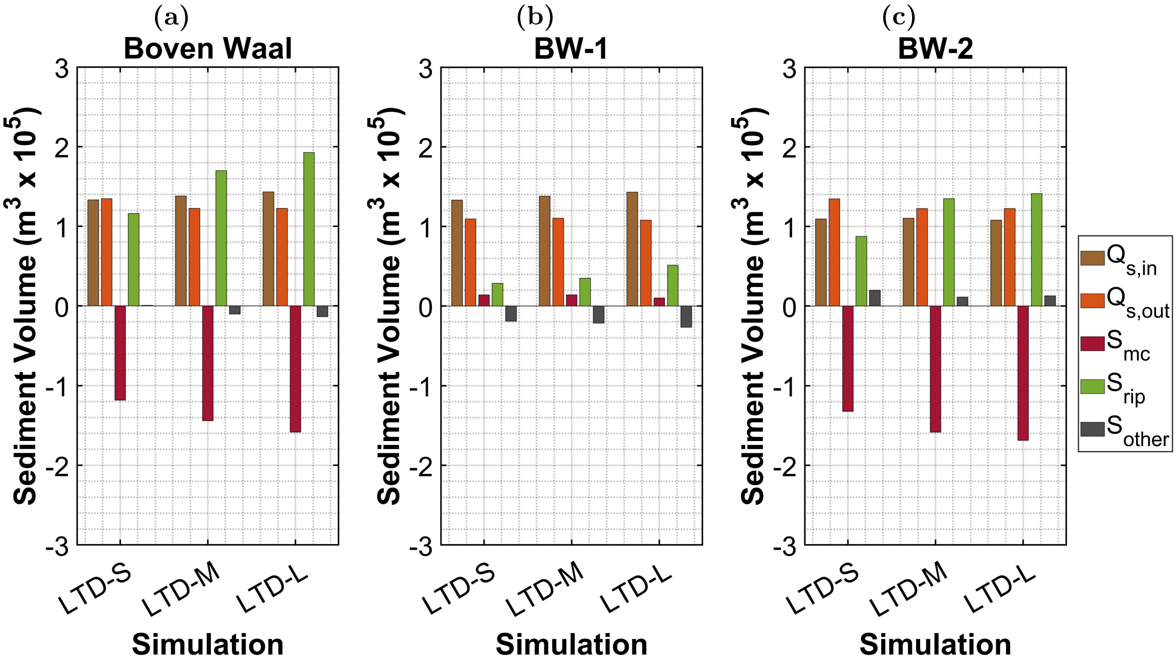

Figure 4.13: Sediment balance for year 1 during the LTD Scenarios for (a) the entire Boven Waal (rkm 867.3-891), (b) the upstream section of the Boven Waal (BW-1; rkm 867.3-882), and (c) the downstream section of the Boven Waal (BW-2; rkm 882-891). Parameters: total sediment volume going in ($Q_{s,in}$), total sediment volume going out ($Q_{s,out}$), total storage in main channel (S_{mc}), total storage in riparian channels (S_{rip}), and total storage in other areas such as groynal areas and floodplains (S_{other}).

Sedimentation in riparian channels

The total volume of sediment entering the Boven Waal in the LTD Scenarios exceeds the sediment volume leaving the system (Figure 4.14a). However, significant reach-averaged erosion still occurs in the main channel due to a considerable amount of sediment being deposited in the riparian channels. In total, a greater volume of sediment is deposited in the riparian channels of the Boven Waal than is eroded from the main channel (Figure 4.14a). Approximately 25% of the sedimentation in the riparian channels occurs within the first year of the simulation (Figure 4.13a), associated with the development of the erosion pits. Significant sedimentation continues to occur throughout the remaining 20-year period. The total sedimentation in the riparian channels ranges from 435,182 m^3 (LTD-S) to 795,069 m^3 (LTD-L) (Figure 4.14a), which would translate to an increase in the reach-averaged bed level of the main channel of approximately 0.14 to 0.22 m if this sediment is deposited in the main channel. This highlights the importance of Effect 4, which counteracts the reduced bed degradation in the Boven Waal.

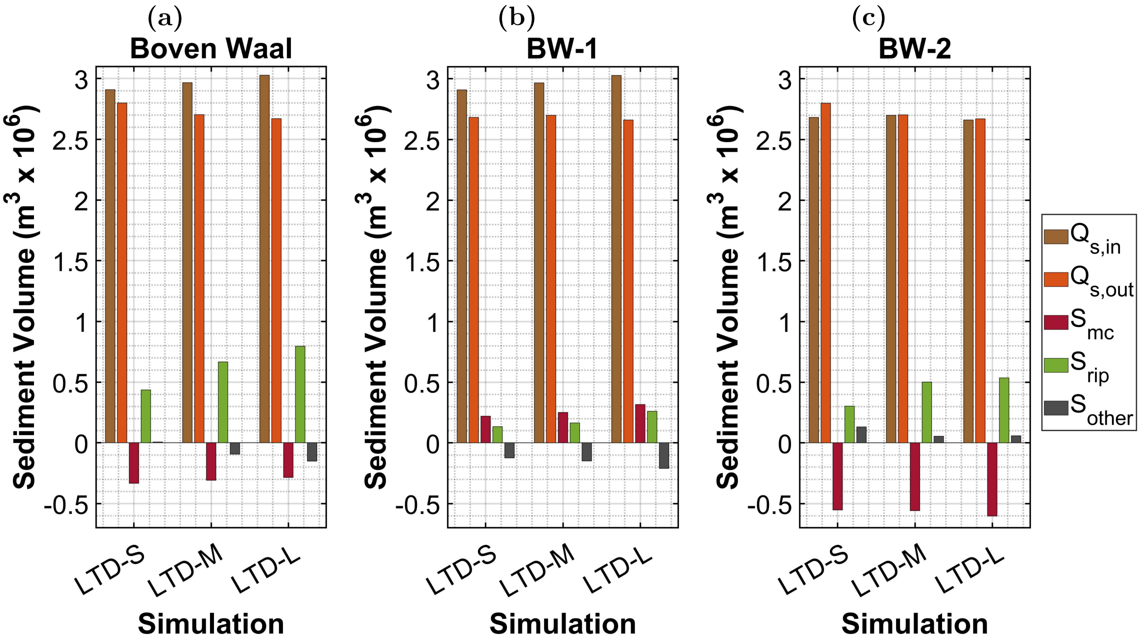

Figure 4.14: Sediment balance for years 1-20 during the LTD Scenarios for (a) the entire Boven Waal (rkm 867.3-891), (b) the upstream section of the Boven Waal (BW-1; rkm 867.3-882), and (c) the downstream section of the Boven Waal (BW-2; rkm 882-891). Parameters: total sediment volume going in ($Q_{s,in}$), total sediment volume going out ($Q_{s,out}$), total storage in main channel (S_{mc}), total storage in riparian channels (S_{rip}), and total storage in other areas such as groynal areas and floodplains (S_{other}).

The sedimentation in the riparian channels occurs because flow entering these channels experiences a sharp reduction in sediment transport capacity due to much lower flow velocities in the riparian channels compared to the main channel. This reduction in flow velocity is primarily caused by the inlet weirs, which induce a substantial momentum loss in the flow. A contributing factor to the significant sedimentation observed in the riparian channels is that the LTDs result in relatively high initial flow velocities at the inlet locations (Figure 4.10). These velocities are even significantly increased compared to the Reference Scenario for Lobith discharges up to 2601 m^3/s. Consequently, the main channel flow at the inlet locations is capable of transporting significantly more sediment, as sediment transport capacity scales nonlinearly with flow velocity. As a result, the flow entering the riparian channels at the inlet experiences a sharper decrease in sediment transport capacity, leading to increased sedimentation. The sedimentation in the riparian channels is most pronounced during the initial phase of the simulation, when sediment transport capacity at these inlet locations is highest. Over time, as erosion occurs at the inlet locations (Figure 4.11c), flow velocities—and, consequently, sediment transport capacity—decline (as explained in the previous section concerning Effect 3). This decline causes the difference in sediment transport capacity between the main channel and the riparian channels at the inlet location to decrease, leading to less sedimentation in the riparian channels.

The sedimentation in the riparian channels is considerably more substantial in the downstream section of the Boven Waal (BW-2) than in the upstream section (BW-1), despite the downstream section being significantly shorter (9 km compared to 14.7 km) (Figures 4.14b and 4.14c). Moreover, most sedimentation in the riparian channels occurs in Scenario LTD-L and least in Scenario LTD-S. Both of these differences are attributable to the depth of the riparian channels.

The riparian channels in the downstream section of the Boven Waal are significantly deeper than those in the upstream section, and the channels in Scenario LTD-L are deeper compared to those in Scenario LTD-S. Deeper riparian channels extract more flow from the main channel. This flow experiences a sharp decrease in sediment transport capacity upon entering the riparian channels. The higher the volume of flow extracted, the greater the sediment load carried, thereby resulting in increased sedimentation in the deeper riparian channels. This effect particularly counteracts the reduced erosion observed during moderate to high Lobith discharges in the downstream section of the Boven Waal (Effect 1; Figure 4.9c), with the counteracting effect being most pronounced in Scenario LTD-L. In this section, the total volume of sedimentation in the riparian channels is even of similar order of magnitude compared to the total volume of erosion (Figure 4.14c).

Summary
The LTDs lead to a significant reduction in bed degradation in the main channel of the Boven Waal compared to the Reference Scenario. This reduction is primarily because the LTDs cause a substantial decrease in erosion in the main channel of the Boven Waal during moderate to high discharges (1954 to 7009 m^3/s). From a reach-averaged perspective, this results in approximately 0.54m of accumulated sedimentation over a 20-year period during these discharges. Despite this positive effect, overall reach-averaged bed degradation still occurs. This is largely attributed to the significant erosion that is caused by the LTDs during low discharges (1020 to 1543 m^3/s), which leads to approximately 0.46 m of accumulated reach-averaged erosion over a 20-year period during these discharges. Additionally, though less pronounced, sedimentation in the riparian channels further contributes to bed degradation, by reducing the sediment availability for the main channel. A key factor in local bed degradation is the development of erosion pits at the LTD transition zones, which exacerbates degradation at these locations. The impact of the erosion pits on reach-averaged bed degradation, however, is minimal in comparison to the contribution of the other effects.

4.2.3 Effect on the bed degradation in the Pannerdensch Kanaal

The LTD Scenarios significantly reduce bed degradation in the Pannerdensch Kanaal compared to the Reference Scenario, ultimately resulting in considerable overall sedimentation (~0.06-0.11m; Figure 4.16a). Initially, flow conditions in the Pannerdensch Kanaal cause reach-averaged erosion. However, as a response to the erosion that begins in the Boven Rijn from year 3 onward (as discussed in the following section), the erosion trend in the Pannerdensch Kanaal shifts toward aggradation. This aggrading trend is further amplified by the influence of the LTDs in the Boven Waal.

The reducing impact of LTDs on bed degradation in the Pannerdensch Kanaal is mainly driven by two opposing effects caused by changes in the discharge distribution as a result of the backwater effects from the LTDs. This is shown by the schematic overview in Figure 4.15. The physical processes behind these effects are explained in more detail in the theoretical background (Section 2.2).

The LTDs reduce erosion during moderate to high Lobith discharges (1954 to 7009 m^3/s) in the Pannerdensch Kanaal compared to the Reference Scenario (Effect 1), even resulting in increased sedimentation during Lobith discharges of 2601 and 5506 m^3/s (Figure 4.16b). The only exception is observed at a discharge of 1954 m^3/s, during which the LTDs lead to reduced sedimentation in the Pannerdensch Kanaal—an effect that will be discussed later in this section. However, the effect of the LTDs in reducing bed degradation during moderate to high discharges is partially counteracted by a reduction in sedimentation during low discharges (1020 to 1543 m^3/s) compared to the Reference Scenario (Effect 2) (Figure 4.16b). Nevertheless, the effect during moderate to high discharges (Effect 1) is more pronounced than the effect during low discharges (Effect 2), since the LTDs cause increased reach-averaged sedimentation in the Pannerdensch Kanaal compared to the Reference Scenario.

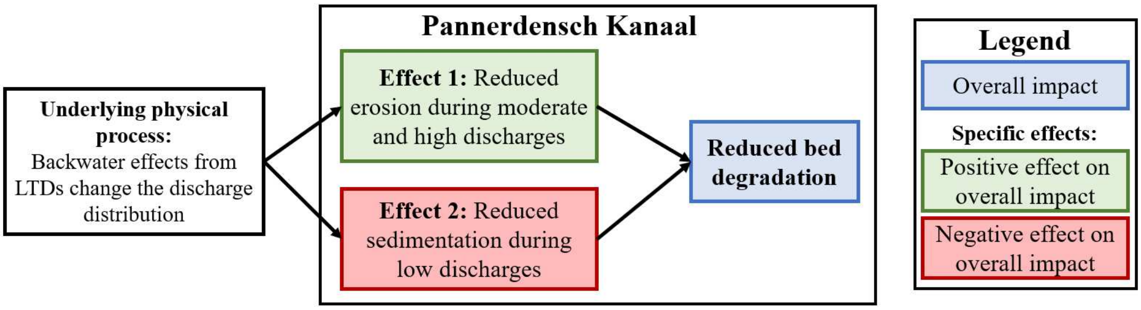

Figure 4.15: Conceptual overview of how the LTDs lead to reduced bed degradation in the Pannerdensch Kanaal.

Scenario LTD-L results in the largest increase in reach-averaged sedimentation in the Pannerdensch Kanaal compared to the other LTD Scenarios (Figure 4.16a). This is due to the fact that Scenario LTD-L features the largest riparian channels, thereby drawing the most discharge to the Waal during moderate to high discharges, resulting in the least discharge directed to the Pannerdensch Kanaal. Consequently, Effect 1 is most pronounced in Scenario LTD-L, leading to greater reach-averaged sedimentation relative to the other scenarios. Effect 2 is relatively consistent across all LTD Scenarios since they have a similar impact on the low discharge distribution.

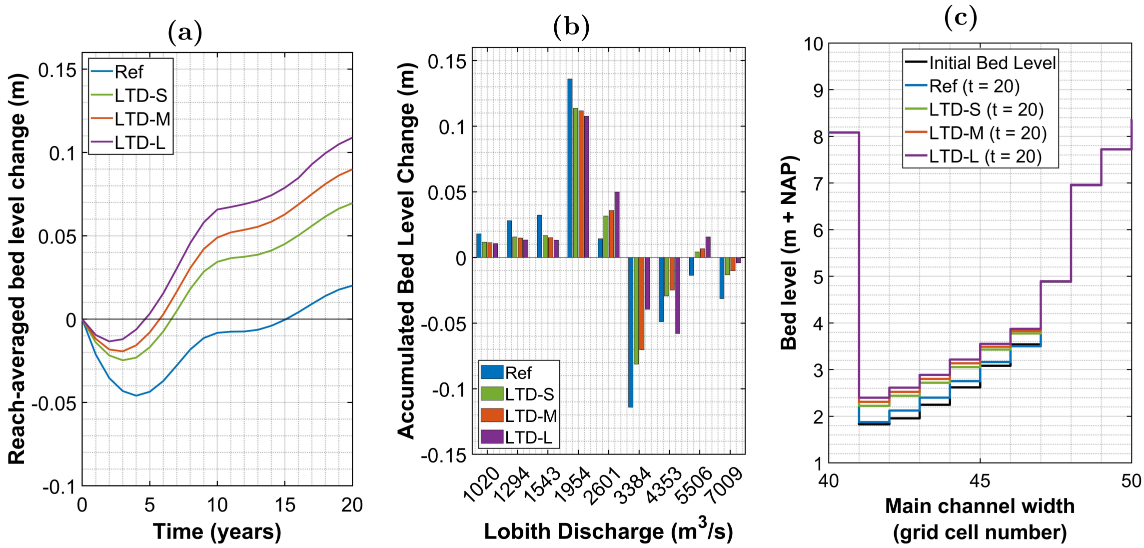

Figure 4.16: (a) Reach-averaged bed level change in the main channel of the Pannerdensch Kanaal (rkm 867.3 - 878.3) over time relative to t = 0 for the Reference Scenario and LTD Scenarios. (b) The accumulated bed level change (m) in the main channel of the Pannerdensch Kanaal during each Lobith discharge over 20 years of morphological development. (c) Cross-sectional bed level initially and after 20 years for each of the scenarios at river kilometer 867.8 in the Pannerdensch Kanaal, viewed in flow direction.

The accumulated bed level change in the Pannerdensch Kanaal during a Lobith discharge of 1954 m^3/s is relatively high (Figure 4.16b), as this discharge has by far the longest duration in the model compared to other discharges (111 days). This extended duration allows significantly more time for bed level adjustments compared to other discharges. Strikingly, there is less reach-averaged sedimentation occurring in the LTD Scenarios during this discharge than in the Reference Scenario (Figure 4.16b), despite the fact that the LTDs cause less discharge to be directed towards the Pannerdensch Kanaal during this Lobith discharge (~10 m^3/s; see Figure 4.5b). This discrepancy can be explained by the reduced erosion observed during the higher discharges in the LTD Scenarios. In the Reference Scenario, significant erosion of the bed level in the Pannerdensch Kanaal occurs during the higher discharges, leading to larger water depths during the subsequent 1954 m^3/s discharge. The increased water depth results in reduced flow velocities, due to conservation of mass, thereby allowing for significant sedimentation during this discharge. In contrast, during the LTD Scenarios, the bed level in the Pannerdensch Kanaal has decreased substantially less during the higher discharges, resulting in smaller water depths during the subsequent 1954 m^3/s discharge than in the Reference Scenario. Consequently, there is less sedimentation compared to the Reference Scenario. The minor reduction in discharge directed to the Pannerdensch Kanaal in the LTD Scenarios is insufficient to counteract this effect.

4.2.4 Effect on the bed degradation in upstream and downstream reaches

The bed degradation in the Boven Rijn and Midden Waal is significantly influenced by the LTDs, due to the physical processes described in the theoretical background (Section 2.2). In short, the bed degradation in the Boven Rijn is impacted by the backwater effects of the LTDs, whereas the bed degradation in the Midden Waal is primarily affected by changes in sediment transport capacity induced by the LTDs within the Boven Waal. Similar to the Pannerdensch Kanaal, the effects on these reaches are opposite across the low and moderate to high Lobith discharge ranges, with the effects during moderate to high discharges being the most dominant in determining the overall impact on bed degradation.

The LTDs lead to increased reach-averaged bed degradation in the Boven Rijn compared to the Reference Scenario (Figure 4.17a). This is mainly driven by increased erosion during moderate to high discharges (2601 to 7009 m^3/s) (Figure 4.17b), as the backwater effects of the LTDs cause flow velocities to rise during these discharges relative to the Reference Scenario. This increased erosion is somewhat mitigated by increased sedimentation throughout the low discharge range (1020 to 1543 m^3/s) (Figure 4.17b), during which the LTDs cause a reduction in flow velocities in the Boven Rijn.

Scenario LTD-L leads to the most pronounced increase in reach-averaged erosion in the Boven Rijn (Figure 4.17a) due to the higher increase in erosion throughout the moderate to high discharge range (2601 to 7009 m^3/s) than the other LTD Scenarios (Figure 4.17b). The larger riparian channels in this scenario result in lower water levels in the Boven Waal during these discharge conditions compared to the other LTD Scenarios, leading to a stronger backwater effect on the Boven Rijn. In contrast, the effects on water levels during low discharges are similar across all LTD Scenarios.

A remarkable pattern in the reach-averaged bed level development of the Boven Rijn is the initial aggrading trend, which subsequently transitions into a degrading trend (Figure 4.17a). Initially, the flow conditions in the Boven Rijn lead to reach-averaged sedimentation. However, this trend is reversed as upstream sedimentation starts to occur leading to decreased sediment transport to the Boven Rijn.

