MASTER THESIS

# SEDIMENT NOURISHMENTS IN THE RIVER WAAL TO MITIGATE BED DEGRADATION

## A NUMERICAL MODELLING STUDY

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SWECO

# Sediment nourishments in the River Waal to mitigate bed degradation: a numerical modelling study

**Master thesis**


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## Preface

In front of you lies the thesis I wrote as the final part of the Master programme Civil Engineering & Management at the University of Twente. This thesis was written during my graduation internship at Sweco from February until September 2022.

I am grateful to all the people who have contributed to this report. Firstly, I would like to thank Niels Welsch, my daily supervisor from Sweco, for guiding me through the process, providing me with his expertise and for being my sparring partner when I faced problems. A big thank you also to Roel Velner for providing me with the opportunity to perform this research at Sweco and also for offering his expert knowledge. Aside from my supervisors, I would like to thank the colleagues at Sweco for the warm welcome.

Additionally, I would like to thank my supervisors from the University of Twente. Especially Vasileios Kitsikoudis, who was my daily supervisor from the university. It felt like I could reach out to him with questions at any time and I always took something valuable from the meetings we had. He also pushed me to make the most of it when things did not go as I wanted to and made sure I stayed on track. Additionally, I would like to thank Denie Augustijn for overseeing the graduation process and making sure that everything went smoothly.

Moreover, I want to thank Saskia van Vuren from Rijkswaterstaat for providing me with her extensive knowledge on the Dutch river system and the 'Integral River Management' programme. She also asked critical questions where needed and indicated the knowledge gaps in the work field. Her involvement in the whole process greatly enhanced the practical relevance of my thesis.

Furthermore, I would like to thank my fellow student Thorvald Rorink for showing me around the model and helping me in getting the right output. Finally, I would like to thank Victor Chavarrias and his colleagues at Deltares, who are the developers of the model I have used. They answered my questions and put in their time and effort to help me to solve issues that I could not fix myself.

I hope you enjoy reading my thesis.

Birgit de Lange
*Utrecht, September 2022*

## Summary

Over the past century, the bed level of the Waal has degraded by 1-2 metres. By itself, this poses problems such as a decrease of stability of structures, cables & pipes on the river bed and a decrease in the groundwater level in the vicinity of the river. Moreover, the rate of degradation is not equal along the river, which causes problems with regards to the navigability of ships over the river. Additionally, since degradation is not equal in all branches of the Rhine, the discharge distribution at the bifurcation points is affected. This decreases flood safety during high discharges and limits the supply of fresh water to the North and East of the Netherlands during low and middle discharges.

This study confirms that without future human interventions, the bed slope of the Waal will continue to decrease over the next 50 years. Consequently, the Boven-Waal and the largest part of the Midden-Waal degrade with an average degradation rate of 1.3 cm/year. Within the 'Integral River Management' (IRM) programme of Dutch local and national governments, solutions are sought to stop bed degradation in the Waal. This can be done by decreasing the erosivity of the flow or by increasing the bed level and increasing the resistance of the bed through sediment nourishments. The latter is investigated in this research.

The aim of this research is to determine how sediment nourishments can be used to mitigate bed degradation in the River Waal. The research question that is answered in this study is:

**"What are the morphological effects of sediment nourishments in the Waal and how can they be used to mitigate bed degradation?"**

The development of the bed is modelled by simulating the morphological development of the Dutch Rhine branches in a 1-D model. Sediment nourishments with various characteristics are implemented in the model to evaluate their effect on the development of the bed. The characteristics that are varied are the sediment composition, the initial location of the nourishment, the nourishment distribution and the nourishment volume.

Sediment nourishments are found to be able to increase the bed level over a longer section than the initial length of the nourishment. Upstream of the nourishments, a reduction in bed degradation of up to 4 cm is found through the backwater effects of the nourishments. This reduction increases when the nourishment is placed further upstream or when the nourishment volume is increased. Downstream of the original nourishment location, erosion is reduced through downstream translation of the nourishment. While the nourishment propagates downstream it disperses, meaning that its height reduces while its length increases. After 50 years, the nourishments still locally reduce erosion by an order of centimetres. The larger nourishments evaluated in this study are capable of reducing erosion by at least 5 cm over almost the complete degrading reach of the Waal. The propagation speed and dispersion rate of the nourishment are mostly dependent on the sediment composition and volume of the nourishment.

When a nourishment has a coarser sediment composition than the original bed surface, the nourishment induces additional erosion downstream of the nourishment through a reduction in the mobility of the bed. The magnitude of the additional erosion is dependent on the sediment composition and the volume of the nourishment. Although the additional erosion found in this study is limited to 5 cm at maximum, this is an unwanted effect in an already degrading reach. It is found that by using a distributed nourishment scheme, in which multiple nourishments

are placed several kilometres apart, additional erosion downstream of the nourishment can be prevented.