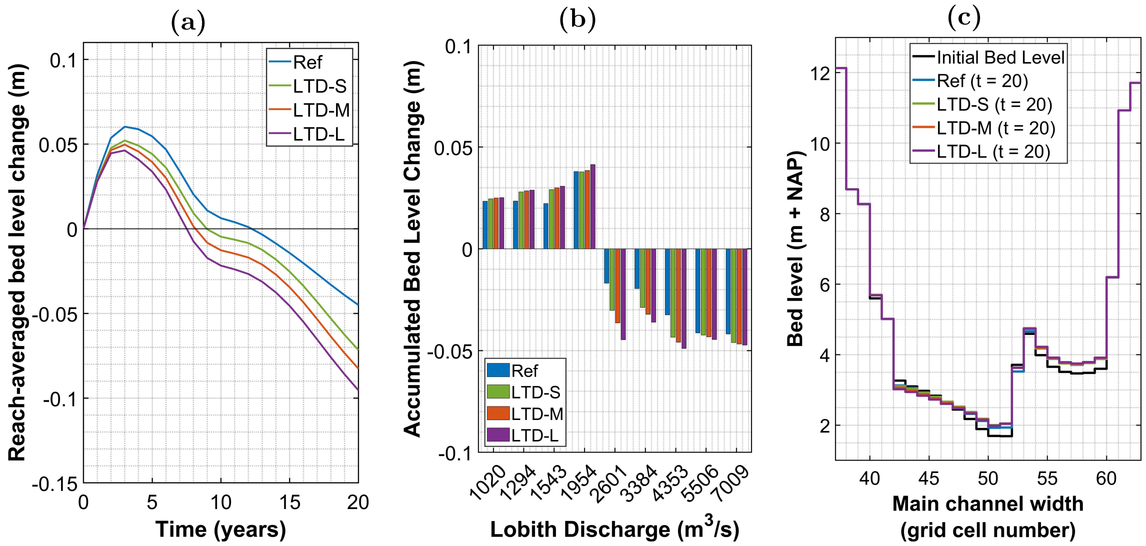

Figure 4.17: (a) Reach-averaged bed level change in the main channel of the Boven Rijn (rkm 857.7 - 867.3) over time relative to t = 0 for the Reference Scenario and LTD Scenarios. (b) The accumulated bed level change (m) in the main channel of the Boven Rijn during each Lobith discharge over 20 years of morphological development. (c) Cross-sectional bed level initially and after 20 years for each of the scenarios at river kilometer 867.3 in the Boven Rijn, viewed in flow direction.

The LTDs cause bed degradation in the Midden Waal to worsen significantly compared to the Reference Scenario (Figure 4.18a). This decline is mainly driven by a significant increase in erosion during moderate to high discharges (1954 to 7009 m^3/s) (Figure 4.18b), attributed to a large jump in sediment transport capacity at the downstream end of the Boven Waal towards the Midden Waal. The LTDs considerably reduce flow velocities during these discharge conditions in the Boven Waal relative to the Reference Scenario, while there are no additional LTDs implemented in the Midden Waal to reduce flow velocities there. The effect is most pronounced for a Lobith discharge of 1954 m^3/s, as this discharge lasts the longest (111 days). The increased erosion is slightly counteracted by reduced erosion during low discharges (1020 to 1543 m^3/s) compared to the Reference Scenario (Figure 4.18b). During these discharge conditions, there is a decrease in sediment transport capacity in the longitudinal direction at the downstream end of the Boven Waal, as the LTDs cause a significant increase in flow velocities relative to the Reference Scenario.

Scenario LTD-L leads to the most significant increase in bed degradation compared to the other LTD Scenarios, because the large riparian channels cause the greatest reduction in flow velocity in the Boven Waal during moderate to high discharges. This reduction results in a higher increase in sediment transport capacity directed towards the Midden Waal. As a consequence, there is more erosion during moderate to high discharges in this scenario compared to the other LTD Scenarios (Figure 4.18b).

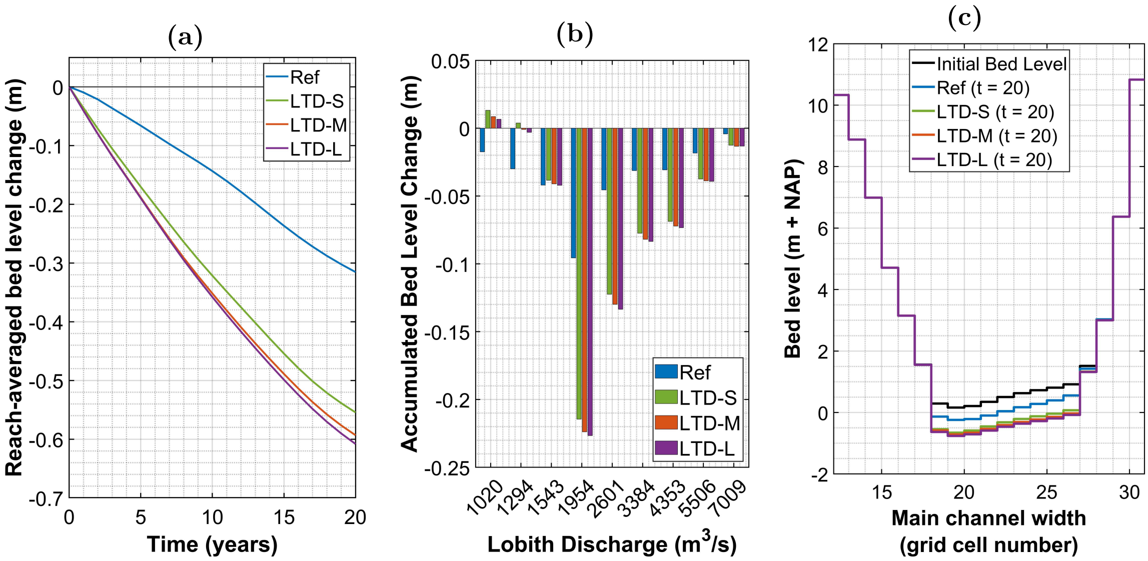

Figure 4.18: (a) Reach-averaged bed level change in the main channel of the Midden Waal (rkm 891 - 911.5) over time relative to t = 0 for the Reference Scenario and LTD Scenarios. (b) The accumulated bed level change (m) in the main channel of the Midden Waal during each Lobith discharge over 20 years of morphological development. (c) Cross-sectional bed level initially and after 20 years for each of the scenarios at river kilometer 892 in the Midden Waal, viewed in flow direction.

4.3 Effects of the summerdike removal and floodplain lowering

This section presents the main effects of the summerdike removal and floodplain lowering in the Pannerdensch Kanaal, in addition to the effects of the LTDs in the Boven Waal. The focus is on how these interventions influence the discharge distribution at the Pannerdensch bifurcation and bed degradation in the Boven Waal, with further discussion on the bed degradation in other affected reaches.

Building upon the structure of the previous research question, this analysis uses the most effective LTD configuration. Since none of the LTD Scenarios clearly stands out in terms of significantly increasing the low discharge partitioning to the Pannerdensch Kanaal and reducing bed degradation in the Boven Waal, their effects on bed degradation in other reaches offer insights for selection. Scenario LTD-S is used because it leads to the least additional erosion in the Midden Waal and Boven Rijn. Additionally, it also results in the smallest increase in discharge drawn to the Waal during high Lobith discharges. This minimizes the changes in discharge partitioning that the interventions in the Pannerdensch Kanaal need to compensate for.

The effects of combined interventions in the Boven Waal and Pannerdensch Kanaal are derived from the simulation of three LTD-FL Scenarios, described in Section 3.2. These are referred to as LTD-S-FL-0.5, LTD-S-FL-2, and LTD-S-FL-3, where the number indicates the level of uniform floodplain lowering in the Pannerdensch Kanaal. The physical processes underlying the effects of the interventions have been qualitatively explained in detail in the theoretical background (Section 2.2). This section will primarily concentrate on discussing the most significant quantitative effects of the interventions regarding the discharge distribution and bed degradation.

4.3.1 Effect on the discharge distribution

One of the primary objectives of implementing summerdike removal and floodplain lowering in the Pannerdensch Kanaal is to compensate for the additional discharge directed to the Waal by the LTDs during the Lobith design discharge of 16,000 m^3/s, thereby meeting the prescribed discharge partitioning. However, the DVR model predicts a substantially different discharge partitioning to the Pannerdensch Kanaal in the Reference Scenario (6167 m^3/s; see Table 4.2) compared to the policy guidelines (5835 m^3/s) (Schropp and Jansen, 2020). This significant discrepancy arises because the DVR model has not been calibrated for these extreme events. Consequently, the focus has been placed on restoring the original extreme discharge distribution as observed in the Reference Scenario.

The LTDs in Scenario LTD-S initially reduce the discharge partitioning to the Pannerdensch Kanaal by 209 m^3/s during a Lobith discharge of 16,000 m^3/s (Table 4.2). This reduction is effectively compensated by the removal of summerdikes and a 0.5-meter floodplain lowering, as Scenario LTD-S-FL-0.5 results in an initial discharge partitioning to the Pannerdensch Kanaal that is approximately equivalent to that in the Reference Scenario. Over time, erosion in the Waal causes a gradual decrease in discharge partitioning to the Pannerdensch Kanaal in Scenario LTD-S-FL-0.5 (37 m^3/s), which results in the extreme discharge partitioning no longer being satisfied. Even so, this decrease is also observed in both the Reference Scenario and Scenario LTD-S. Importantly, this gradual decrease is significantly smaller than the initial reduction (209 m^3/s) that was compensated by the 0.5-meter floodplain lowering.

Table 4.2: Discharge partitioning to the Pannerdensch Kanaal during a Lobith discharge of 16,000 m^3/s for each of the scenarios at the start (t = 0) and end (t = 20) of the simulation.

Scenario	**Discharge partitioning to the Pannerdensch Kanaal (m^3/s)**	
	Initial (t = 0)	**After 20 years (t = 20)**
Ref	6167	6128
LTD-S	5958	5920
LTD-S-FL-0.5	6172	6135
LTD-S-FL-2	6386	6344
LTD-S-FL-3	6474	6421

The second primary objective of the interventions in the Pannerdensch Kanaal is to compensate for the additional discharge directed to the Waal by the LTDs during moderate to high Lobith discharges (1954 to 7009 m^3/s) (Figure 4.19), with the aim of further reducing erosion in the Boven Waal. Scenario LTD-S-FL-0.5 does not fully achieve this objective, as it results in only a limited increase in discharge partitioning during Lobith discharges of 5506 and 7009 m^3/s relative to Scenario LTD-S (Figure 4.19b). This outcome indicates that a relatively simple intervention involving summerdike removal and limited floodplain lowering is insufficient to meet both high discharge distribution objectives simultaneously. The two more extreme scenarios, incorporating 2- and 3-meter floodplain lowering, lead to significantly increased discharge directed towards the Pannerdensch Kanaal during moderate to high discharges compared to Scenario LTD-S (Figure 4.19b). Nevertheless, these scenarios also result in an excessively high discharge partitioning to the Pannerdensch Kanaal during a Lobith discharge of 16,000 m^3/s (Table 4.2). Therefore, these two scenarios will be used to evaluate the impacts of summerdike removal and floodplain lowering in the Pannerdensch Kanaal concerning the second objective.

The LTD-FL scenarios do not exhibit a significantly different impact on discharge distribution during low discharges (1020 to 1543 m^3/s) compared to Scenario LTD-S (Figure 4.19b). Initially, the floodplain lowering in the Pannerdensch Kanaal does not influence these low discharges, as the floodplains do not inundate under such conditions. Furthermore, even after 20 years, no significant difference in discharge partitioning is observed, suggesting that the effect of floodplain lowering on bed level development does not substantially influence the low discharge distribution either.

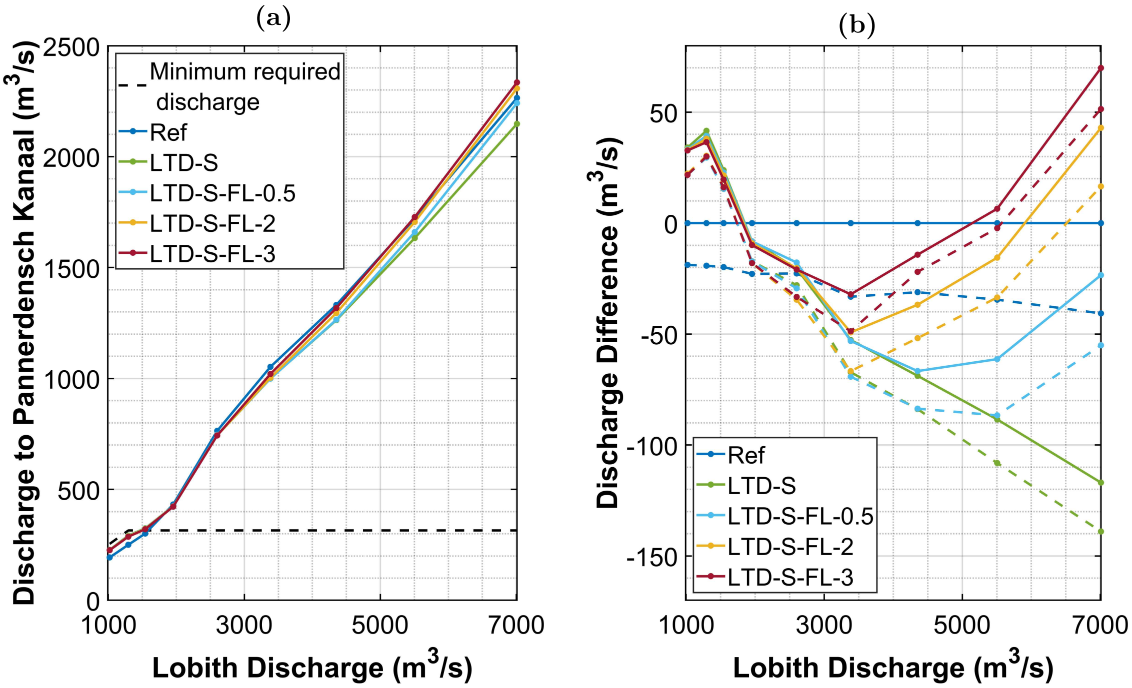

Figure 4.19: (a) Discharge partitioning to the Pannerdensch Kanaal at t = 0. The dashed black line represents the minimum required discharge to the Pannerdensch Kanaal. (b) Difference in discharge partitioning to the Pannerdensch Kanaal with respect to the discharge distribution of the Reference Scenario at t = 0. The solid lines represent the discharge partitioning at t = 0, the dashed lines represent the discharge partitioning at t = 20.

4.3.2 Effect on the bed degradation in the Boven Waal

The implementation of floodplain lowering and summerdike removal in the Pannerdensch Kanaal, in addition to the LTDs in the Boven Waal, does not result in a significant reduction in reach-averaged erosion in the Boven Waal (Figure 4.20a). Specifically, Scenario LTD-S-FL-3 achieves only an additional reduction of approximately 0.4 cm in reach-averaged erosion, on top of the 6.3 cm reduction observed in Scenario LTD-S when compared to the Reference Scenario. The backwater effects of the floodplain lowering on erosion in the Boven Waal are minimal because the reduction in discharge partitioning to the Waal, compared to Scenario LTD-S, is very small relative to the total discharge diverted to the Waal during Lobith discharges 3384 to 7009 m^3/s (order of magnitude of 2%). Furthermore, the LTDs shift the erosion issue in the Boven Waal towards low discharges (1020 to 1543 m^3/s), whereas the floodplain lowering only influences discharge partitioning for Lobith discharges of 3384 m^3/s and above.

The main difference in bed level after 20 years between Scenario LTD-S-FL-3 and Scenario LTD-S is observed at the upstream end of the Boven Waal (river kilometer 867.3 to 868.3), as illustrated in Figure 4.20b. The backwater effect induced by the floodplain lowering lead to decreased flow velocities in the Boven Waal during Lobith discharges ranging from 3384 to 7009 m^3/s. This results in a reduced sediment transport capacity, as it scales nonlinearly with flow velocity. Consequently, the sediment transport capacity gradient at the transition from the Boven Rijn to the Boven Waal is changed, ultimately resulting in a higher bed level in Scenario LTD-S-FL-0.5 after 20 years compared to Scenario LTD-S at the upstream end of the Boven Waal (Figure 4.20b).

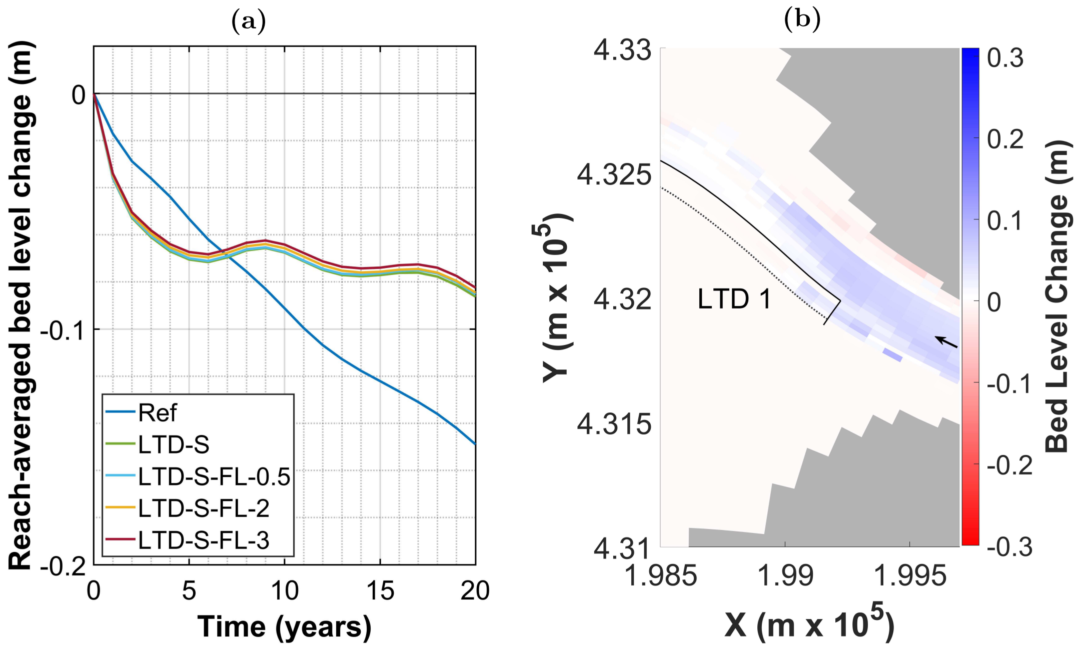

Figure 4.20: (a) Reach-averaged bed level change of the main channel of the Boven Waal (rkm 867.3-891) over time relative to t = 0. (b) the bed level change map between Scenario LTD-S-FL-3 and LTD-S after 20 years of morphological development at the upstream end of the Boven Waal (rkm 867.4 to 868.6). Blue colours indicate a higher bed level in Scenario LTD-S-FL-3. Solid black lines depict the body of LTD 1, whereas the combination of solid and dotted black lines outlines the boundaries of the riparian channel of LTD 1. The black arrow shows the flow direction.

4.3.3 Effect on the bed degradation in the Pannerdensch Kanaal

The implementation of summerdike removal and floodplain lowering in the Pannerdensch Kanaal, in combination with LTDs in the Boven Waal, leads to significantly different bed levels in the Pannerdensch Kanaal after 20 years than observed in the Reference Scenario (Figure 4.21). The bed levels along the intervention section (rkm 869.2-876.7) are generally higher in the LTD-FL Scenarios than in the Reference Scenario. This is evidenced by the predominantly positive values of bed level changes in these Scenarios along this section illustrated by Figure 4.21. In general, Scenario LTD-S-FL-3 shows the largest bed level changes relative to the Reference Scenario, while Scenario LTD-S exhibits the smallest changes. This is because in Scenario LTD-S-FL-3 the highest changes in sediment transport capacity occur compared to the Reference Scenario as a result of its extensive 3-meter floodplain lowering.