Distributing the nourishment over multiple parts can also enhance the performance of the nourishment in reducing bed degradation. Initially, the maximum reduction of erosion that is achieved by a distributed nourishment is smaller but the length over which this reduction is achieved is larger. When the parts of the nourishment are sufficiently large, on the long term the maximum reduction of erosion caused by a distributed nourishment is equal to when the nourishment is not distributed, while the length over which the nourishment reduces erosion is still larger. The net effect of a distributed nourishment is therefore found to be larger than that of a non-distributed nourishment.

It is found that all nourishments simulated here travel into the aggrading section of the Waal after 8 to 15 years. After this, the nourishments contribute to additional sedimentation in an already aggrading reach. The initial location of the nourishment mainly determines the period over which the nourishment is able to reduce erosion in the degrading section of the Waal. By placing the nourishment further upstream, the period over which the nourishment reduces erosion in the degrading section of the Waal can be extended.

Moreover, it is found that increasing the volume of a nourishment can enhance the effects of a nourishment by a larger factor than with which the nourishment volume is increased. By increasing the volume by a factor 2.7, the maximum increase in bed level caused by the nourishment is increased by a factor 3, while the length over which the nourishment reduces erosion by more than 5 cm is increased by a factor 4. Nourishing a larger volume of sediment at once is therefore found to be beneficial.

Finally, it is found that discharge variability due to an uncertainty in discharge conditions does not change the trend of the bed level change. However, it may induce local and temporal changes of up to 0.7 m. This is 0.2 m larger than the maximum height of the nourishments simulated in this research. The bed level changes induced by discharge variability are therefore found to be significant. Additionally, varying discharge conditions affect the propagation speed and dispersion rate of a nourishment. This shows the importance on evaluating the bed level development and the effects of interventions under various discharge conditions.

Currently, the IRM programme is looking for ways to stop bed degradation and increase the bed level of the Waal. Sediment nourishments are one of the solutions that are needed to reach this goal. There are still a lot of unknowns when it comes to defining a nourishment strategy. The knowledge on the behaviour of nourishments gained in this study can be used as a basis to define a nourishment strategy based on practical possibilities and limitations.

# Contents

# 1 Introduction

The bed of the Dutch Rhine branches has degraded over the past century, causing the bed level to decrease by 1 to 2 metres (Blom, 2016). Figure 1.1 shows measurements of the bed elevation taken along the Boven-Rijn and the Waal from 1950 until 2018. The figure illustrates the large-scale degradation of the bed. It is expected that while the rate of degradation has decreased in the past decade, bed degradation will continue in the upcoming decades (Programma Integraal Riviermanagement, 2021).

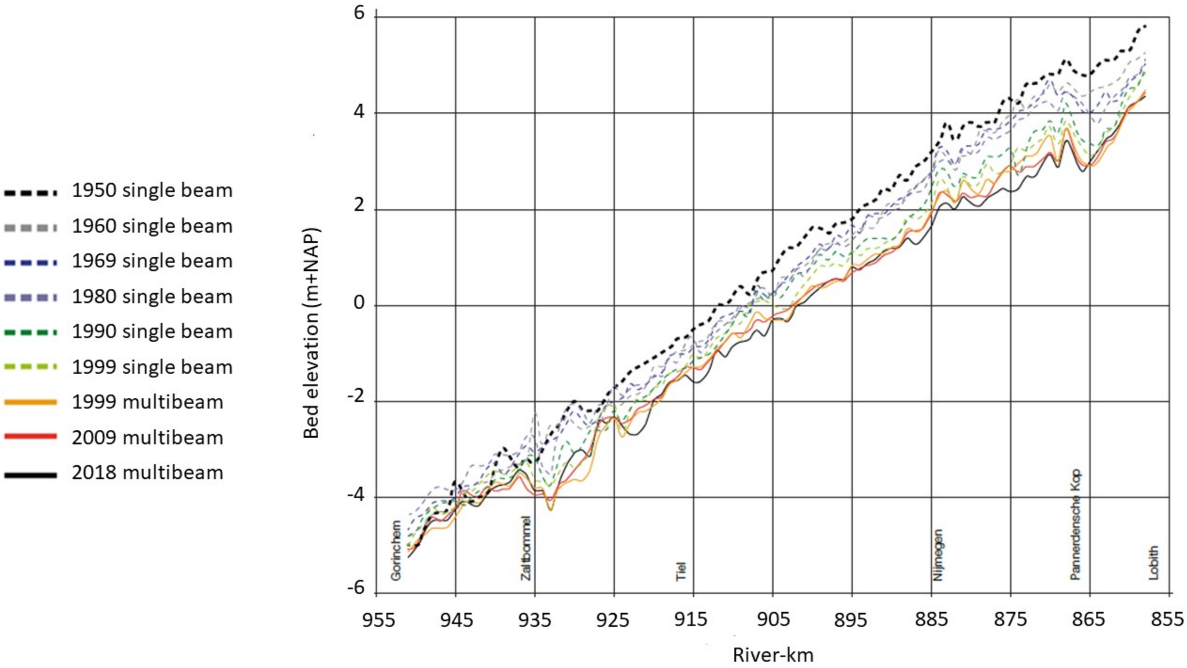


**Figure 1.1:** Width-averaged bed elevation as measured in the Boven-Rijn and Waal from 1950 until 2018 (adapted from Barneveld et al., 2020). The river flows from right to left.

Bed degradation affects various functions of the river. Figure 1.2 provides a schematic overview of the river functions that are affected by long-term and large-scale bed degradation.

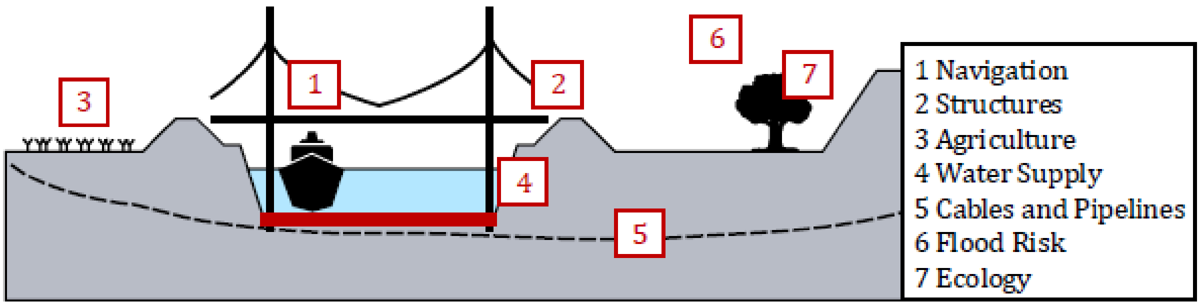


**Figure 1.2:** Overview of the functions of the river that are affected by bed degradation (Rudolph et al., 2018).

Firstly, navigation of ships over the river is affected since bed degradation is not spatially uniform along the whole river. At locations where the bed does not degrade at the same rate as its surrounding (e.g. at fixed layers or structures), a bump in the bed is created. This imposes a hazard for ships through the squat effect (Duffy, 2008) and decreases the maximum draught of the ships and thus their maximum load (Blom, 2016; Barneveld et al., 2022; Klijn et al., 2022).

Over a period of 30 years, this may lead to an increase in transport costs of 20%, in addition to production losses for companies which rely on river transport for their resources (Barneveld et al., 2022).

Secondly, the foundation of structures in the river bed may be exposed, compromising their strength. The same holds for the strength of pipelines and cables that are on or in the river bed, when the surrounding and underlying bed is eroded (Blom, 2016; Berkhof et al., 2018; Barneveld et al., 2022).

Furthermore, a lowering of the bed level induces a lowering of the water level (Blom, 2016). As a consequence, the groundwater table drops, which has negative effects on agriculture, water supply and ecology (Blom, 2016; Barneveld et al., 2022). Agriculture and ecology in the floodplains are further affected since the floodplains inundate less frequently, causing them to dry out and limiting the nutrient supply from the river (Klijn et al., 2022).

Finally, the rate of degradation is not equal in all Rhine branches: the bed level of the Waal decreases faster than the bed level of the Pannerdensch Kanaal and the bed of the IJssel degrades faster than the bed of the Neder-Rijn (Programma Integraal Riviermanagement, 2021; Barneveld et al., 2022). As a consequence, the Waal attracts more water at the bifurcation point at the Pannerdensche Kop and the IJssel attracts more water at the IJsselkop (Barneveld et al., 2022). This causes the discharge distribution at the Pannerdensche Kop and IJsselkop to differ from the standard distribution upon which policies are based (Blom, 2016; Berkhof et al., 2018; Gensen et al., 2021b; Klijn et al., 2022). The flood safety standards are based upon a standard distribution during high discharges. Therefore, while bed degradation may seem beneficial for flood safety at first since the water level decreases along with the bed level, bed degradation poses a threat to flood safety through changes in the discharge distribution (Termes and Huthoff, 2006). Additionally, a shift in discharge distribution during low and middle discharges restricts the supply of fresh water to the North-West of the Netherlands through the Neder-Rijn and Lek, to the North (IJsselmeer) through the IJssel and to the East of the Netherlands through the Twentekanalen (Barneveld et al., 2022). It is expected that climate change will cause extremely low and high discharges to occur more frequently, which increases the severity of these problems (Barneveld et al., 2022).