Significant sedimentation is observed along the section where floodplain lowering is implemented on both sides of the river (rkm 869.2-873). Particularly in Scenario LTD-S-FL-3, a substantial sediment hump forms, leading to sedimentation of up to 1.4 meters over the 20-year period. This is illustrated by Figure 4.22, which shows a substantial increase in bed levels over time along this section. This occurs because the 3-meter floodplain lowering in this scenario leads to the largest reduction in flow velocities along the intervention section, resulting in the most significant decrease in sediment transport capacity.

Upstream of the floodplain lowering (rkm 867.3-869.2), the bed levels in the LTD-FL Scenarios are lower than those in Scenario LTD-S after 20 years (Figure 4.21). This is because of the backwater effects generated by the floodplain lowering. Downstream of the floodplain lowering (rkm 876.7–878.7), bed levels after 20 years are significantly lower compared to the Reference Scenario, as demonstrated by the negative values in Figure 4.21. Scenario LTD-S-FL-3, in particular, exhibits substantial erosion in this region (Figure 4.22). The erosion is caused by an increase in sediment transport capacity at the downstream end of the floodplain lowering. The underlying physical processes responsible for this response have been explained in the theoretical background (Section 2.2.2).

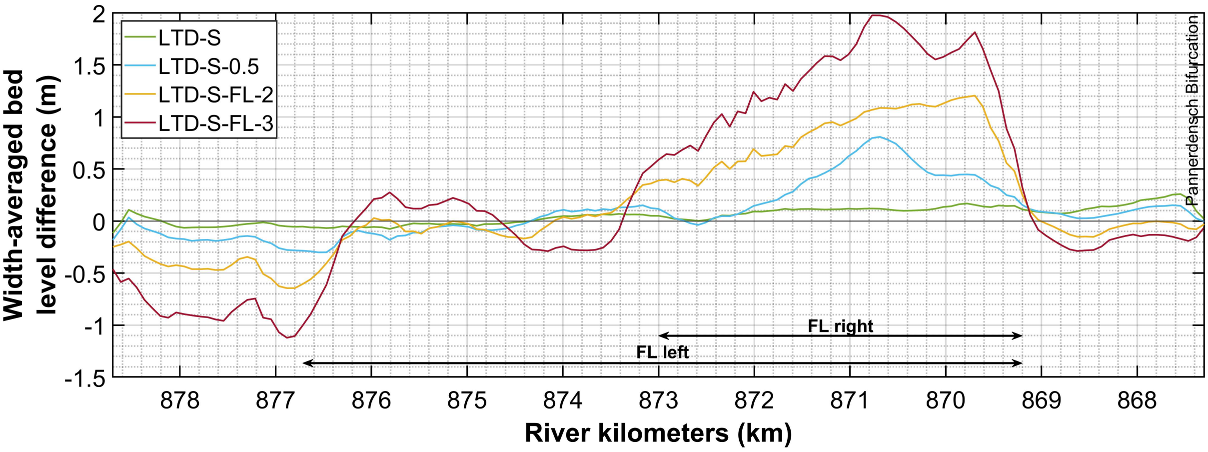

Figure 4.21: Width-averaged bed level difference of the main channel in the Pannerdensch Kanaal with respect to the Reference Scenario after 20 years of bed level development. The black arrows represent the location of the floodplain lowering at the left and right side of the channel.

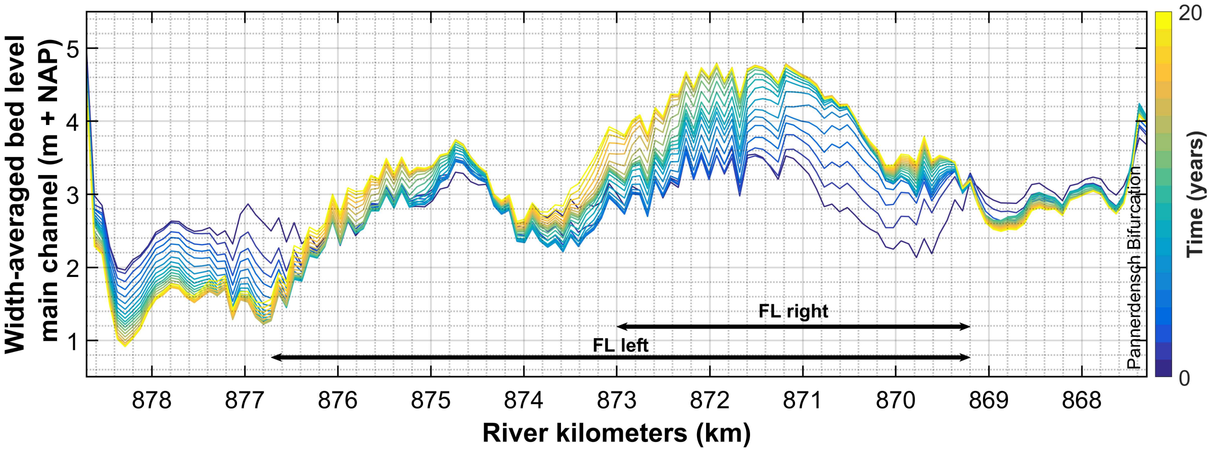

Figure 4.22: Width-averaged bed level development of the main channel during Scenario LTD-S-FL-3 for every year of the simulation. The black arrows represent the location of the floodplain lowering at the left and right side of the channel.

From a reach-averaged perspective, the LTD-FL scenarios lead to significant sedimentation in the Pannerdensch Kanaal after 20 years. This is clearly evident in the substantial positive bed level changes observed in these scenarios shown in Figure 4.23a. In particular, Scenarios LTD-S-FL-2 and LTD-S-FL-3 result in significant reach-averaged sedimentation of 0.19 m and 0.24 m, respectively, compared to Scenario LTD-S, where only 0.07 m of reach-averaged sedimentation is observed. It is important to note that, initially, reach-averaged erosion occurs in the Pannerdensch Kanaal. This pattern is similar to the Reference Scenario and follows the trend observed in the Boven Rijn, where initial sedimentation is followed by erosion. A more detailed explanation of this phenomenon has been provided earlier in the results (Section 4.2.4).

The increased reach-averaged sedimentation occurring in the Pannerdensch Kanaal as a result of the summerdike removal and floodplain lowering is primarily because there is less erosion during Lobith discharges between 3384 and 7009 m^3/s (Figure 4.23b). In Scenario LTD-S-FL-3, reach-averaged sedimentation occurs in the main channel of the Pannerdensch Kanaal over a 20-year period across all these Lobith discharges. This is demonstrated by the positive accumulated bed level change for Lobith discharges between 3384 and 7009 m^3/s, shown in red in Figure 4.23b. During lower discharges, the influence of the implemented summerdike removal and floodplain lowering on the reach-averaged bed level change in the Pannerdensch Kanaal are limited. While some variations between the scenarios exist, these are not discussed as they are not relevant to the main message.

In conclusion, the implementation of summerdike removal and floodplain lowering within the Pannerdensch Kanaal leads to a significant increase in reach-averaged sedimentation in the main channel of this branch. This increase is especially pronounced in Scenarios LTD-S-FL-2 and LTD-S-FL-3, which show reach-averaged sedimentation of 0.19 and 0.27 m over a 20-year period, compared to just 0.07 m in Scenario LTD-S. The most sedimentation occurs along the section where floodplain lowering is implemented on both sides of the Pannerdensch Kanaal (rkm 869.2-873), leading to the formation of sedimentation humps that locally reach up to 1.4 m for Scenario LTD-S-FL-3.

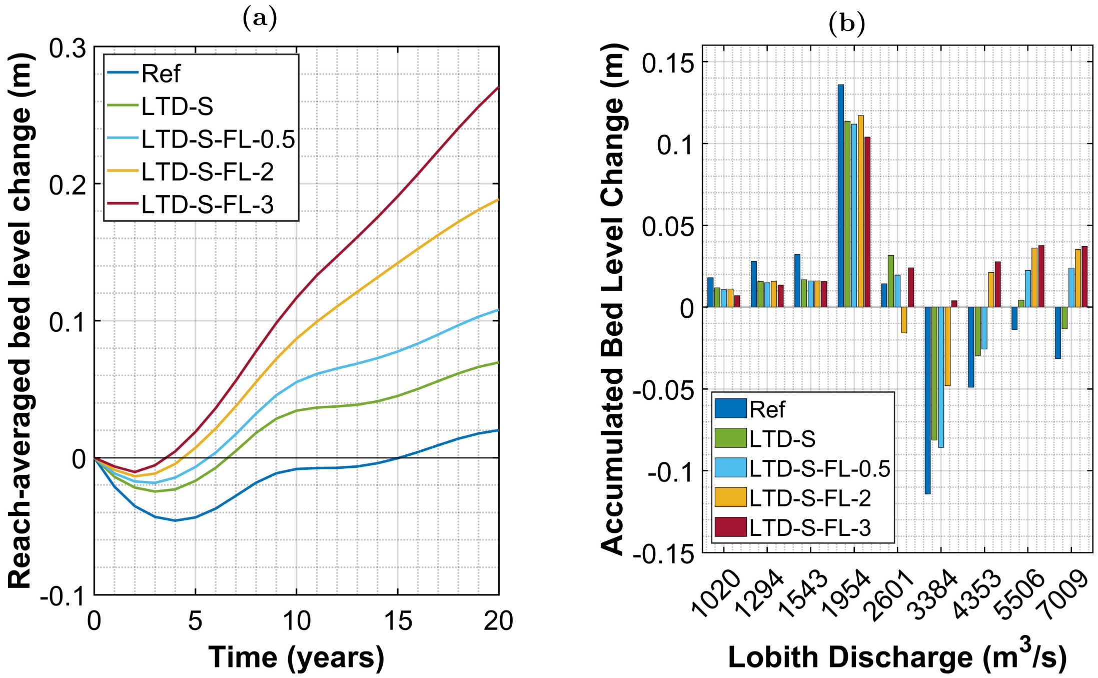

Figure 4.23: (a) Reach-averaged bed level change in the main channel of the Pannerdensch Kanaal (rkm 867.3 - 878.3) over time relative to t = 0. (b) The accumulated reach-averaged bed level change (m) in the main channel of the Pannerdensch Kanaal during each Lobith discharge over 20 years of morphological development. Positive values indicate sedimentation, while negative values indicate erosion.

4.3.4 Effect on the bed degradation in upstream and downstream reaches

The interventions in the Boven Waal and Pannerdensch Kanaal also influence bed degradation in the upstream and downstream reaches. This section focuses on the primary effects of these interventions on bed degradation in the Boven Rijn, Boven Nederrijn, and Boven IJssel, which are the reaches most significantly impacted by the summerdike removal and floodplain lowering in the Pannerdensch Kanaal.

The implementation of summerdike removal and floodplain lowering in the Pannerdensch Kanaal, alongside LTDs in the Boven Waal, results in increased reach-averaged erosion over a 20-year period in the main channel of the Boven Rijn compared to Scenario LTD-S (Figure 4.24a). Both interventions lead to higher flow velocities in the Boven Rijn during high discharges due to backwater effects, which in turn increases erosion during these discharges, as detailed in the theoretical background (Section 2.2.2). In the Reference Scenario, reach-averaged erosion in the Boven Waal is 4.5 cm over a 20-year period (Figure 4.24a). This increases to 7.2 cm in Scenario LTD-S due to the influence of the LTDs, and further rises to 8.2 cm with the additional summerdike removal and 3-meter floodplain lowering in Scenario LTD-S-FL-3. Therefore, while the interventions in the Pannerdensch Kanaal contribute to an increase in reach-averaged erosion in the Boven Rijn, this effect is relatively modest compared to the more significant increase already induced by the LTDs in Scenario LTD-S compared to the Reference Scenario.

Erosion in the Boven Rijn is not consistently uniform across the transverse profile of the main channel. Although there are sections that exhibit a more uniform pattern, variability is typically observed in bends. For instance, as illustrated by the cross-sectional bed level at river kilometer 863.5 in Figure 4.24b, erosion occurs on the outer side of the bend (grid cells 42-51) in both Scenario LTD-S (green) and Scenario LTD-S-FL-3 (red) over a 20-year period. This is indicated by lower bed levels in these scenarios compared to the initial bed level (black). In contrast, sedimentation takes place on the inner bend (grid cells 53-60) within the same scenarios. This pattern arises because flow velocities are generally higher in the outer bends, leading to erosion, while they are lower in the inner bends, resulting in sedimentation. The cross-sectional bed level change just upstream of the Pannerdensch bifurcation does not exhibit such clear patterns (Figure 4.24c). Additionally, the relatively small bed level changes in this area suggest that flow and sediment partitioning at the bifurcation is not significantly affected.

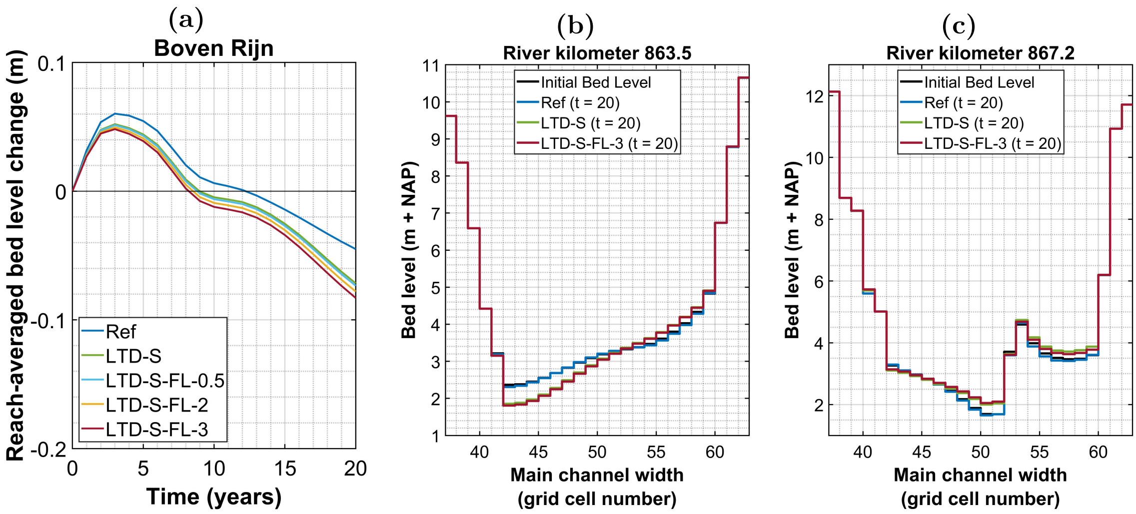

Figure 4.24: (a) Reach-averaged bed level change in the main channel of the Boven Rijn (rkm 853.2-967.3) over time relative to t = 0. (b-c) Cross-sectional bed level initially (black) and after 20 years for the Reference Scenario and Scenarios LTD-S and LTD-S-FL-3 at (b) river kilometer 863.5 and (c) 867.2 in the Boven Rijn, viewed in flow direction.

The implementation of summerdike removal and floodplain lowering in the Pannerdensch Kanaal, in addition to LTDs in the Boven Waal, results in increased reach-averaged erosion over a 20-year period in downstream reaches. This is evident from Figure ... where the LTD-FL scenarios (light blue, yellow and red) lead to higher negative bed level changes than the Reference Scenario (dark blue) and Scenario LTD-S (green). This is because the summerdike removal and floodplain lowering cause an increase in sediment transport capacity downstream of them. The increased reach-averaged erosion for Scenario LTD-S-FL-0.5 valt nog mee, because it impacts the sediment transport capacities within the floodplain lowering section the least, maar the inreased reach-averaged erosion in Scenarios LTD-S-FL-2 and LTD-S-FL-3 is really significant.

The relatively high difference in reach-averaged bed level change between the Boven Nederrijn and Boven IJssel, as shown in Figure 4.25, can be attributed to the shorter length of the Boven Nederrijn, which covers only 13.2 km compared to the 46.7 km of the Boven IJssel. The increased erosion resulting from the summerdike removal and floodplain lowering primarily occurs in the upstream section of these reaches. Consequently, the impact of this erosion on the reach-averaged bed level change is logically greater in the shorter reach.

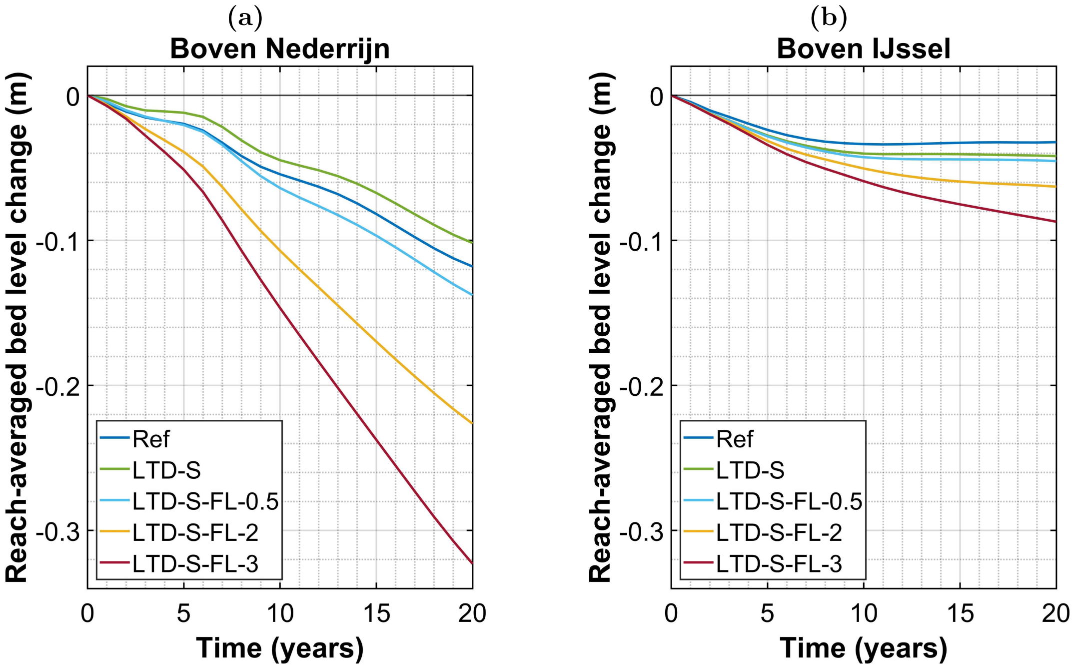

Figure 4.25: Reach-averaged bed level change over time relative to t = 0 in the main channel of (a) the Boven Nederrijn (rkm 878.3 - 891.5) and (b) the Boven IJssel (rkm 878.3 - 925).

In conclusion, the summerdike removal and floodplain lowering in the Pannerdensch Kanaal exacerbate bed degradation in both the upstream and downstream reaches, in addition to the effects of the LTDs. The scenarios involving 2- and 3-meter floodplain lowering have a particularly significant impact, while the scenario with 0.5-meter floodplain lowering has a more moderate effect. Although the impact of these interventions on increasing bed degradation in the Boven Rijn is relatively modest compared to the exacerbation already caused by the LTDs, their influence on increasing bed degradation in the Boven Nederrijn and Boven IJssel is considerable.

5 Discussion

This chapter provides a discussion on the study's findings. First, Section 5.1 reflects on the model's limitations and reliability. After that, Section 5.2 reflects on the effects of the interventions and discusses the effects of the interventions in relation to other studies. Finally, Section 5.3 reflects on the potential role of the proposed interventions in restoring the low discharge distribution and stopping bed degradation in the Boven Waal.

5.1 Reflection on the model's limitations and reliability

This study employs the latest version of the DVR model (Sloff et al., 2024), which is recognized as a state-of-the-art 2D morphological model for the Dutch Rhine branches. It is considered the most advanced tool currently available for investigating the morphological dynamics of these branches. The use of a 2D model allows for the inclusion of complex flow behaviors, such as spiral flow and sorting effects, which influence the distinct development of inner and outer bends. This is particularly relevant for the Boven Waal, as there are some significant bends located here. Additionally, the model has been significantly enhanced in terms of accurately capturing sediment transport gradients and large-scale bed level trends compared to earlier versions (Sloff et al., 2024). However, despite these improvements, the model remains a simplified representation of reality, which introduces inherent differences between the simulated outcomes and actual river behavior. The following paragraphs highlight key model limitations and their potential impact on the study's results.

5.1.1 Spin-up method

The initial bed composition in the DVR model consists of width-averaged values, but the prescribed spin-up method for the DVR model does not include a separate spin-up step for the bed composition (Sloff et al., 2024). Instead, the method employs a local spin-up for fixed layers and a simultaneous spin-up for both the bed composition and bed level across the entire domain. Typically, sediment composition is coarser in outer bends and finer in inner bends due to bend sorting. Consequently, the current spin-up method tends to overestimate erosion in outer bends until bend sorting is established. As a result, the bed level after the spin-up may not be fully accurate. However, since this initial bed level is used consistently across all scenarios, the impact of this initial inaccuracy on the study's results is limited as relative changes among scenarios are examined.

5.1.2 Upstream boundary condition

The DVR model uses a discharge hydrograph as an upstream boundary condition, based on a long-term average of measured discharges at Lobith from 2011 to 2020 (Sloff et al., 2024). However, this discharge hydrograph inherently introduces significant uncertainty, which directly translates into uncertainty regarding the model's predictions of morphological development. If higher average discharges occur in reality than those used in the model, this will automatically lead to greater sediment transport. For example, in the near future, discharges could increase significantly due to climate change, which would result in increased bed degradation, as demonstrated by Pfeijffer (2023). Additionally, the model's discharge hydrograph does not account for peak discharges above 10,000 m^3/s, while these could have a significant and complex impact on the morphological development of the Rhine branches, as suggested by Chowdhury et al.

(2023). However, it remains uncertain whether the DVR model could accurately simulate the morphological effects of these peak flows, as it likely does not account for all relevant processes. This uncertainty arises from the fact that these processes are not fully understood in reality either.

5.1.3 Modelling of sediment transport

The DVR model is primarily designed to predict large-scale morphological trends rather than small-scale processes (Sloff et al., 2024). One limitation is that it models all sediment transport, including both bed load and suspended load, as bed load transport using the Meyer-Peter and Müller (1948) sediment transport equation (Sloff et al., 2024). Typically, suspended load should be modeled through an advection-diffusion equation, which accounts for its transport over longer distances. In the DVR model, however, suspended load is modelled as bed load, leading to earlier deposition than would occur in reality. While this limitation affects small-scale morphological developments, it does not significantly alter the large-scale trends examined in this study. A process where uncertainty is introduced as a result of this limitation is the sediment transport over the inlet sill into the riparian channels associated with the LTDs, as will be discussed in more detail in Section 5.2.2 of the discussion.

Furthermore, the new version of the DVR model applies different calibration coefficients (α) for the Meyer-Peter and Müller (1948) sediment transport equation across the various branches of the Rhine to improve the accuracy of large-scale morphological predictions (Sloff et al., 2024). This leads to a particularly significant difference in calibration coefficients between the Boven Rijn ($\alpha = 0.3$) and the Pannerdensch Kanaal ($\alpha = 0.75$). This abrupt change may cause some localized morphological effects at the transition between these two branches, such as some overestimated erosion at the upstream end of the Pannerdensch Kanaal. However, these small-scale processes do not significantly impact the broader morphological trends studied here.

The need for different calibration coefficients per Rhine branch for the Meyer-Peter and Müller (1948) sediment transport equation likely originates from an unknown limitation of the DVR model, due to which the model fails to adequately capture the relevant physical processes that cause these variations between branches. Although the model developers do not know the exact nature of this limitation, it indicates that some underlying physical mechanisms influencing sediment transport and morphological development are not fully represented in the model. The calibration coefficients in the DVR model are specifically calibrated to match the large-scale morphological trends observed in the Reference Scenario. However, when interventions are implemented, they introduce new conditions in which the physical mechanisms that are not fully captured by the model could lead to a different morphological response than what the model predicts with the current calibration coefficients. The DVR model appears to particularly miss a key process in the Pannerdensch Kanaal, as indicated by the significantly different calibration coefficient required for this branch. However, the model results show that the bed level development in the Pannerdensch Kanaal does not have a significant impact on the bed degradation in the Boven Waal and the low discharge distribution. Therefore, the overall effect on the main study's results is presumably limited.

An important limitation in the modeling of sediment transport is the use of the active layer concept. The active layer refers to the portion of the sediment bed that interacts with the flow and is available for transport (Chavarrías et al., 2019). However, the thickness of this active layer is highly uncertain (Sloff et al., 2024), as its optimal value cannot be physically determined, making it a modeling artefact rather than a physically grounded parameter. An important process where the active layer concept introduces uncertainty is the development of the erosion pits at the LTD transitions, as the erosion occurring at these locations is of similar magnitude as the height of the active layer (1m). This is discussed in more detail in Section 5.2.3 of the discussion.

5.1.4 Use of a morphological acceleration factor

The DVR model uses significantly higher morphological acceleration factors for lower Lobith discharges compared to higher discharges (Sloff et al., 2024). For example, a morphological acceleration factor of 1440 is applied to low Lobith discharges, such as 1020 and 1294 m^3/s, while a factor of 120 is used for moderate to high discharges between 4353 and 7009 m^3/s. This is done because bed level changes generally tend to be significantly lower during low flows (Sloff et al., 2024). However, in this study, low flows become highly morphologically active due to the substantial main channel narrowing caused by the LTDs. Especially at the transitions between LTDs where individual grid cells experience erosion of up to 100cm within one low discharge step in the first year of the simulation. In reality, this erosion increases the cross-sectional area, reducing flow velocities and, consequently, sediment transport capacities over time. This natural feedback limits further erosion. However, the use of high morphological acceleration factors in the model does not fully account for this reduction in erosion over time. For instance, at a Lobith discharge of 1020 m^3/s, the model simulates only 51 minutes, after which the bed level changes are multiplied by an acceleration factor of 1440, representing a morphological period of 51 days. During those 51 minutes, the cross-sectional area has not increased significantly yet, meaning local sediment transport capacities are still high. Nevertheless, the erosion occurring in that short period is extrapolated over the entire 51 days, leading to an overestimation of erosion.

5.2 Reflection on the effects of the interventions

This section reflects on the effects of the interventions implemented in this study. First, Section 5.2.1 compares the effects of the LTDs with findings from prior research, focusing on their effect on bed degradation and the low discharge distribution. Subsequently, Sections 5.2.2 and 5.2.3 focus on two specific effects of the LTDs: the sedimentation within the riparian channels and the formation of erosion pits at the transitions between the LTDs. These phenomena are analyzed in comparison to previous studies, with a particular emphasis on reflecting upon the accuracy of these observed effects in light of the model's limitations. Finally, the effects of the proposed interventions are evaluated within a broader context, focusing on their implications for the morphological development of a bifurcating river system, with comparisons drawn to findings from other relevant studies.

5.2.1 Comparison of effects with previous LTD studies

This section compares the effects of the proposed LTDs on low discharge partitioning and bed degradation with findings from earlier studies concerning LTDs in the Boven Waal (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024). While the LTD configurations in those studies are largely similar, the configuration proposed in this study introduces significant differences, particularly the use of larger riparian channels and a greater main channel with reduction. It is also essential to keep in mind that most of these earlier studies utilized older versions of the DVR model, with the exception of the work by Sloff et al. (2024).

The LTD configuration proposed in this study leads to a significantly greater increase in low discharge partitioning to the Pannerdensch Kanaal compared to the LTD configurations presented in previous studies (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024). This is particularly evident when comparing the findings of Sloff et al. (2024), which report an increase in low discharge partitioning to the Pannerdensch Kanaal of approximately 7 m^3/s. In contrast, this study observes an initial increase ranging from 24 to 43 m^3/s caused by the LTDs, which slightly decreases to 16 to 31 m^3/s after 20 years. This difference is explained by the much larger main channel width reduction of 65 meters caused by the LTDs in this study, as opposed to the 20-meter reduction in the previous studies (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024).

Both this study and previous research on LTDs (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024) demonstrate that the LTDs are effective in mitigating bed degradation in the Boven Waal. While the overall effects appear relatively similar across the studies, there are differences in the underlying causes. In this study, the significantly larger riparian channels lead to increased sedimentation during moderate to high discharges, whereas the greater main channel width reduction contributes to more pronounced erosion during low discharges. The effectiveness of the LTDs in the previous studies regarding bed degradation in the Boven Waal is not as significantly counteracted by erosion during low discharges as in this study. The LTDs in the study by Ten Brink (2024) even result in substantial reach-averaged sedimentation in the Boven Waal, indicating that the configuration in that study is more effective than the one proposed here. However, this difference also largely originates from differences in the model versions used. Ten Brink (2024) employed an intermediate version of the DVR model, which already predicts less erosion in the Reference Scenario (-0.73 cm/yr) compared to the new version used in this study (-1.05 cm/yr).

The LTDs in this study lead to an opposite pattern of reach-averaged sedimentation in the upstream section (rkm 867.3–882) and significantly increased reach-averaged erosion in the downstream section (rkm 882–891) of the Boven Waal. This pattern aligns with findings from previous research (Sloff et al., 2024; Ten Brink, 2024), which recommended enlarging the downstream riparian channels to establish a sediment transport gradient, aiming to also effectively mitigate bed degradation in the downstream section. In this study, efforts were made to establish such a gradient, which has resulted in a significant reduction of erosion during moderate to high discharges in the downstream section. However, despite this improvement, considerable increased erosion persists in this section, suggesting that the riparian channels may still be insufficiently large to fully address this problem. Moreover, two other key differences between the effects of LTDs in this study and those observed in the studies by Sloff et al. (2024) and Ten Brink (2024) contribute to the significantly increased erosion in the downstream section of the Boven Waal as a result of the LTDs in this study. First, as discussed in the previous paragraph, the much greater erosion during lower discharges in this study exacerbates the overall degradation. Second, the larger riparian channels proposed in this study result in increased sedimentation within the riparian channels themselves. This means that a substantial portion of the eroded sediment becomes trapped within the riparian channels and does not re-enter the main channel, unable to contribute to the reduction of erosion in the main channel.

5.2.2 Reflection on the accuracy of predicted sedimentation in riparian channels

The model results in this study show significant sedimentation occurring in the riparian channels associated with the LTDs. This trend aligns with real-world observations, as sedimentation is observed in the riparian channels of the existing LTDs in the Waal (De Jong et al., 2021). Furthermore, these existing riparian channels also exhibit considerable sedimentation within the DVR model, as discussed in the study by Paarlberg et al. (2021), which concludes that riparian channels are morphologically more active than typical side channels. This phenomenon of sedimentation in riparian channels can be physically explained by the significantly lower flow velocities in these channels compared to those in the main channel. As a result, the flow entering the riparian channels experiences a substantial reduction in sediment transport capacity, which leads to significant sediment deposition.

Remarkably, the riparian channels in this study show significantly more sedimentation than the existing LTDs in the Waal. This can be attributed to the fact that the riparian channels of the proposed LTDs are much larger, allowing for increased flow and, consequently, more sediment to enter the riparian channels, which leads to increased sedimentation. This trend is also observed in this study, where more sedimentation occurs in the larger riparian channels compared to the smaller ones. However, it is important to note that an increase in flow entering riparian channels does not necessarily imply that the volume of sediment entering these channels will increase proportionally (Jammers, 2017). A critical consideration is how accurately the sedimentation in the relatively large riparian channels of this study is predicted by the DVR model.

The process of sediment transport over the inlet sills of the riparian channels is highly complex and not fully understood, nor is it completely captured by the DVR model (Paarlberg et al., 2021). Significant uncertainties related to accurate predictions originate from the division of flow between the main channel and the riparian channel, as well as the local grid resolution. Additionally, the DVR model treats all sediment transport as bed load transport, while the suspended component of sediment transport plays a crucial role in the distribution of sediment between the riparian and main channels.

In the DVR model, bed level changes are determined using the Exner equation based on the sediment transport capacity gradient over a grid cell (Sloff et al., 2024). The model is depth-averaged, which means that it assumes that the depth-averaged sediment transport capacity accurately represents the amount of sediment (both suspended and bed load) entering the riparian channels over the inlet sill. However, in reality, sediment concentration is non-uniform across the water column, being higher near the riverbed and lower near the water surface. Since only the flow above the inlet sill enters the riparian channels, the proportion of suspended sediment to flow entering these channels is likely lower in reality than suggested by a depth-averaged approach. Because of this discrepancy, the DVR model presumably overestimates the volume of sediment entering the riparian channels and, consequently, the observed sedimentation. Moreover, the bed load transport over the inlet sill is significantly influenced by the geometry of the sill (Jammers, 2017). This geometry is not included in the model, due to which additional uncertainty is introduced regarding the predicted sediment transport over the inlet sills of the riparian channels.

5.2.3 Reflection on development of erosion pits at the LTD transitions

The development of the erosion pits at the transitions of the LTDs in this study has not been significantly observed in previous studies (Pfeijffer, 2023; Sloff et al., 2024; Ten Brink, 2024). This is because the flow at the transitions between the LTDs in this study passes through a much narrower passage. The reduction in main channel width caused by LTDs on one side of the channel is already much greater in this study compared to earlier ones. However, at the transitions, this reduction occurs on both sides of the channel, leading to the formation of significant erosion pits. This is largely explained by physical processes as already discussed in the results section, but a model artefact introduces uncertainty regarding the development of these erosion pits.

The model introduces uncertainty regarding the development of the erosion pits in this study by not accounting for armoring effects in the sediment transport processes. In reality, finer sediments are typically eroded from the riverbed, while coarser sediments remain, forming a protective armoring layer over the finer material beneath. This armoring layer reduces the erodibility of the bed and prevents further erosion until a strong enough flood event occurs to displace the coarse sediments. This typically occurs in gravel bed rivers, but the bimodal sediment grain size distribution in the Boven Waal suggests that armoring could play a significant role in the natural erosion processes at the LTD transitions (Figure 5.1). However, the DVR model uses an active layer, representing the sediment of the upper 1 meter of the bed, which is available for sediment transport. After each time step, the model mixes the sediment in this active layer and, after erosion, includes sediment from a deeper sediment layer. As a result, although the composition of the active layer becomes coarser over time, new fine sediments are available for erosion (Figure 5.1). This active layer approach thus prevents the formation of an armoring layer. Given that the erosion at the LTD transitions is of comparable order of magnitude to the height of the active layer, this model artefact is significant and may exacerbate the development of erosion pits, assuming armoring is indeed occurring in the Boven Waal.

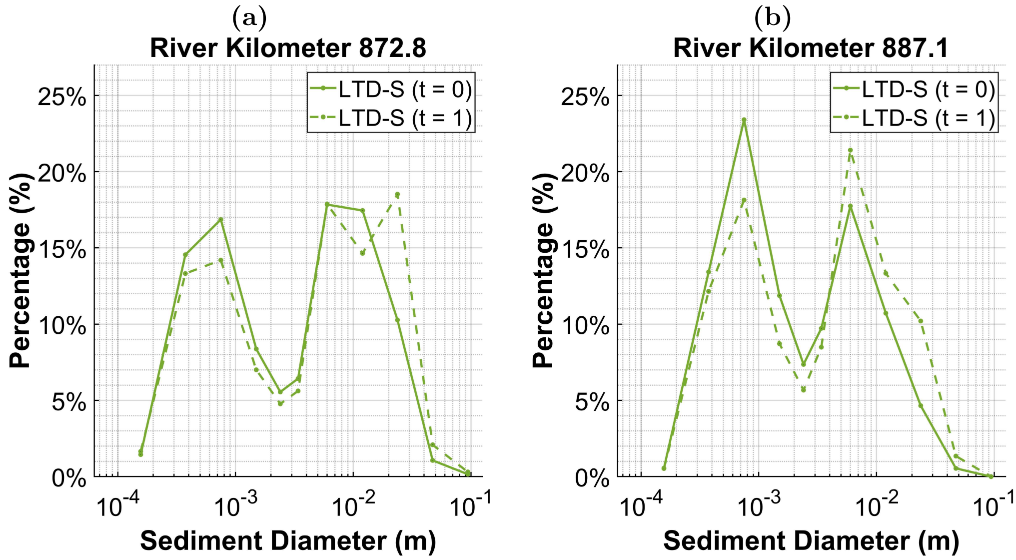

Figure 5.1: Grain size distribution in the main channel of the Boven Waal during Scenario LTD-S at (a) river kilometer 872.9 (transition between LTD 1 and LTD 2) and (b) river kilometer 887.2 (transition between LTD 5 and 6) at the start of the simulation (solid line) and after year 1 (dashed line).

5.2.4 Effects of interventions in a bifurcating river system

Limited research have been done yet that focuses on analyzing the effects of interventions in a bifurcating river system. This section discusses the implications of this study's findings for the morphological development of a bifurcating river system as a response to interventions.

The LTDs in the Boven Waal have opposing effects on discharge distribution across two Lobith discharge ranges (low versus moderate and high discharges). However, moderate and high discharges (ranging from 1954 to 7009 m^3/s) appear to be more dominant in relation to morphological development. These conditions lead to increased discharge partitioning towards the Waal, resulting in significant sedimentation in the Pannerdensch Kanaal. This finding aligns with the idealized modeling study of two similar bifurcating branches by Gao et al. (2024), which indicates that channel deepening in one branch causes more discharge to flow to that branch, subsequently leading to significant sedimentation in the adjacent branch.

Summerdike removal and floodplain lowering in the Pannerdensch Kanaal increases discharge partitioning to that branch, with a comparable magnitude to the effect of the LTDs. However, this change does not lead to sedimentation or significantly reduced erosion in the Waal compared to the LTDs, which contrasts with the findings of Gao et al. (2024). This discrepancy arises because the branches in this study are not equal in size. The change in discharge partitioning is more significant relative to the total discharge of the Pannerdensch Kanaal, than it is to the total discharge in the Boven Waal. Consequently, this study's findings suggest that an intervention in the larger branch of a bifurcating river system leads to a more substantial morphological response in the opposing branch than an intervention in the smaller branch does.

5.3 The potential of using proposed interventions to restore the low discharge distribution and stop bed degradation in the Boven Waal

The interventions analyzed in this study demonstrate significant improvement in terms of increasing low discharge partitioning to the Pannerdensch Kanaal and reducing bed degradation in the Boven Waal. However, these improvements are not sufficient to fully achieve the ultimate goals of restoring the low discharge distribution and stopping bed degradation in the Boven Waal. This section reflects on the potential role that the proposed interventions can play as a part of a broader approach to meeting these ultimate objectives.

First, the feasibility of implementing the proposed interventions is evaluated. Following that, potential improvements regarding the current interventions are evaluated that could further increase low discharge partitioning to the Pannerdensch Kanaal and reduce bed degradation in the Boven Waal. Finally, there is discussed what additional interventions could potentially be part of the overall approach to restore the low discharge distribution and stop bed degradation in the Boven Waal.

5.3.1 Evaluating the feasibility of proposed interventions

The main issue concerning the feasibility of implementing the LTDs is their significant negative impact on the navigation width in the Boven Waal. They reduce the main channel width from 260 meters to 195 meters, which is already below the required width of 230 meters for shipping (Klijn et al., 2022). However, at the transitions between the LTDs, the remaining main channel width is even smaller, approximately 130 meters, which is far below the required width for shipping. This design has been maintained in this study due to the focus on effect assessment rather than analyzing an optimal design; however, with such a substantial reduction in main channel width, there should definitely be considerable space between subsequent LTDs in practice. Otherwise, it would not be feasible for navigation, especially considering that the Boven Waal is already challenging to navigate due to its bends.