The causes of bed degradation consist of three main components. Firstly, many training works have been executed in the Dutch Rhine since the seventeenth century (Ylla Arbós et al., 2021), as is summarised in Figure 1.3. Until the twenty-first century, the main goal of these training works was to facilitate shipping and increase flood safety (Visser, 2000). To ensure a navigable depth during low flows, the main channel of the river was narrowed. As a consequence, higher flow velocities are induced (Blom, 2016). The flow is then able to transport more sediment and the bed is eroded. This was sped up by dredging works, which served to enhance navigability and mine sediment (Visser, 2000). Finally, the reduction and coarsening of the sediment supply from upstream have a large influence on the system. In the German section of the Rhine, dams were built, which act as sediment traps. To counter this, sediment nourishments are applied in Germany, which generally have a composition that is coarser than the bed (Blom, 2016; Frings et al., 2019). Natural sorting of sediment and the downstream shift of the gravel-sand transition of the Rhine enhances the coarsening of the sediment supply from upstream (Blom, 2016; Frings et al., 2019). When less sediment is transported into the Dutch section of the Rhine, the flow is able to pick up more sediment in the Dutch section of the Rhine, which therefore further enhances degradation. The process of the interaction between the flow, the bed and sediment transport is further explained in Chapter 2.

| Period | River km | Intervention |
|---|---|---|
| 1639 | 928-931 | Meander cutoff |
| 1649 | 875-883 | Meander cutoff |
| 1655 | 930-935 | Meander cutoff |
| 1775-1776 | 860-880 | Meander cutoffs (net shortening since 1600 ~10%) |
| 1850-1870 | 858-952 | Training works for flood protection: - Channel narrowing (Bovenrijn: from 500 to 440 m; Waal: from 500 to 360 m), embankment construction |
| 1870-1890 | 858-952 | Training works for improvement of navigation: - Channel narrowing (Bovenrijn: from 440 to 360 m; Waal: from 360 to 310-320 m), groyne construction |
| 1900-1916 | 858-952 | Extension of training works: - Channel narrowing (from 310-320 to 265-300 m), groyne lengthening |
| 1900- | 858-952 | Dredging for navigation and construction purposes, volumes reaching 1'500'000 m³/a. Since 1992, dredged sediment is reallocated. |
| 1985-1988 | 858-861 | Fixed bed installation |
| 1996-1999 | 925-928 | Fixed bed installation |
| 1996-1999 | 925-928 | Bottom vanes installation |
| 2009-2020 | 858-952 | Room for The River measures to increase conveyance capacity, mostly dike relocation and floodplain lowering |
| 2014 | 858-861 | Fixed bed installation |
| 2016 | 862-864 | Nourishment of a 30-cm-thick layer of gravel |
| 2019 | 862-864 | Nourishment of 70'000m³ of gravel |

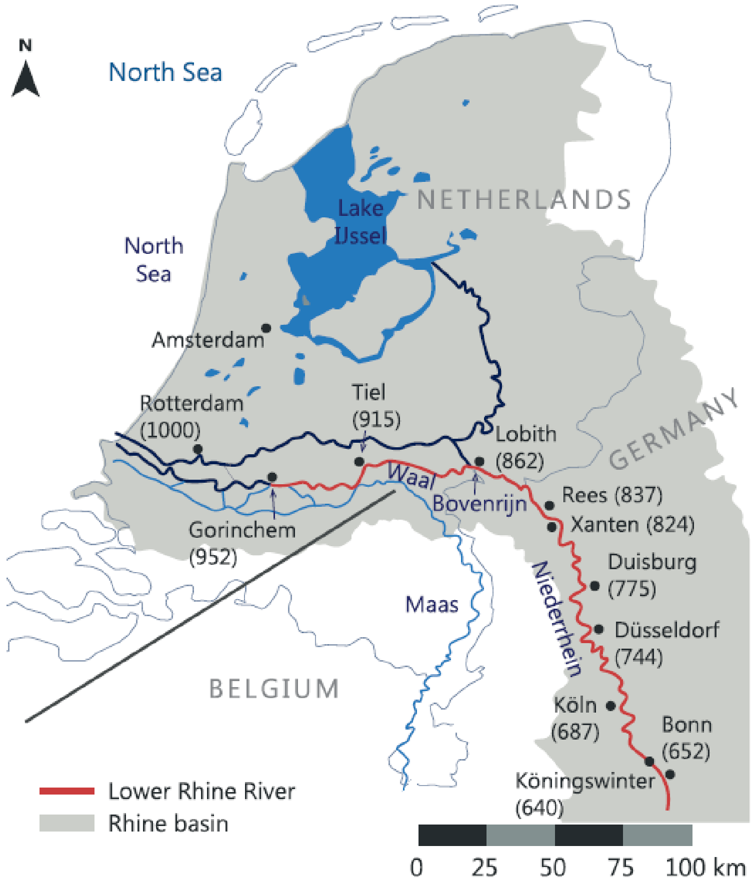


**Figure 1.3:** Overview of human interventions in the Dutch Rhine since the seventeenth century (adapted from Ylla Arbós et al., 2021).