The interventions in the Pannerdensch Kanaal, particularly those involving a 2- and 3-meter lowering of the floodplain, are quite extreme and likely not feasible from a practical point of view. It requires substantial excavation of large areas, including agricultural land, and results in these areas being inundated much more frequently than before, making certain land uses, such as agriculture, in these areas no longer feasible. These types of interventions have been adopted in this study because they provide a relatively straightforward way to assess the effect of compensating for the additional discharge directed to the Waal by the LTDs during moderate to high discharges. However, in practice, the use of side channels could be more advantageous, as they can achieve similar effects to floodplain lowering while impacting a smaller floodplain area.

5.3.2 Potential of improving current interventions

The greatest potential for further increasing low discharge partitioning to the Pannerdensch Kanaal with the current interventions lies in narrowing the main channel width of the Boven Waal even more. However, this is not feasible from a navigation perspective and would exacerbate the erosion during low discharges, thereby counteracting the goal of reducing bed degradation in the Boven Waal.

The potential of using LTDs to reduce bed degradation in the Boven Waal would be large if an effective solution could be found to mitigate their negative effects on bed erosion. A major improvement could be achieved by implementing a less drastic reduction in the main channel width, as this would substantially reduce the erosion occurring during low discharges and the formation of erosion pits. This, however, comes at the cost of a smaller increase in low discharge partitioning to the Pannerdensch Kanaal. Nevertheless, over time, the stabilizing or even rising bed level in the Boven Waal also could have a positive impact on low discharge partitioning, by preventing further declines in low discharge partitioning to the Pannerdensch Kanaal (currently at 9-12 m^3/s) or potentially increasing it.

To improve the LTD design in a way that further reduces bed degradation in the Boven Waal while still maintaining its positive effect on low discharge partitioning to the Pannerdensch Kanaal, a different design is needed. This could possibly be achieved by only implementing a more moderate reduction in main channel width for the LTDs in the downstream section (rkm 882-891). The LTDs in the upstream section (rkm 867.3-882), close to the bifurcation, keep their current design to maintain the desired impact on the low discharge partitioning to the Pannerdensch Kanaal. In the downstream section, where the impact on discharge partitioning is less pronounced, a more moderate reduction in main channel width could significantly reduce the erosion that occurs during low discharges, as well as limit the formation of erosion pits. This approach would effectively decrease bed degradation in the downstream section, where erosion is most severe under the current LTD design. However, it remains to be seen to what extent this change in the downstream LTD design would affect the low discharge partitioning.

The current LTD design at the transitions between the LTDs does not suffice from both a bed degradation and navigation perspective. Implementing a more moderate reduction in channel width could help decrease the formation of erosion pits while simultaneously increasing navigational width at these critical points. However, unless the width reduction is relatively small, these transitions are likely to remain problematic. To explore other potential improvements, sediment nourishment could be considered at the transitions to mitigate the erosion pits. However, this approach does not address the underlying causes of their formation, meaning that the pits will reemerge over time. Furthermore, this solution does not effectively resolve the navigation challenges associated with the current design, necessitating a more comprehensive strategy.

A potential improvement to the current LTD design at the transitions between them would be to increase the spacing between subsequent LTDs. This modification could help prevent severely increased local flow velocities caused by the extremely narrowed passages. Additionally, it prevents these points becoming bottlenecks for navigation. However, this approach also means that the flow does not experience channel widening during moderate to high discharges between subsequent LTDs, while this occurs upstream and downstream along the LTDs. Consequently, this could still lead to the formation of erosion pits, similar to what is currently observed at the outflow point from the Spiegelwaal between LTDs 4 and 5 (rkm 886-886.5). To mitigate this issue, it may be beneficial to implement main channel widening between subsequent LTDs. This strategy would likely prevent the significant erosion pits from developing.

With the current LTD design, significant sedimentation occurs in the riparian channels associated with the LTDs leaving less sediment available for the main channel. Decreasing this sedimentation would present an important improvement of the current LTD design concerning bed degradation in the Boven Waal. One potential modification would be to implement higher inlet heights. By increasing the inlet height, the portion of the water column that enters the riparian channels would decrease, as it would only allow the upper segment of the water column to flow into these channels. This upper portion typically has lower sediment concentrations than the lower segments, thereby reducing the overall sediment inflow to the riparian channels. Additionally, using a steeper sill could reduce the amount of bed load transport entering the riparian channel (Jammers, 2017). However, these processes are not well represented in the DVR model, complicating the assessment of their effects. Furthermore, increasing the inlet height would result in reduced flow extraction during moderate discharges, which is a process that enhances erosion. Therefore, it remains uncertain whether these adjustments have significant potential in reducing bed degradation.

Another potential improvement to reduce sedimentation in the riparian channels of the LTDs is to decrease the inlet height. This contrasts with the previous suggestion of increasing the inlet height; however, it ensures that the sediment deposited in the riparian channels during lower flows is largely eroded during high flows (De Ruijsscher et al., 2019). This process would not only reduce maintenance but, more importantly, also results in sediment re-entering the main channel. Alternatively, this process could be done by human interference, involving dredging the sediment from the riparian channels and depositing it as nourishment in the main channel. However, this latter approach significantly disturbs the riparian channels, which serve as favorable environments for ecosystems due to their relatively low flow velocities. Therefore, if such interventions are deemed necessary, they should only be done on a very infrequent basis to limit ecological disruption.

Further potential improvements to the current interventions aimed at reducing bed degradation in the Boven Waal could involve a more extensive level of floodplain lowering in the Pannerdensch Kanaal (>3m). However, the proposed 3-meter floodplain lowering has demonstrated minimal impact on bed degradation in the Boven Waal. While increasing the extent of floodplain lowering may lead to some further reduction in bed degradation, this effect is relatively minor compared to the magnitude of the intervention required. Consequently, this approach lacks significant potential to substantially enhance the reduction of bed degradation in the Boven Waal.

To conclude, there is considerable potential to improve the design of the LTDs to further reduce bed degradation in the Boven Waal. On the contrary, there is little potential for enhancing the LTD design to increase low discharge partitioning to the Pannerdensch Kanaal. Moreover, the improvements aimed at reducing bed degradation in the Boven Waal may even reduce the increased low discharge partitioning to the Pannerdensch Kanaal. LTDs can thus play a significant role within the overall approach of restoring the low discharge distribution and stopping bed degradation in the Boven Waal, but additional river interventions are needed.

5.3.3 Potential of additional interventions

Additional interventions are needed to complement the proposed interventions in developing an effective approach to restore the low discharge distribution and stop bed degradation in the Boven Waal. Therefore, this section reflects on the potential for combining the proposed interventions with other river interventions.

A potential additional intervention to further reduce bed degradation in the Boven Waal could be the lowering of groynes. This intervention has been shown to enhance the effectiveness of reducing bed degradation when combined with LTDs (Ten Brink, 2024). However, the impact of groyne lowering is significantly smaller compared to that of the LTDs. It thus has the potential to be combined with LTDs and be part of the overall approach to restore the low discharge distribution and stop bed degradation in the Boven Waal, but it is unlikely to play a major role in achieving these objectives.

Another potential additional intervention could be sediment nourishments, which has been shown to be effective in reducing bed degradation (Czapiga et al., 2022a; De Lange, 2022; Liptiay, 2023). Although the combination of sediment nourishment with LTDs has not yet been investigated, it could serve as a valuable addition to reduce downstream bed degradation. This is particularly important because bed degradation in downstream sections is exacerbated by the upstream decrease in sediment transport capacity caused by the LTDs. Sediment nourishment could be implemented both within the LTD section, particularly at the beginning of the downstream section in the Boven Waal (rkm 882-891), where significant erosion is occurring, and downstream of the LTDs to help mitigate the increased bed degradation in the Midden Waal. When sediment nourishments are applied within the section of the LTDs, it is essential to ensure that they are not placed too close to the inlet of a riparian channel from an upstream perspective. Doing so could lead to significant sedimentation in the riparian channels.

Apart from sediment nourishments, the increased bed degradation in the Midden Waal resulting from the LTDs can be mitigated by extending the LTDs along the Midden Waal. However, it is crucial to implement increasingly larger riparian channels in the downstream direction to effectively reduce sediment transport capacities in this longitudinal direction. Without this adjustment, significantly increased bed degradation in the Midden Waal will still occur (Sloff et al., 2023; Pfeijffer, 2023). Regardless of the feasibility of constructing such large riparian channels, there will always be a downstream end of the LTDs beyond which a significant increase in sediment transport capacity occurs, leading to substantial erosion. Thus, it seems more promising to implement sediment nourishments at the downstream end of the LTDs to compensate for the decreased sediment transport caused by the LTDs.

Sediment nourishments applied in the most upstream part of the Boven Waal, close to the Pannerdensch bifurcation, could potentially further enhance the low discharge partitioning to the Pannerdensch Kanaal. The increase in water level resulting from these sediment nourishments leads to a greater discharge directed toward the Pannerdensch Kanaal through backwater effects. However, it is crucial that the sediment nourishment is sufficiently long and high to create such a significant backwater effect. A potential downside is that it could result in a significant decrease in water depth which obstructs navigation. Additionally, the sediment nourishment erodes over time, which would result in a decreasing partitioning to the Pannerdensch Kanaal. This scenario would necessitate repetitive nourishments to maintain effectiveness.

Another intervention that could further enhance low discharge partitioning to the Pannerdensch Kanaal, in addition to the effects of the LTDs, is the widening of the main channel of the Pannerdensch Kanaal during low discharges. The low discharge partitioning at the Pannerdensch bifurcation is primarily determined by the ratio between the dimensions of the main channel of the Pannerdensch Kanaal and the Waal. While the LTDs narrow the main channel of the Waal, widening the main channel of the Pannerdensch Kanaal could increase the ratio of low discharge directed to the Pannerdensch Kanaal. However, a potential downside is that water depth in the Pannerdensch Kanaal during low flows could be reduced due to this widening, although this would be partially offset by the increased discharge to the Pannerdensch Kanaal. Nevertheless, this type of intervention holds significant potential, and it is definitely worth investigating how combining it with the LTDs in the Boven Waal could lead to further increases in low discharge partitioning to the Pannerdensch Kanaal.

A more ambitious and far-reaching measure to increase low discharge partitioning to the Pannerdensch Kanaal would be to construct a barrier-like arm at the Pannerdensch bifurcation. This barrier should would aim to widen the opening towards the Pannerdensch Kanaal while narrowing the opening towards the Boven Waal. The barrier would remain lowered during low flows, directing more flow to the Pannerdensch Kanaal. Conversely, during moderate to high flows, the barrier would be raised, thereby having no impact on discharge distribution. However, such a rigorous intervention at a bifurcation is inherently risky. Very little is understood about the precise functioning of the bifurcation and why it remains relatively stable despite substantial differences in flow partitioning between both branches. Therefore, predicting the morphological effects of such an intervention and assessing its potential applicability is quite challenging.

To summarize, other river interventions are necessary in addition to the proposed interventions in order to restore the low discharge distribution and stop bed degradation in the Boven Waal. Additional interventions with significant potential include sediment nourishments and groyne lowering in the Boven Waal, and main channel widening in the Pannerdensch Kanaal.

6 Conclusions & Recommendations

6.1 Conclusions

This study aims to increase low discharge partitioning to the Pannerdensch Kanaal and reduce the bed degradation in the Boven Waal by implementing interventions in both the Boven Waal and the Pannerdensch Kanaal. It investigates the effects of LTDs in the Boven Waal, as well as additional summerdike removal and uniform floodplain lowering in the Pannerdensch Kanaal, in relation to these two objectives. The following sections provide answers to the two research sub-questions (Sections 6.1.1 and 6.1.2) and the main research question of this study (Section 6.1.3).

6.1.1 Conclusion research sub-question 1

The effects of the implementation of LTDs in the Boven Waal are analyzed in order to answer research sub-question 1:

"What is the effect of LTDs in the Boven Waal on the low discharge distribution at the Pannerdensch bifurcation and the bed degradation in the Boven Waal and Pannerdensch Kanaal?"

It is found that the LTDs significantly increase the low discharge partitioning to the Pannerdensch Kanaal, as a result of the substantial reduction in main channel width they cause in the Boven Waal during low Lobith discharges (1020 to 1543 m^3/s), decreasing the width from approximately 260 meters to 195 meters. Initially, the low discharge partitioning to the Pannerdensch Kanaal rises by 24 to 42 m^3/s relative to the Reference Scenario. The reduced erosion in the Boven Waal caused by the LTDs then ensures that the decrease in low discharge partitioning over a 20-year period is much smaller (-9 to -12 m^3/s) compared to the Reference Scenario (approximately -20 m^3/s). As a result, after 20 years, there is still significantly more low discharge partitioning to the Pannerdensch Kanaal than there was initially observed in the Reference Scenario (+15 to 30 m^3/s).

The LTDs ensure that the required discharge partitioning to the Pannerdensch Kanaal at a Lobith discharge of 1543 m^3/s (required: 315 m^3/s; (Klijn et al., 2022)) is met both at the beginning and the end of the 20-year period. However, during Lobith discharges of 1020 and 1294 m^3/s, there remains a shortfall, with at least an additional 23 m^3/s needed to meet the required discharge partitioning. In conclusion, while the LTDs in this study are effective in increasing low discharge partitioning to the Pannerdensch Kanaal, their impact still falls short of fully achieving the required low discharge partitioning criteria.

The implementation of the LTDs leads to a significant reduction in bed degradation in the main channel of the Boven Waal, even resulting in significant reach-averaged sedimentation of approximately 9 to 10 cm in the upstream section (river kilometers 867.3-882). This positive outcome is primarily attributed to the LTDs' effectiveness in substantially mitigating erosion during moderate to high Lobith discharges (ranging from 1954 to 7009 m^3/s), which cumulatively produce an impressive 46 cm of reach-averaged sedimentation in the Boven Waal over a 20-year period. This constitutes a major step in stopping the bed degradation in the Boven Waal during moderate to high discharges. Nonetheless, the analysis reveals that the LTDs do not perform as effectively as anticipated, still leading to approximately 8 cm of reach-averaged erosion in the Boven Waal, compared to the 15 cm of erosion observed in the Reference Scenario.

It is found that the substantial reach-averaged sedimentation occurring during moderate to high Lobith discharges, caused by the LTDs in the Boven Waal, is counteracted by three negative effects associated with the LTDs. The most significant effect is that the LTDs, due to their substantial reduction in main channel width, result in low Lobith discharges becoming highly erosive in the Boven Waal. Cumulatively, this leads to approximately 54 cm of reach-averaged erosion in the main channel of the Boven Waal over a 20-year period. Additionally, local bed degradation is significantly exacerbated by the development of erosion pits at the transitions of the LTDs during the first year, resulting in local erosion of up to 1 meter. This phenomenon also contributes to the reach-averaged erosion in the Boven Waal (4 cm in year 1), particularly in the downstream section (river kilometers 882 to 891), as a large portion of the eroded sediment is deposited in the riparian channels. The third negative effect of the LTDs is that significant sedimentation occurs within the riparian channels over the 20-year period, with a total volume ranging from 435,182 m^3 to 795,069 m^3. The most sedimentation is observed in the scenario with the deepest riparian channels. If this sediment were to be deposited in the main channel, it would translate into an increase in reach-averaged bed level of approximately 0.14 to 0.22 m.

In addition to the effects on low discharge distribution and bed degradation in the Boven Waal, the LTDs also significantly impact bed degradation in the Pannerdensch Kanaal, Boven Rijn, and Midden Waal. Specifically, the LTDs exacerbate erosion in the Midden Waal, resulting in reach-averaged erosion of 0.55 to 0.61 m over a 20-year period, compared to 0.32 m observed in the Reference Scenario. Similarly, increased erosion is noted in the Boven Rijn, but less pronounced as in the Midden Waal. Conversely, the Pannerdensch Kanaal experiences significantly greater reach-averaged sedimentation compared to the Reference Scenario. The effects of the LTDs are opposite across the low and moderate to high Lobith discharge ranges. It is found that the effect of the LTDs during moderate to high Lobith discharges are dominant regarding their impact on the bed degradation of the adjacent branches. Additionally, it is found that larger riparian channels in an LTD Scenario amplify the effects on bed degradation in the adjacent river branches.

6.1.2 Conclusion research sub-question 2

The combined effects of implementing summerdike removal and floodplain lowering in the Pannerdensch Kanaal, along with LTDs in the Boven Waal, have been analyzed to answer research sub-question 2:

"What is the effect of summerdike removal and varying levels of floodplain lowering in the Pannerdensch Kanaal in addition to LTDs in the Boven Waal on the moderate, high and extreme discharge distribution at the Pannerdensch bifurcation and the bed degradation in both branches?"

The analysis reveals that the combination of summerdike removal and uniform floodplain lowering in the Pannerdensch Kanaal cannot simultaneously compensate for the additional discharge directed to the Waal by the LTDs across the full range of moderate to extreme Lobith discharges. The intervention with 0.5-meter floodplain lowering (Scenario LTD-S-FL-0.5) effectively compensates for the additional discharge drawn to the Waal during an extreme Lobith discharge of 16,000 m^3/s, by increasing discharge partitioning to the Pannerdensch Kanaal with 214 m^3/s compared to a scenario with only LTDs (LTD-S). While erosion in the Waal leads to a gradual decrease in discharge partitioning to the Pannerdensch Kanaal over time, this reduction (~38 m^3/s) is similar in both the Reference Scenario and Scenario LTD-S-FL-0.5. On the other hand, interventions with 2- to 3-meter floodplain lowering are needed to significantly compensate for the additional discharge directed to the Waal as a result of the LTDs during moderate to high Lobith discharges (1954 to 7009 m^3/s). However, these more extreme interventions result in an excessive increase in discharge partitioning to the Pannerdensch Kanaal during a Lobith discharge of 16,000 m^3/s (+428 to 516 m^3/s).

One of the primary objectives of implementing interventions in the Pannerdensch Kanaal is to further reduce bed degradation in the Boven Waal, beyond the reductions already achieved by the LTDs. This is approached by compensating for the additional discharge directed to the Waal during moderate to high Lobith discharges, which occurs as a result of the implementation of LTDs. The 2- and 3-meter floodplain lowering in the Pannerdensch Kanaal aims to counteract this by decreasing the discharge partitioning to the Waal compared to a scenario involving only LTDs. However, the analysis reveals that these interventions are not effective in significantly reducing bed degradation in the Boven Waal beyond what the LTDs already achieve. The scenario involving 3-meters floodplain lowering only achieves a marginal additional reduction of about 0.4 cm in reach-averaged erosion in the main channel of the Boven Waal over a 20-year period, on top of the 6.3 cm reduction achieved by the LTDs.

Within the Boven Waal, the interventions in the Pannerdensch Kanaal have minimal positive impact on mitigating bed degradation. However, the interventions involving 2- and 3-meter floodplain lowering significantly exacerbate bed degradation in the Boven Rijn, Boven Nederrijn, and Boven IJssel, particularly leading to a substantial increase in reach-averaged erosion in the downstream reaches compared to a scenario with only LTDs. In contrast, the scenario with a 0.5-meter floodplain lowering does not exhibit such a pronounced increase in erosion in these reaches.

The removal of summerdikes and the implementation of floodplain lowering within the Pannerdensch Kanaal lead to a significant increase in sedimentation in this branch. Particularly the scenarios involving 2- and 3-meter floodplain lowering which result in reach-averaged sedimentation of 0.19 and 0.27 m over a 20-year period in comparison to 0.07 m in a scenario with only LTDs. It is found that the 2- and 3-meter floodplain lowering have a much greater effect on bed level development in the Pannerdensch Kanaal, in addition to the impact of the LTDs, than the LTDs have on their own. The reach-averaged sedimentation is mainly occurring along the first part of the floodplain lowering (river kilometer 869.2 to 873.2), where the 2- and 3-meter floodplain lowering results in large sedimentation humps, locally reaching up to 1.4 meters.

6.1.3 Conclusion to main research question

The following main research question is answered based on the answers to the two research sub-questions:

"How can varying interventions in the Boven Waal and Pannerdensch Kanaal be used to increase low discharge partitioning to the Pannerdensch Kanaal and reduce the bed degradation in the Boven Waal?"

The study shows that LTDs are effective in significantly increasing low discharge partitioning to the Pannerdensch Kanaal by substantially reducing the main channel width of the Boven Waal. The implementation of the proposed LTDs leads to considerable progress toward achieving the required low discharge partitioning. However, the findings show that this remains insufficient to fully meet the required low discharge partitioning. This shortfall persists despite a substantial reduction in the main channel width from 260 to 195 meters, which is already below the current navigational requirement of a minimum width of 230 meters. Therefore, additional interventions are necessary in addition to reducing the main channel width in the Boven Waal.

The research demonstrates that LTDs are effective in mitigating bed degradation in the Boven Waal, particularly during moderate to high Lobith discharges (1954 to 7009 m^3/s), during which they cumulatively result into reach-averaged sedimentation due to the widening of the main channel. This constitutes a significant step toward stopping bed degradation in the Boven Waal. However, this positive effect is counteracted by several negative effects, predominantly caused by the substantial reduction in the main channel width. This reduction leads to low discharges becoming highly erosive, effectively shifting the erosion problem from moderate to high discharges to low discharges. Additionally, severe localized erosion occurs at the transitions between LTDs, where the extreme narrowing due to channel width reductions on both sides leads to the development of significant erosion pits. Therefore, the study indicates that using LTDs for increasing low discharge partitioning to the Pannerdensch Kanaal significantly counteracts the goal of reducing bed degradation in the Boven Waal.

The additional interventions in the Pannerdensch Kanaal do not significantly reduce bed degradation in the Boven Waal. It was presumed that these interventions could mitigate erosion in the Boven Waal by compensating for the extra discharge drawn to the Waal due to the LTDs during moderate to high discharges. The study, however, reveals no significant potential for such interventions in the Pannerdensch Kanaal, which aim to increase riverbed capacity during moderate to high discharges, to effectively reduce bed degradation in the Boven Waal. In fact, the interventions including 2- and 3-meter floodplain lowering significantly worsen bed degradation in upstream and downstream branches, including the Boven Rijn, Boven Nederrijn, and Boven IJssel. A more modest intervention in the Pannerdensch Kanaal, including a 0.5-meter floodplain lowering, appears to be useful in maintaining the required discharge distribution during extreme Lobith discharges (16,000 m^3/s) for flood safety, without significantly worsening bed degradation in the other branches.

In conclusion, LTDs should be included in the strategy to increase low discharge partitioning to the Pannerdensch Kanaal and to reduce bed degradation in the Boven Waal, as they demonstrate strong potential in addressing both objectives. However, the extent of main channel width reduction proposed in this study is not optimal, as it introduces significant erosion during low discharges and does not meet navigational requirements. A more balanced approach, including the combination with other river interventions, is needed to meet the required low discharge partitioning to the Pannerdensch Kanaal and stop bed degradation in the Boven Waal.

6.2 Recommendations

The proposed interventions are not sufficient to restore the low discharge distribution and stop bed degradation in the Boven Waal. Therefore, various recommendations are made for further research to contribute to finding an overall approach with which these ultimate goals can be achieved.

6.2.1 Model improvements

It is recommended to investigate the effect of using a three-step spin-up method instead of the current two-step method on the initial bed level with which the simulations are performed. The additional step would involve spinning up the bed composition separately, before allowing bed level changes to occur. The current spin-up method lacks this step, even though the model input relies on width-averaged bed composition values. As a result, the initial bed level used in the model may be less accurate. Investigating the significance of this difference between both approaches could determine if the three-step approach leads to more reliable model results.

As for the upstream boundary condition, it is recommended to explore the effects of using different hydrographs when examining the effects of interventions on bed degradation. The upstream hydrograph introduces considerable uncertainties regarding bed level development, especially since river discharges could change significantly in the future due to climate change. Additionally, it is advised to investigate the influence of peak flows on bed degradation and discharge distribution, as these potentially cause substantial changes in both processes (Chowdhury et al., 2023). In order to model these effects, the DVR model would need to be improved to better capture hydrodynamics during such extreme discharges.

Another recommendation to improve the model would be to reconsider the high morphological acceleration factors applied to low discharges, particularly when implementing LTDs that cause significant main channel width reductions in the Boven Waal, as seen in this study. Due to the considerable narrowing of the main channel, low discharges become highly morphologically active, challenging the assumption that these discharges result in less morphological change. Therefore, the use of high morphological acceleration factors for low discharges may no longer be accurate under these conditions.

To more accurately simulate sedimentation in the riparian channels, it is recommended to incorporate the suspended load component into the model. Additionally, improvements are needed to better represent the bed load transport over the inlet sill, which could be achieved by local grid refinement and including the effects of varying sill geometries, among other factors. These enhancements would lead to more accurate estimations of the amount of sediment entering the riparian channels.

6.2.2 Improving the proposed LTD design

Although the proposed LTDs already contribute significantly to reducing bed degradation in the Boven Waal, there remains substantial potential for enhancing the LTD design to further reduce bed degradation. In general, it is recommended to use a more modest main channel width reduction than proposed in this study, where the main channel width in the Boven Waal is reduced from 260 to 195 meters. This is needed to more effectively mitigate bed degradation, as the current main channel width reduction results into severe erosion during low discharges.

To maintain the effectiveness of the proposed LTDs on the low discharge partitioning to the Pannerdensch Kanaal, while also further reducing bed degradation in the Boven Waal, it is recommended to explore the impact of varying main channel width reductions in different sections of the Boven Waal. In the upstream section (rkm 867.3-882), the LTDs should still significantly reduce the main channel width (e.g., by 40-65 meters) to substantially increase the low discharge partitioning to the Pannerdensch Kanaal. In contrast, the LTDs in the downstream section (rkm 882-891) should induce a smaller width reduction (e.g., 20 meters) to more effectively mitigate erosion, as most erosion occurs in this section. It is advised to investigate how this smaller reduction in main channel width in the downstream section influences the low discharge partitioning to the Pannerdensch Kanaal. Additionally, it is recommended to examine at which distance from the Pannerdensch bifurcation a smaller main channel width reduction no longer significantly impacts the increase in low discharge partitioning to the Pannerdensch Kanaal. This would help in identifying the point from which the LTDs can reduce the main channel width less drastically without affecting the desired outcomes for discharge partitioning.

To prevent the formation of substantial erosion pits at the transitions between the LTDs and to avoid creating bottlenecks for shipping, it is recommended to maintain sufficient spacing between successive LTDs. This spacing will help ensure that flow velocities do not become excessively high due to the very narrow passages created at the current transitions between LTDs. Additionally, it is recommended to slightly widen the main channel along the suggested spacing between the LTDs to prevent the development of erosion pits in these areas during moderate to high discharges. This widening is essential because, without it, a significant increase in sediment transport capacity occurs at the upstream end of these areas, since the main channel upstream of these spacing does experience expansion during moderate to high discharges due to the riparian channels,

To reduce the amount of sedimentation in riparian channels, it is recommended to investigate the effects of different inlet sill heights and possibly geometries. A higher and steeper inlet sill could decrease the amount of sediment entering the riparian channels, while a lower inlet sill might allow for the sediment deposited in the riparian channel during lower flows to be eroded again during higher flows, causing it to re-enter the main channel. It would be interesting to examine how much this affects sedimentation in the riparian channels and how that, in turn, impacts bed degradation in the Boven Waal. It is important to note that, in order to accurately assess the effects of a higher and steeper inlet sill on sediment transport over the sill, model improvements are needed, as discussed in the previous section.

6.2.3 Exploring the combination with additional river interventions

It is recommended to investigate the combined effects of LTDs and sediment nourishments on bed degradation in the Boven Waal. This combination could be effective, as sediment nourishments may compensate for increased downstream erosion resulting from the reduced sediment transport capacities caused by the upstream LTDs. For instance, sediment nourishments could be applied at the upstream end of the downstream section of the Boven Waal (rkm 882-891), where significantly increased erosion occurs, as well as at the downstream end of the LTDs to mitigate increased erosion in the Midden Waal. However, when combining both interventions, it is crucial that the sediment nourishment is not placed too close to the inlet of a riparian channel from an upstream perspective, as this could lead to excessive sedimentation in the riparian channels.

Another recommendation regarding the combination with sediment nourishments is to explore their potential as a (short-term) measure to further enhance low discharge partitioning to the Pannerdensch Kanaal. This would require significant sediment nourishment at the upstream end of the Boven Waal, which would need to be repeated over time due to erosion. It should be investigated how long and high this sediment nourishment needs to be in order to significantly increase low discharge partitioning to the Pannerdensch Kanaal in conjunction with the LTDs. Based on the findings regarding the required dimensions, a decision could be made on the feasibility of this approach.

It is recommended to combine multiple interventions that increase low discharge partitioning to the Pannerdensch Kanaal, as this helps to avoid the need for a single intervention to be excessively extreme. Therefore, in addition to interventions in the Boven Waal that increase the low discharge partitioning to the Pannerdensch Kanaal, it is recommended to explore interventions in the Pannerdensch Kanaal that could achieve a similar effect. Specifically, the effect of widening the main channel in the Pannerdensch Kanaal should be investigated alongside the implementation of LTDs in the Boven Waal. Research should focus on determining the necessary increase in main channel width in the Pannerdensch Kanaal to significantly enhance low discharge partitioning to this branch. Furthermore, considering navigation, it is essential to assess the effects of this channel widening on water depths during low discharges.

References

Barneveld, H., M. Boersema, F. Schuurman, and Vriend. H. de (2021). *Het verhaal van het sediment.* Tech. rep. Rijkswaterstaat.

Becker, A. (2021). *Slim suppleren Boven-Waal.* Tech. rep. Deltares, Rijkswaterstaat.

Blom, A. (2016). *Bed degradation in the Rhine River.* Tech. rep. TU Delft.

Chavarrías, V., G. Stecca, A. Siviglia, and A. Blom (2019). "A regularization strategy for modeling mixed-sediment river morphodynamics". *Advances in Water Resources* 127, pp. 291–309. DOI: 10.1016/J.ADVWATRES.2019.04.001.

Chowdhury, M. Kifayath, Astrid Blom, Clàudia Ylla Arbós, Merel C. Verbeek, Max H.I. Schropp, and Ralph M.J. Schielen (2023). "Semicentennial Response of a Bifurcation Region in an Engineered River to Peak Flows and Human Interventions". *Water Resources Research* 59 (4). DOI: 10.1029/2022WR032741.

Czapiga, M., A. Blom, and E. Viparelli (2022a). "Sediment Nourishments to Mitigate Channel Bed Incision in Engineered Rivers". *Journal of Hydraulic Engineering* 148 (6). DOI: 10.1061/(ASCE)HY.1943-7900.0001977.

Czapiga, M., A. ; Blom, and E. Viparelli (2022b). "Efficacy of Longitudinal Training Walls to Mitigate Riverbed Erosion". *Water Resources Research* 58 (12). DOI: 10.1029/2022WR033072.

De Jong, J., V. Chavarrias, and W. Ottevanger (2021). *Eindevaluatie pilot Langsdammen in de Waal: hydromorphological data and observations.* Tech. rep. Deltares.

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

De Ruijsscher, T. V., A. J.F. Hoitink, S. Naqshband, and A. J. Paarlberg (2019). "Bed morphodynamics at the intake of a side channel controlled by sill geometry". *Advances in Water Resources* 134 (0309-1708), p. 103452. DOI: 10.1016/J.ADVWATRES.2019.103452.

Eerden, H. (2022). *WaalSamen, Pilot Langsdammen : samenvatting rapportages integrale evaluatie pilot.* Tech. rep. Rijkswaterstaat.

Gao, W., D. Shao, Z. Wang, Z. Zhu, and Z. Yang (2024). "System-Wide Effects of Local Bed Disturbance on the Morphological Evolution of a Bifurcating Channel Network". *Journal of Geophysical Research: Earth Surface* 129 (3). DOI: 10.1029/2023JF007514.

Huthoff, F., A. Paarlberg, J. Vieira, and S. A. K. De Jong (2015). *Globaal ontwerp langsdammen; Rijnsplitsingspuntengebied en overige Rijntakken.* Tech. rep. HKV Lijn in Water.

Jammers, S.M.M. (2017). *Sediment transport over sills of longitudinal training dams. MSc Thesis.* TU Delft.

Klijn, F., H. Leushuis, M. Treurniet, W. Van Heusden, and S. Van Vuren (2022). *Systeembeschouwing Rijn en Maas ten behoeve van ontwerp en besluitvorming.* Tech. rep. Den Haag: Programma Integraal Rivier Management; Ministerie van Infrastructuur en Water.

Liptiay, E.J.A. (2023). *Supply-driven nourishment strategies for mitigating bed degradation in the Waal. MSc Thesis.* University of Twente, Sweco.

Meyer-Peter, E. and R. Müller (1948). "Formulas for bed-load transport". *Proceedings 2nd IAGR World Congress. Stockholm, Sweden*, pp. 39–64.

Ouwerkerk, S., F. Huthoff, M. Zuijderwijk, and L. De Wit (2023). *Systeemmaatregelen IRM Rijn en Maas.* Tech. rep. HKV, Witteveen+Bos.

Paarlberg, A.J., A.Y.A. Omer, and M.F.M. Yossef (2021). *Eindevaluatie pilot Langsdammen in de Waal : Delft3D simulations.* Tech. rep. HKV Lijn in Water and Deltares.

Parker, G., P. C. Klingeman, and D. G. McLean (1982). "Bedload and size distribution in paved gravel-bed streams." *Journal of the Hydraulics Division - ASCE* 108 (HY4), pp. 544–571.

Pfeijffer, C. (2023). *The effects of different designs of longitudinal training dams on countering bed degradation for different discharge scenarios in the River Waal. MSc Thesis.* University of Twente, Royal HaskoningDHV.

Programma Integraal Riviermanagement (2023). *Naar een toekomstbestendig rivierengebied Ontwerp Programma onder de Omgevingswet (POW) Integraal Riviermanagement.* Tech. rep. Programma Integraal Riviermanagement.

Rorink, T. (2022). *The potential of side channels to mitigate large-scale bed degradation in the Dutch Rhine distributaries: A 1D-modelling study. MSc Thesis.* University of Twente, Witteveen+Bos.

Schropp, M. and T. Jansen (2020). *Opties afvoerverdeling hoogwater Rijntakken.*

Sloff, K. (2011). *DVR toolbox for sediment management in the Rhine delta.* Tech. Rep. Deltares.

Sloff, K. (2019). *Prognose bodemligging Rijntakken 2020-2050: trends voor scheepvaart en waterbeschikbaarheid.* Tech. rep. Deltares.

Sloff, K., A. Becker, A. Paarlberg, and P. Van Denderen (2024). *2D morfologisch model IRM.* Tech. rep. Deltares.

Sloff, K., A. Paarlberg, P. Van Denderen, H. Barneveld, and E. Mosselman (2023). *Onderbouwing beleidskeuze bodemligging IRM.* Tech. rep. HKV, Deltares.

Ten Brink, R. M. (2024). *Combining river interventions to mitigate bed degradation in the Boven-Waal. MSc Thesis.* University of Twente, Royal HaskoningDHV.

Van Maren, D. S., J. G.W. Beemster, Z. B. Wang, Z. H. Khan, R. A. Schrijvershof, and A. J.F. Hoitink (2023). "Tidal amplification and river capture in response to land reclamation in the Ganges-Brahmaputra delta". *CATENA* 220. DOI: 10.1016/J.CATENA.2022.106651.

Van Vuren, S., A. Paarlberg, and H. Havinga (2015). "The aftermath of "Room for the River" and restoration works: Coping with excessive maintenance dredging". *Journal of Hydro-Environment Research* 9 (2), pp. 172–186. DOI: 10.1016/J.JHER.2015.02.001.

Welsch, N. (2021). *Two-Dimensional Morphological Modelling of the Effects of the Room for Living Rivers Vision in the Middle-Waal. MSc Thesis.* University of Twente, Sweco.

Ylla Arbós, C., A. Blom, C. J. Sloff, and R. M.J. Schielen (2023). "Centennial Channel Response to Climate Change in an Engineered River". *Geophysical Research Letters* 50 (8). DOI: 10.1029/2023GL103000.

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

Appendices

A Elaboration on the technical implementation of the interventions in the DVR model

To implement the interventions in the DVR model, various input files need to be adjusted. For the LTDs in the Boven Waal, this has been largely done using the Baseline tool, specifically Baseline version 5.3.4 in ArcMap version 10.6. The Baseline database 'baseline-rijn-j18_5_v2', corresponding to the latest DVR model version, is used for this purpose. The LTDs in the Boven Waal are schematized within this existing GIS schematization according to the Baseline protocol associated with the DVR model. This GIS schematization is then converted into Delft3D input files using Baseline, which averages data over grid cells and snaps it to grid cell edges. As a result, the bathymetry, weir, and roughness files (U- and V-direction) are modified.

For the implementation of summerdike removal and floodplain lowering in the Pannerdensch Kanaal, input files have been directly modified without the use of Baseline. This approach is chosen because the modifications required for these interventions are simpler. Additionally, the author's understanding of the input files significantly improved during the process of implementing the LTDs, making direct modification more feasible.

The types of input files modified in the DVR model for the LTDs are listed in Table A.1 For the summerdike removal and floodplain lowering interventions, only the bathymetry and weir files are changed (Table A.1). The following two sub-sections explain in more detail how the input files are modified for both interventions. These sections only describe how the input files of the DVR model are changed to implement the interventions. The exact dimensions and schematization choices have already been explained in Methodology Section 3.2

Table A.1: Overview of the types of input files modified in the DVR model for the implementation of the interventions. The x's in the 3rd and 4th column indicate whether a specific type of input file has been modified for a particular intervention.

Type of input file	File extension	LTDs	Summerdike Removal & Floodplain Lowering
Bathymetry	.dep	x	x
Sediment layer thickness	.thk	x	
Sediment fractions	.frc	x	
Weirs	.wr	x	x
Roughness in the U-direction	.aru	x	
Roughness in the V-direction	.arv	x	

A.1 LTDs in the Boven Waal

The grid cells that have been modified for the LTD implementation are highlighted as transparent in Figure A.1, while the darker cells indicate areas that are left unchanged.

First, the groynes that are present at the location of the riparian channels in the Reference Scenario (brown lines in Figure A.1) have been removed from the weir file of the Boven Waal. Following this, new weirs are added to represent the inlet and crest of the LTDs. Specifically, weirs in the V-direction are implemented to reflect the inlet height across the upstream grid cells of the riparian channels (Figure A.1). Additionally, weirs in U-direction have been added along the main channel side of the riparian channels (Figure A.1). The weirs at the upstream two grid cells consist of the inlet height, while those further downstream along the riparian channel represent the crest height.

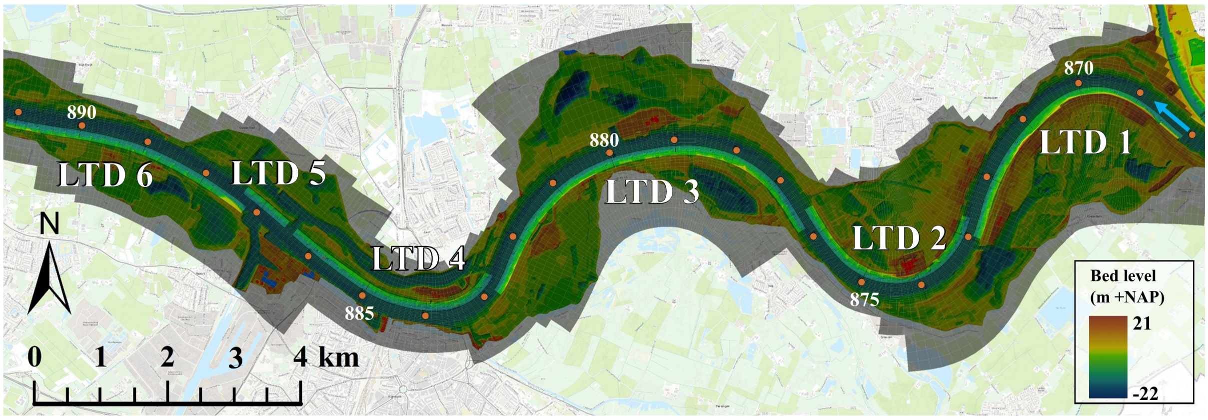

Figure A.1: The location of the riparian channels for the six LTDs in the Boven Waal (rkm 867.3-891) displayed on top of the DVR model grid and the original riverbed depth before the introduction of LTDs. Transparent grid cells represent the riparian channels, while darker cells indicate unchanged areas. The light blue arrow represents the flow direction. The brown dots represent river kilometers.