While the consequence of the interventions before the year 2000 was mainly a decrease in the flow width, the vision on river management in the Netherlands changed after the (near-)floods of 1993 and 1995. The 'Room for the River' program was designed and executed, which had the main goal of increasing the discharge capacity of the Dutch rivers by giving the river 'more room to flow' (Van Vuren et al., 2015; Ylla Arbós et al., 2021). As a side effect, this decreases the erosion rate, even though the process of bed degradation is not stopped (Van Vuren et al., 2015).

Following the 'Room for the River' program, in 2019 the program 'Integrated River Management' (IRM) was set up by local and national governments. They aim to enhance the different functions of the Rhine and Meuse by looking at integrated solutions which treat the whole system as one to address multiple problems at a time. Currently, this has led to a consideration of the system (Systeembeschouwing) (Klijn et al., 2022), a note of possible policy options (Nota Realistiche Beleidsopties) and a report, which conclude that climate change and bed degradation have serious consequences for the functioning of the river systems (Deltacommissaris, 2021).

In Section 1.1, the knowledge gap regarding the reduction of bed degradation and the problem that is addressed in this research is explained. Section 1.2 provides the research questions that are answered in this research. Subsequently, Section 1.3 gives a description of the study area. Finally, Section 1.4 provides a reading guide for this report.

## 1.1 Problem statement

The process of bed degradation is currently slowing down because the slope of the Waal decreases, which decreases flow velocities (Klijn et al., 2022). However, the process will not be fully stopped in the near future and the problems that are caused by the degradation of the bed are becoming more evident (Klijn et al., 2022). Therefore, methods to further slow down and eventually stop or even reverse the degradational trend are currently being investigated. There are two ways in which bed degradation can be mitigated: by decreasing the erosivity of the flow or by increasing the resistance of the bed surface to erosion (Klijn et al., 2022). To elevate the bed level of the river to compensate past bed degradation, sediment nourishments are required (Barneveld et al., 2022; Klijn et al., 2022).

The erosivity of the flow can be reduced by increasing the flow width of the river or diverting a part of the discharge. River widening can be achieved by lowering groynes, lowering floodplains, constructing side channels or longitudinal dams and by creating nature-friendly banks (Barneveld et al., 2022).

The World Wildlife Fund (WWF), together with five partnering nature organisations, set up the plan and vision 'Room for Living Rivers' (Beekers et al., 2018). The issues that they address are creating more room and nature along rivers, enhancing flood safety and stopping continuous bed degradation and they aim to solve this by adapting an integral approach (Beekers et al., 2018). Welsch (2021) calculated the effect of three different interventions as proposed in the 'Room for Living Rivers' programme: the construction of side channels, floodplain lowering and the removal of summer dikes. He concluded that while the interventions may help in countering bed degradation, the effects are only seen locally, close to the intervention. He concluded that interventions should be imposed over a longer distance in order to be effective. Barneveld et al. (2022) also stress that such interventions are implemented along the whole reach in which degradation takes place.

Rorink (2022) also did a modelling study of the effect of side channels on bed degradation as proposed in the 'Room for Living Rivers' programme. He concluded that individual side channels that are active almost 100% of the time can mitigate bed degradation by 10-15% over 100 years. Moreover, he found that implementing side channels in the Waal and the Pannerdensch Kanaal simultaneously may lead to a local reduction in erosion of up to 35%. In none of the scenarios he studied, bed degradation could fully be stopped. Barneveld et al. (2019) also studied the proposed interventions in the 'Room for Living Rivers' programme and they concluded that river widening is not enough to fulfil the aim of stopping bed degradation. They concluded that sediment nourishments are needed to reach this goal. Other interventions could then be used to reduce the volume of sediment that is needed.

However, there is still a lack of knowledge on how sediment nourishments in the Dutch Rhine would behave. In the Netherlands, sediment nourishments were previously only used along the coast to nourish beaches. In 2016 and 2019, two pilot studies were performed to test whether sediment nourishments could be used in the Dutch Rhine (Niesten and Becker, 2018). While the first evaluations of these nourishments show that they can increase water levels locally, no conclusions have yet been drawn on their ability to decrease bed degradation (Niesten and Becker, 2018). Further results of this pilot are still to be published.

A 1D modelling study into the general effects of sediment nourishments in rivers has been done by Czapiga et al. (2022). Their goal was to determine how the nourishment scheme, sediment composition and volume of the nourishment influence the efficiency of mitigating bed degradation. They concluded that nourishments are effective in mitigating bed degradation when the equilibrium bed slope of the river channel is increased. That means that the nourishment strategy should be adapted to the characteristics of the sediment. By using coarse sediment in the nourishment, the sediment flux is coarsened, leading to an increased equilibrium bed slope. The nourishment should then be distributed over multiple smaller parts to prevent erosion downstream of the nourished reach. Another option is using fine sediment in the nourishment. The volume should then be large enough to increase the equilibrium bed slope. Adding fine sediment in smaller volumes enhances rather than reduces erosion, through increased mobility of the bed (Czapiga et al., 2022). The study presented here focuses on the former case, in which sediment is used with a composition equal to or coarser than the bed.

While the characteristics of the system Czapiga et al. (2022) studied are loosely based on the Niederrhein (the most downstream German section of the Rhine before it enters the Netherlands), the geometry of the studied river section was overly simplified. Moreover, Czapiga et al. (2022) used a constant representative discharge as the upstream boundary condition, rather than a variable discharge hydrograph. In the IRM programme, ambitions have been described with regards to using sediment nourishments to stop bed degradation. Moreover, they have provided arguments for choosing certain possible nourishment strategies but there is not yet enough information to choose the best strategy (Klijn et al., 2022). No modelling studies with regards to sediment nourishments have yet been performed in this programme. This study aims to extend the general knowledge on the behaviour of sediment nourishments and their potential to mitigate bed degradation in the Waal by applying nourishments in the Waal and by applying variable discharge conditions.

To conclude, there is a lack of knowledge regarding the behaviour of nourishments in the Waal and on how nourishments can be implemented to mitigate bed degradation. This study aims to fill a part of this knowledge gap by studying the effect of various nourishments in the Waal under variable discharge conditions.

## 1.2 Research aim and questions

This research aims to determine how sediment nourishments can be applied in the Waal to mitigate bed degradation. By implementing nourishments with varying characteristics in a 1D-model of the Rhine branches under non-steady discharge conditions, the large-scale and long-term morphological effect of nourishments on the bed development of the Waal is investigated. To structure the research, the main research question and corresponding sub-questions are defined.

The main research question that is answered in this research is:

**What are the morphological effects of sediment nourishments in the Waal and how can they be used to mitigate bed degradation?**

With the following corresponding sub-questions:

1. How do the bed level and sediment composition of the Waal develop over the next 50 years, without human interference?
2. What are the morphological effects of nourishments of varying grain sizes, locations, nourishment distributions and volumes in the Waal?
3. How are the development of the bed and the behaviour of a nourishment influenced by discharge variability due to uncertainty in the discharge time series?

## 1.3 Study area

After the Rhine enters the Netherlands at Lobith (rkm 862), it flows for 6 km until it reaches the bifurcation point at Pannerden (rkm 868). At this bifurcation point, called the Pannerdensche Kop, the Rhine splits up into the Waal and the Pannerdensch Kanaal. After another 11 km, the Pannerdensch Kanaal bifurcates at the IJsselkop (rkm 878) into the Neder-Rijn and the IJssel. The branch of interest in this study is the Waal. Figure 1.4 shows an overview of the Dutch Rhine system.