The bathymetry file of the Boven Waal has been changed in order to schematize the depth of the riparian channels. The bed level values present at the riparian channels have been replaced by the bed level of the riparian channels as described in Section 3.2. The bed level of the grid cells upon which the inlet sill and crest is located is made slightly higher in comparison to the bed level of the rest of the riparian channel in order to compensate for the decrease in cross-sectional area that the LTD bodies cause. This increase is determined based on the inlet and crest height, the slope of the LTD body (1:2.5) and the width of the body at the crest level (2 meters).

The roughness values at the location of the LTDs and associated riparian channels have been modified for both the U- and V-direction to reflect the presence of this intervention. For the grid cells that only cover the riparian channel, the Nikuradse roughness height is set to 0.2. The grid cells partially covered by the LTD body are assigned a slightly higher Nikuradse roughness height, as the LTD bodies have a roughness height of 0.4. Baseline automatically calculated the resulting roughness for these mixed cells, based on the proportion of the cell area covered by the LTD body and the riparian channel, leading to an approximate Nikuradse roughness height of 0.23 for these cells.

The sediment input files of the Boven Waal have been adjusted to ensure that the riparian channels do not contain sediment at the start of the simulation. This was achieved by setting the sediment layer thickness and sediment fractions in the corresponding grid cells to zero. Specifically, 7 sediment layer thickness files were modified, along with a total of 77 sediment fraction files, as there are 11 defined sediment fractions for each of the 7 sediment layers.

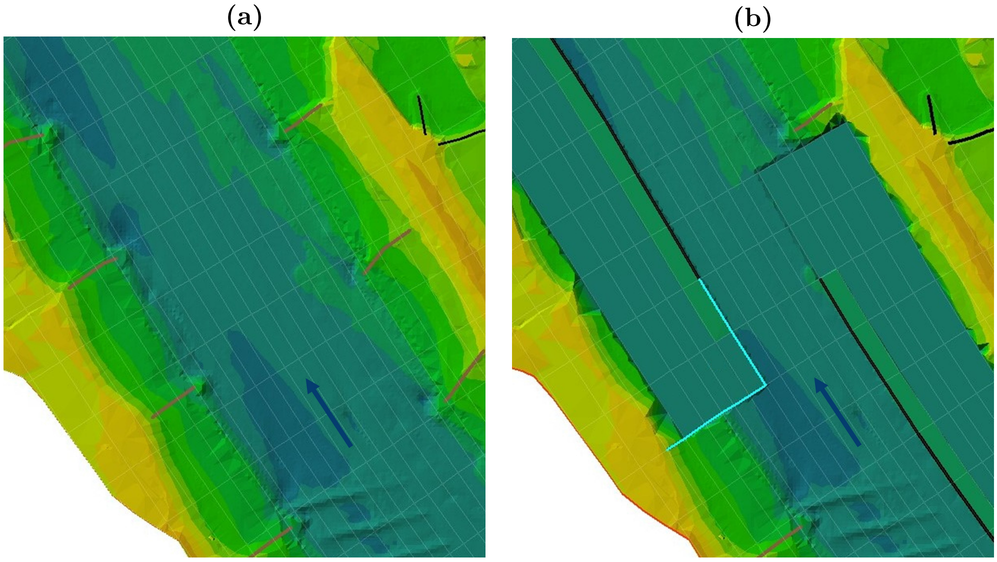

Figure A.2: (a) Top view of the original main channel (Reference) in the Boven Waal around river kilometer 876.2. Brown lines represent groynes. (b) Top view of the main channel after implementation of LTDs 3 and 4. The black line represents the LTD crest, the blue line represents the LTD inlet.

A.2 Summerdike lowering and floodplain lowering in the Pannerdensch Kanaal

The grid cells that have been modified for the implementation of floodplain lowering are highlighted as transparent in Figure A.3, while the darker cells represent areas that remain unchanged. The summerdikes that have been removed are indicated by the red lines in Figure A.3.

The weirs associated with the removed summerdikes are deleted from the weir file of the Pannerdensch Kanaal. Following that, the bathymetry file of the Pannerdensch Kanaal is adjusted. First, the bed levels of the grid cells at the locations of the summerdikes are decreased such that they match the level of the surrounding grid cells. After that, the uniform floodplain lowering is schematized by decreasing the bed level of the corresponding grid cells by the specified floodplain lowering height. It is important to note that grid cells with bed levels below 8.0 m + NAP have not been modified. Additionally, if the bed levels after lowering dropped below this threshold, they were reset to 8.0 m + NAP, ensuring that the intervention does not affect low discharge conditions.

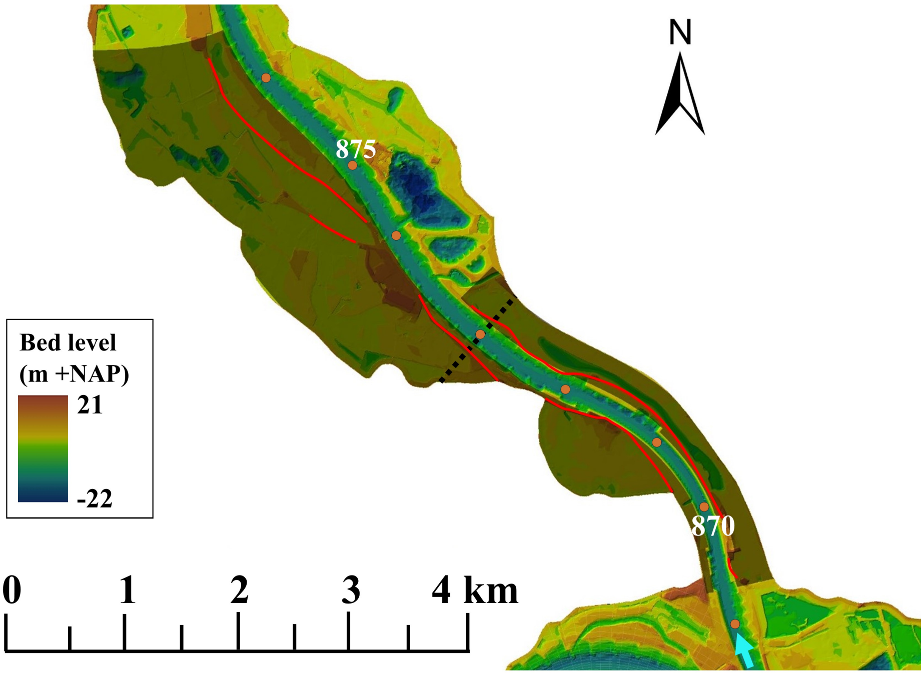

Figure A.3: Location of the floodplain lowering (darker areas) and the summer dikes (red lines) that have been removed in the Pannerdensch Kanaal. The brown dots represent river kilometers. The light blue arrow indicates the flow direction.

B Model input for simulating the Lobith design discharge

The provided DVR model is not yet capable of simulating the Lobith design discharge of 16,000 m^3/s. To enable this, the model has been expanded. First, files are added that represent the boundary conditions during such a discharge. An overview of these files is given in Table B.1. The boundary conditions are determined using a similar methodology as applied by the original model creators for other discharges in the DVR model (Sloff et al., 2024).

The upstream boundary condition is set to the Lobith discharge, which is 16,000 m^3/s. This discharge is divided across 58 grid cells. However, this division is non-uniform because the main channel grid cells convey more discharge than the floodplain grid cells. To determine an appropriate division, the available discharge division used for a Lobith discharge of 7009 m^3/s in the DVR model is used. During this discharge, all river grid cells convey discharge. The additional 8991 m^3/s during a Lobith discharge of 16,000 m^3/s is assumed to be uniformly distributed over the grid cells, added on top of the division used for the 7009 m^3/s Lobith discharge.

The downstream boundary conditions are determined using rating curves (in Dutch: "Betrekkingslijnen") along the river. These curves provide water levels corresponding to each river kilometer for various Lobith discharges. For the simulation of a Lobith discharge of 16,000 m^3/s, the water levels at the downstream boundaries of the Waal and IJssel are determined using the "Betrekkingslijnen 2022". The water level at the Nederrijn is based on "Betrekkingslijnen 2018". This is in line with the approach for the other discharges in the DVR model (Sloff et al., 2024).

Table B.1: Overview of the boundary condition files that have been added to the DVR model to represent the boundary conditions during a Lobith design discharge of 16,000 m^3/s.

Type of boundary condition	**Branch**	**Filename**	**Value**
Upstream boundary condition (discharge)	Boven Rijn	br0Q16000.bct	16,000 m^3/s
Downstream boundary conditions (water level)	Waal	wl2cQ16000.bct	5.488 m + NAP
	IJssel	yac3Q16000.bct	0.629 m + NAP
	Nederrijn	nr1aQ16000.bct	12.325 m + NAP

Three lateral flow files need to be added to represent the lateral flows that are present in the DVR model during a Lobith discharge of 16,000 m^3/s. An overview is provided in Table B.2. The lateral inflow from the Oude IJssel and Twentekanaal during this discharge is provided by Sloff et al. (2024). However, there is no specific data available for the flow extraction by the culvert of the Spiegelwaal. In the model, this flow extraction is set to zero during high discharges, as significant flow extraction occurs through weir overflow under these conditions. Therefore, this lateral flow is also set to zero during a Lobith discharge of 16,000 m^3/s.

Table B.2: Overview of lateral flow files that have been added to the DVR model to represent the lateral flows during a Lobith design discharge of 16,000 m^3/s.

Type of lateral flow	**Filename**	**Discharge (m^3/s)**
Flow extraction by culvert Spiegelwaal	wl2aQ16000.dis	0
Inflow from Oude IJssel	yac12Q16000.dis	65.58
Inflow from Twentekanaal	yac3Q16000.dis	54.25

Other files that need to be added to simulate a Lobith discharge of 16,000 m^3/s include the location of the downstream boundary condition in the Nederrijn (*nr1aQ16000.bnd*) and files containing morphology parameters for each of the nine reaches (**Q16000.mor*). Since these parameters remain consistent across all Lobith discharges, they can be just duplicated and renamed to correspond with the new discharge scenario.

C Additional simulation results

C.1 Initial hydraulics

C.1.1 Initial water levels in the Boven Waal during Scenario LTD-S

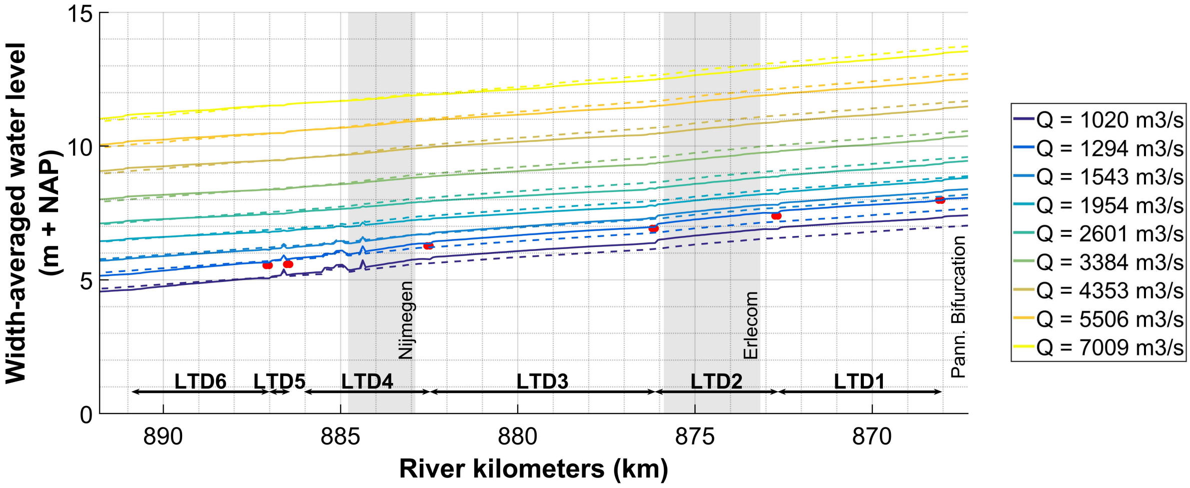

Figure C.1: Initial width-averaged water levels in the Boven Waal for the different Lobith discharges in the Reference Scenario (dashed lines) and in Scenario LTD-S (solid lines). The red dots represent the inlet height of the different LTDs. The grey areas represent the fixed layer at Nijmegen and the bed groynes at Erlecom. The black arrows represent the LTDs.

C.1.2 Initial flow velocities in the Boven Waal

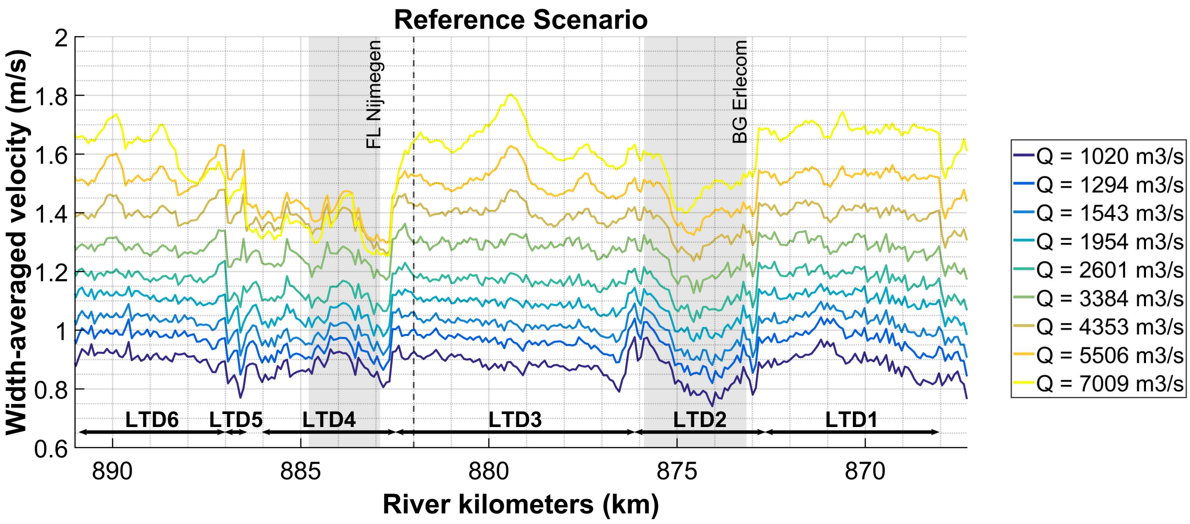

Figure C.2: Initial width-averaged flow velocities in the main channel of the Boven Waal across the various Lobith discharges in the Reference Scenario. The grey areas represent the fixed layer at Nijmegen and the bed groynes at Erlecom. The black arrows represent the LTDs.

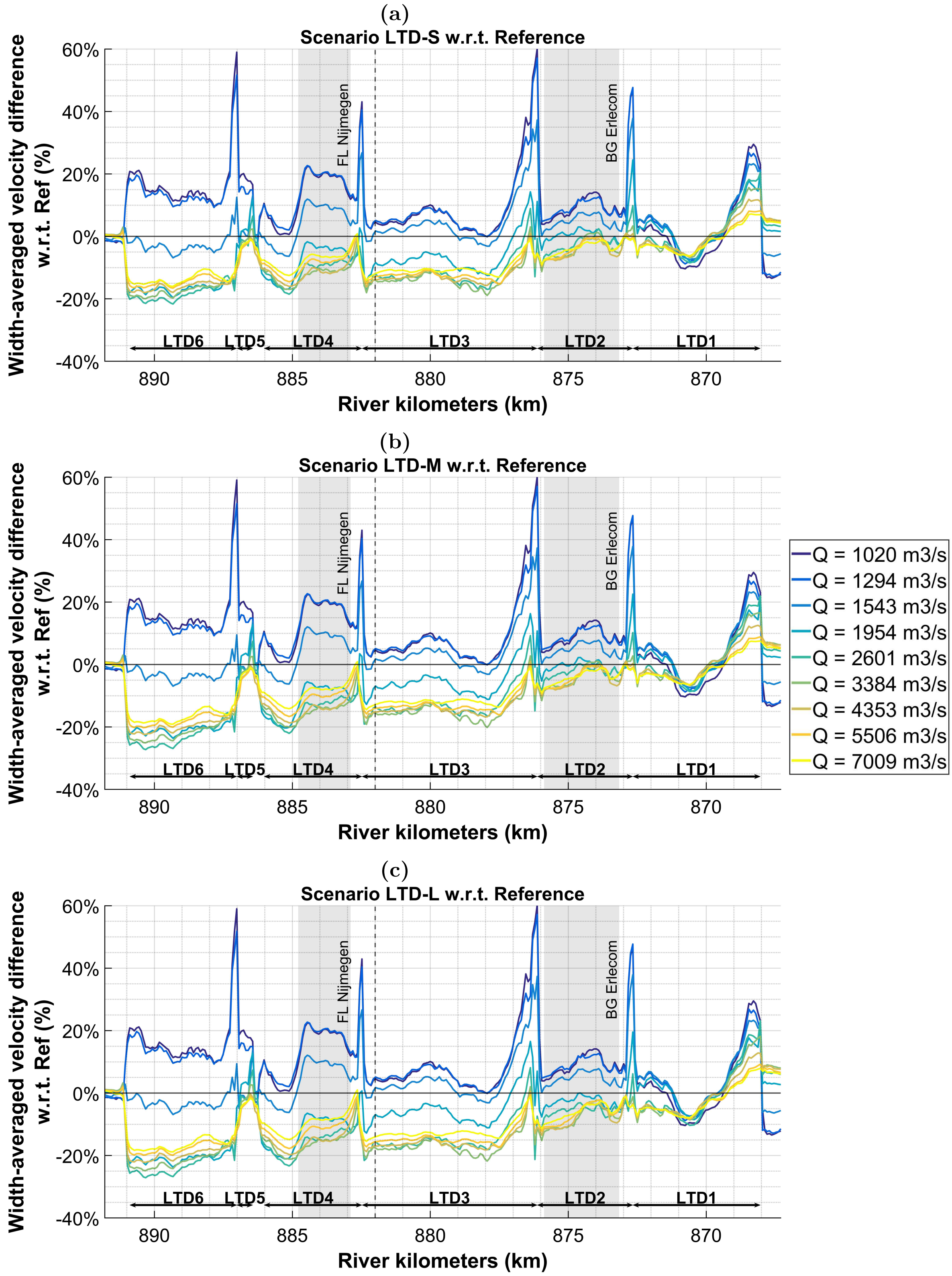

Figure C.3: Percentage difference in initial width-averaged flow velocities in the main channel of the Boven Waal between the LTD Scenarios and the Reference Scenario. The grey areas represent the fixed layer at Nijmegen and the bed groynes at Erlecom. The black arrows represent the LTDs.

C.1.3 Initial flow velocities in the Pannerdensch Kanaal

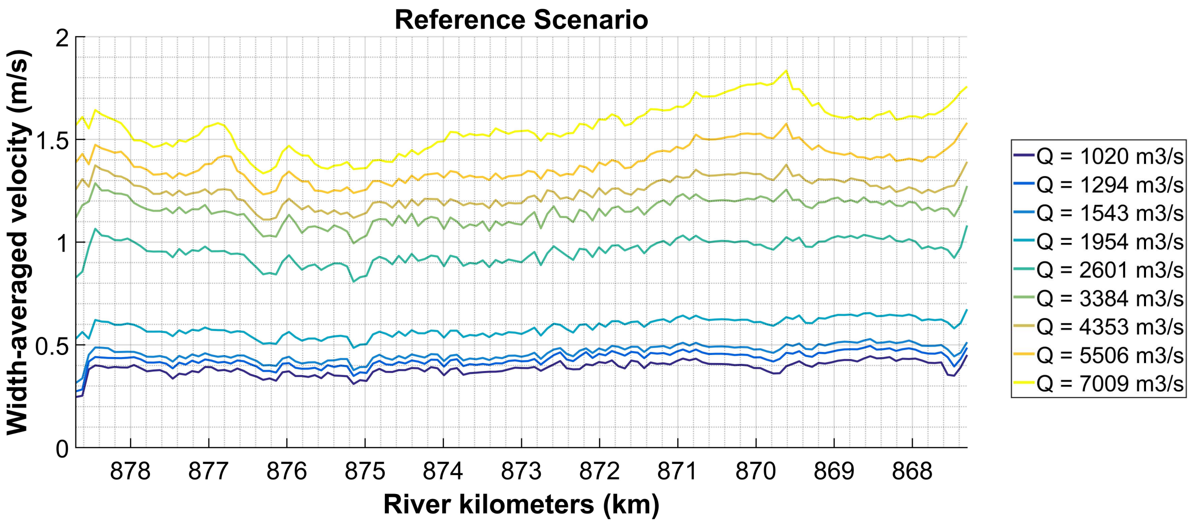

Figure C.4: Initial width-averaged flow velocities in the main channel of the Pannerdensch Kanaal across the various Lobith discharges in the Reference Scenario.

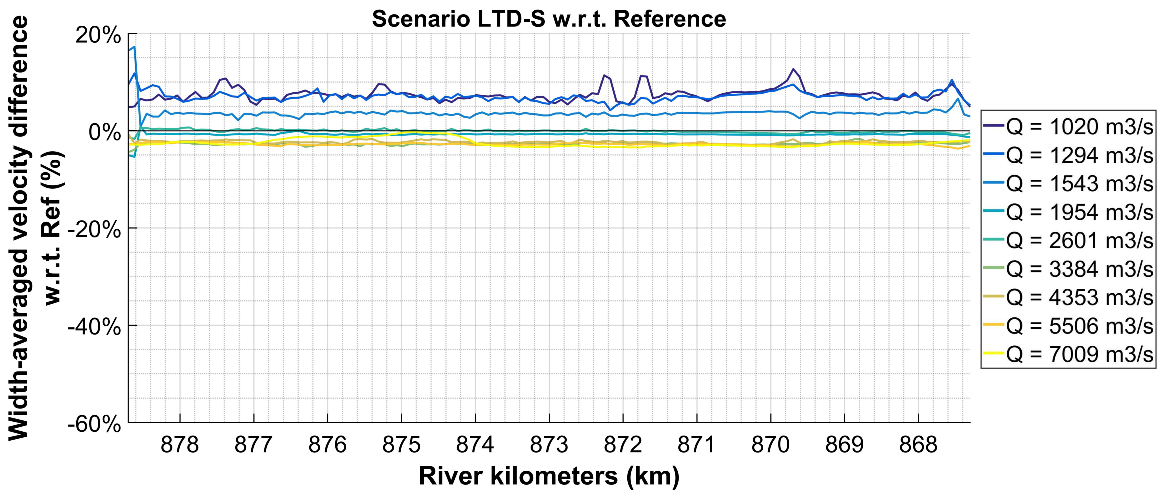

Figure C.5: Percentage difference in initial width-averaged flow velocities in the main channel of the Pannerdensch Kanaal between Scenario LTD-S and the Reference Scenario.

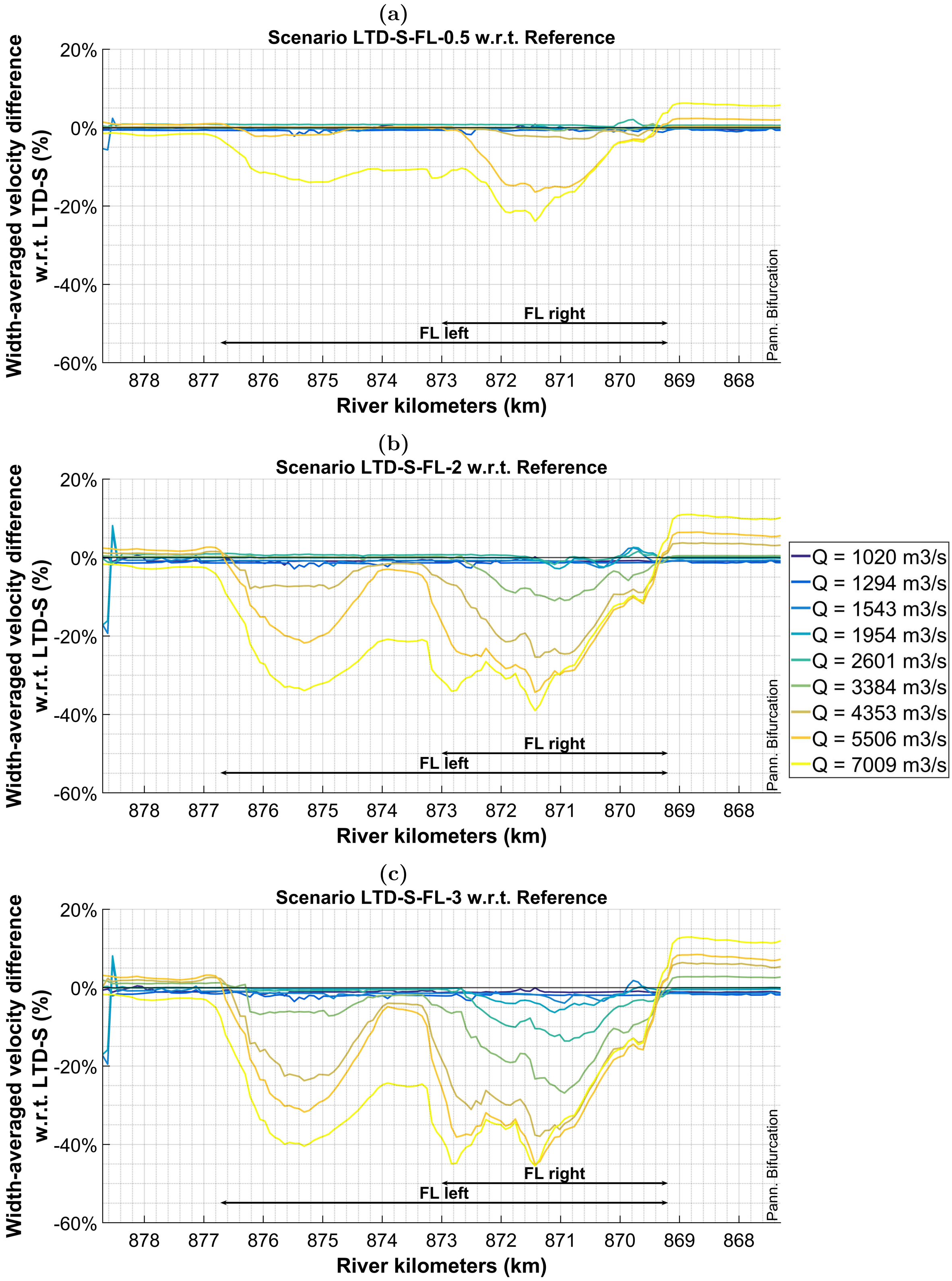

Figure C.6: Percentage difference in initial width-averaged flow velocities in the main channel of the Pannerdensch Kanaal between the LTD-FL Scenarios and Scenario LTD-S. Negative values indicate lower flow velocities in the LTD-FL Scenarios compared to Scenario LTD-S. The black arrows represent the location of the floodplain lowering at the left and right side of the channel.

C.2 Bed level development in the Boven Waal and Pannerdensch Kanaal after 20 years

C.2.1 Bed level change in the Boven Waal

In the following figures, red areas indicate erosion, while blue areas represent sedimentation. Solid green lines depict LTD bodies, and the combination of solid and dotted green lines outlines the boundaries of the riparian channels. The black line marks the boundary between the upstream (rkm 867.3-882) and downstream section (rkm 882-891) of the Boven Waal. The black arrow indicates the flow direction.

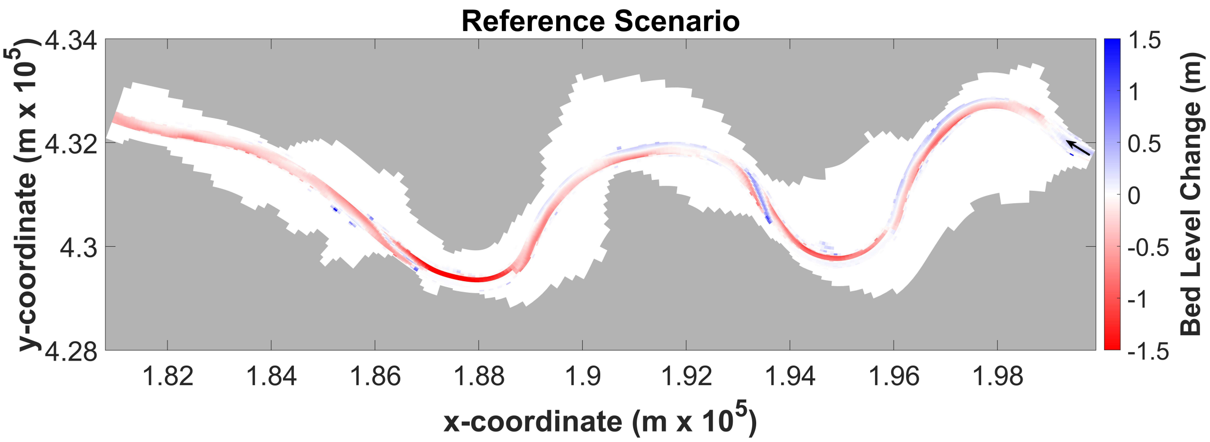

Figure C.7: Bed level change in the Boven Waal over 20 years of morphological development during the Reference Scenario.

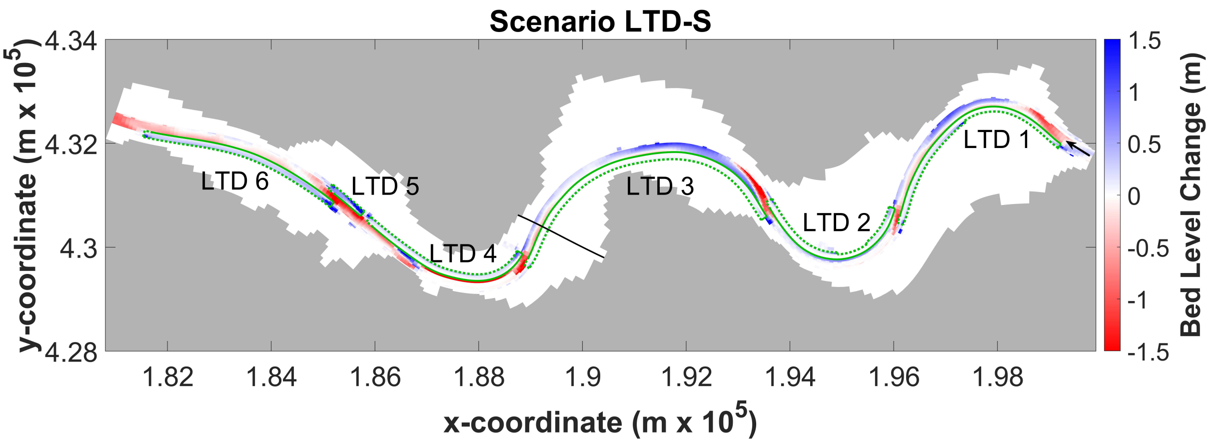

Figure C.8: Bed level change in the Boven Waal over 20 years of morphological development during Scenario LTD-S.

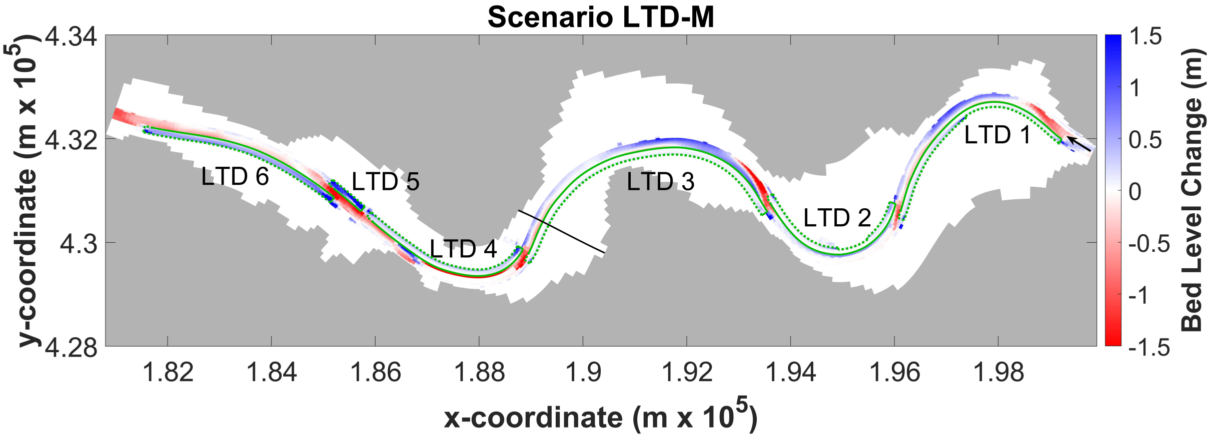

Figure C.9: Bed level change in the Boven Waal over 20 years of morphological development during Scenario LTD-M.

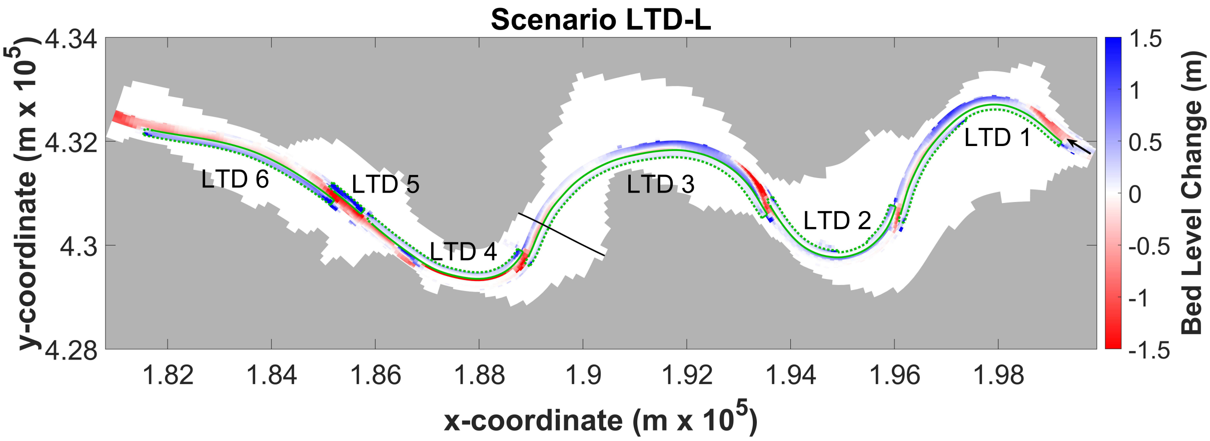

Figure C.10: Bed level change in the Boven Waal over 20 years of morphological development during Scenario LTD-L.

C.2.2 Bed level change in the Pannerdensch Kanaal

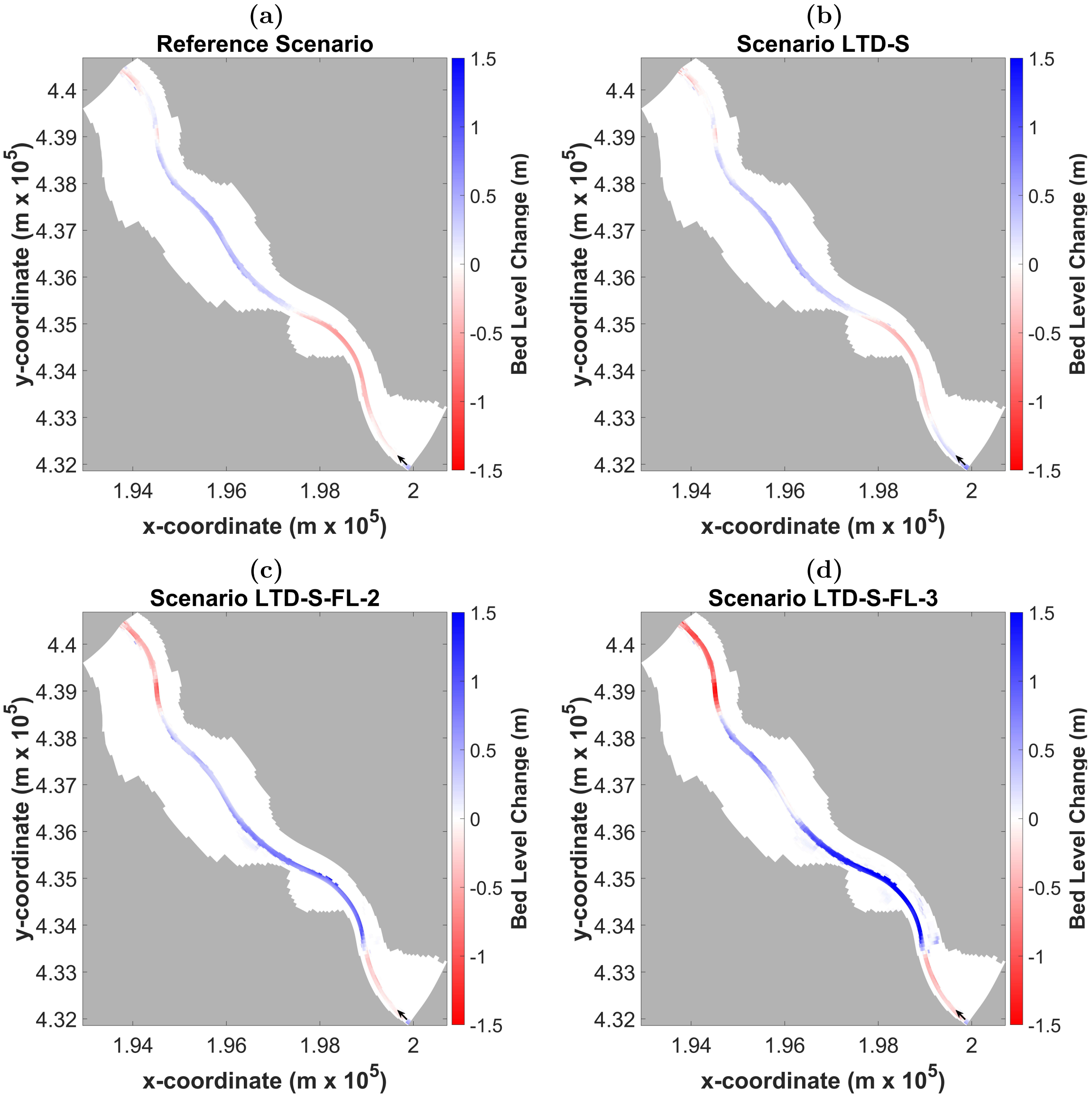

Figure C.11: Bed level change in the Pannerdensch Kanaal over 20 years of morphological development during (a) the Reference Scenario, (b) Scenario LTD-S, (c) Scenario LTD-S-FL-2, and (d) Scenario LTD-S-FL-3. Blue areas indicate sedimentation, while red areas indicate erosion. The black arrow represents the flow direction.