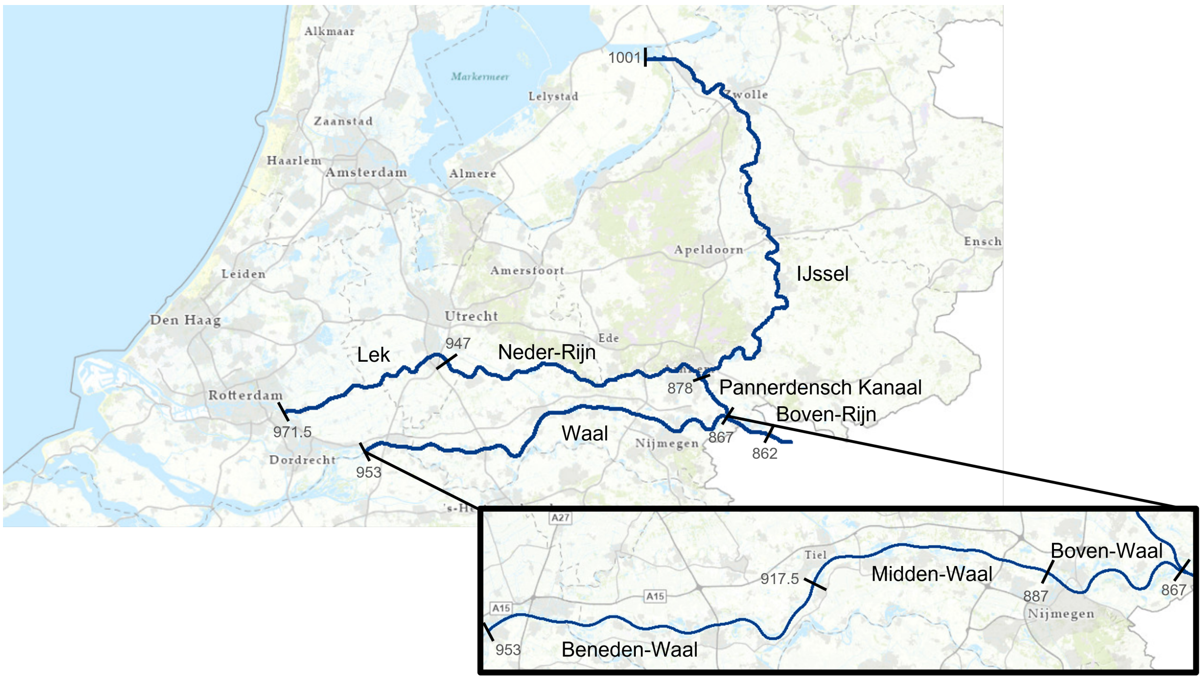


**Figure 1.4:** Map showing the Dutch Rhine system. The lower image zooms in on the Waal. The chainage of the locations of the borders is indicated in grey in river-kilometres. Adapted from map made by the author in ArcGIS using a topographic basemap by Esri Nederland (2022).

The Waal can be subdivided in downstream direction into the Boven-Waal, which reaches from the Pannerdensche Kop (rkm 868) until just downstream of Nijmegen (rkm 887); the Midden-

Waal, which reaches until Tiel-Passewaaij (rkm 917.5); and the Beneden-Waal, which reaches until Woudrichem (rkm 953).

The Boven-Waal (rkm 868-887) is characterised by the presence of four bends (Programma Integraal Riviermanagement, 2021). Furthermore, two large interventions are implemented in this river section. Firstly, bottom groynes were constructed in the outer section of the bend near Erlecom (rkm 873-876) and secondly, a fixed layer was applied over the whole width of the river in the bend near Nijmegen (rkm 883-885). Both interventions were constructed with the aim of maintaining navigability through the river bend (Havinga, 2016).

The Midden-Waal (rkm 887-917.5) is a relatively straight part of the Waal, except for the bend near Tiel (rkm 913.5). Along the sides of the main channel, groynes were constructed to push the water to the centre of the main channel to maintain a navigable water depth during low discharges. In the 'Room for the River' programme, these were lowered along the whole river section (Programma Integraal Riviermanagement, 2021). Additionally, between Wamel (rkm 911) and Ophemert (rkm 922), the groynes were replaced by longitudinal dams (Programma Integraal Riviermanagement, 2021). Both interventions were done to increase the discharge capacity of the Waal. At Tiel (rkm 913.5), the Amsterdam-Rijnkanaal connects the Waal and the Neder-Rijn via locks.

The Beneden-Waal (rkm 917.5-953) is the most downstream part of the Waal. This section is characterised by gentle bends, except for the sharper bend at Sint Andries (rkm 927). In the bend at Sint Andries (rkm 925-928), a fixed layer is applied in the outer bend. Just like the fixed layers at Erlecom and Nijmegen, this fixed layer was constructed to maintain navigability. Moreover, in this reach, there are also groynes present along the side of the main channel, which were lowered in the 'Room for the River' programme (Programma Integraal Riviermanagement, 2021). Downstream of Sint Andries (rkm 927), the tidal forcing of the North Sea influences the river (Programma Integraal Riviermanagement, 2021).

All nourishments in this research are implemented in the Waal. While the effect of the nourishments on the discharge distribution at the Pannerdensche Kop and the corresponding change in bed level of the Pannerdensch Kanaal is noted where relevant, mitigating or countering these influences is outside of the scope of this research.

## 1.4 Reading guide

Firstly, Chapter 2 provides the most relevant theoretical background to this research. Chapter 3 describes the methodology of the research, comprising of an explanation of the used model, the model input and a description of the scenarios that are evaluated. In Chapter 4, the results of the various simulated scenarios are shown, analysed and explained. Each sub-section of this chapter answers one of the three research sub-questions that are posed. Chapter 5 provides a discussion about the used methodology and the obtained results. Finally, in Chapter 6 the main research question is answered and recommendations for further research are given.

# 2 Theoretical background

This chapter provides some relevant theoretical background to this research. The process of morphodynamic development is explained in Section 2.1 and the theoretical hydrodynamic and morphodynamic response of a river system to a nourishment is explained in Section 2.2.

## 2.1 Morphodynamics

Morphodynamics in rivers is a complex concept, because the water that flows through the system and the sediment that is transported through and stored in the system interact with each other in all directions (De Vries, 1975). When modelling morphodynamics, this interaction is split up into three separate components: the channel pattern, the water flow and the sediment transport. These factors all influence each other and depend on one another. Therefore, this is also called the morphodynamic feedback loop. Figure 2.1 shows a schematisation of the morphodynamic feedback loop (Kitsikoudis and Huthoff, 2021).

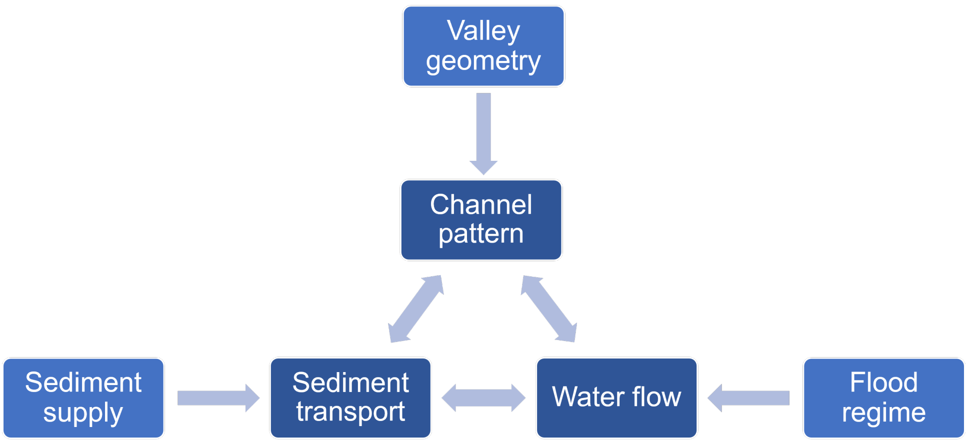


**Figure 2.1:** The morphodynamic feedback loop (adapted from Kitsikoudis and Huthoff, 2021).

Each of the three components is influenced by external conditions. The channel pattern is partly dictated by the geometry of the valley the river flows through, the discharge is largely determined by the flood regime that occurs upstream and the sediment transport is partly determined by the amount of sediment that is transported into the system from upstream.

Moreover, the three components strongly influence each other. The characteristics of the channel pattern, such as the bed slope, the roughness and the available flow width, dictate how water is discharged. This determines the flow characteristics, such as the flow velocity. As the flow propagates downstream, it exerts a certain force on the bed. If this force is large enough, sediment particles from the bed are entrained and transported by the flow. When sediment is eroded from the bed or deposited on the bed, the channel pattern changes.

Also the other way around the three components influence each other. The channel pattern determines the sediment transport, because the characteristics of the bed determine the force that is required to entrain sediment. Subsequently, the sediment transport influences the water flow because the flow requires energy to transport the sediment. Therefore, the flow loses energy through sediment transport, which decreases flow velocities. Finally, how the water flows influences the channel pattern.

Sediment is either transported as bed load, in which the sediment particles move over the bed surface by hopping, rolling or sliding; or as suspended load, in which the sediment particles stay in the flow for a longer period (Ribberink, 2011). Sediment transport can be divided into two types, based on its source: bed material load and wash load. Wash load is by definition very fine suspended load, that is transported from upstream areas. Wash load does not have any interaction with the bed and therefore, its volume is solely determined by the supply from upstream and not by the sediment transport capacity of the flow (Ribberink, 2011). Since it does not have a significant influence on the development of the bed of the main channel, this type of sediment transport is not considered in most morphological studies (Biedenharn et al., 2006) and it is also not included in this study. Bed material load comprises of both bed load transport and suspended transport. The bed material load does interact with the bed and therefore mainly determines the morphodynamic development of the main channel.

A river tends to go to an equilibrium, in which the three components of the morphodynamic feedback loop are in balance (Mackin, 1948; Arkesteijn et al., 2019). When a river is in equilibrium, the slope has adjusted in such a way that the velocity of the flow is such that the flow has exactly the sediment transport capacity that is required to transport all of the sediment influx from upstream (Mackin, 1948; Blom et al., 2017; Arkesteijn et al., 2019). When changes in either of the three components of the morphodynamic loop occur and these changes are large enough, the river moves to a new equilibrium. The Dutch Rhine is currently not in equilibrium, since it is still responding to large changes made to the river over the past centuries (Zuijderwijk et al., 2020).

The definitions of different equilibria by Arkesteijn et al. (2019) are adopted here. Arkesteijn et al. (2019) describe various forms of equilibria, which are schematised in Figure 2.2. A static equilibrium (a) can only be reached when the controls are constant over time. The main controls of the river system include the incoming discharge, the sediment influx and the downstream water level (Arkesteijn et al., 2019). If averaged over time, the sediment transport capacity and the sediment load are equal, but fluctuations may exist over time, this is referred to as a dynamic equilibrium (b). Arkesteijn et al. (2019) define a quasi-equilibrium state as a state that is reached when the time-scale at which the river responds to changes is much smaller than the time-scale at which the controls change. When no perturbations exist around this equilibrium, it is called a static quasi-equilibrium (c) and when they do, Arkesteijn et al. (2019) refer to this as a dynamic quasi-equilibrium (d).

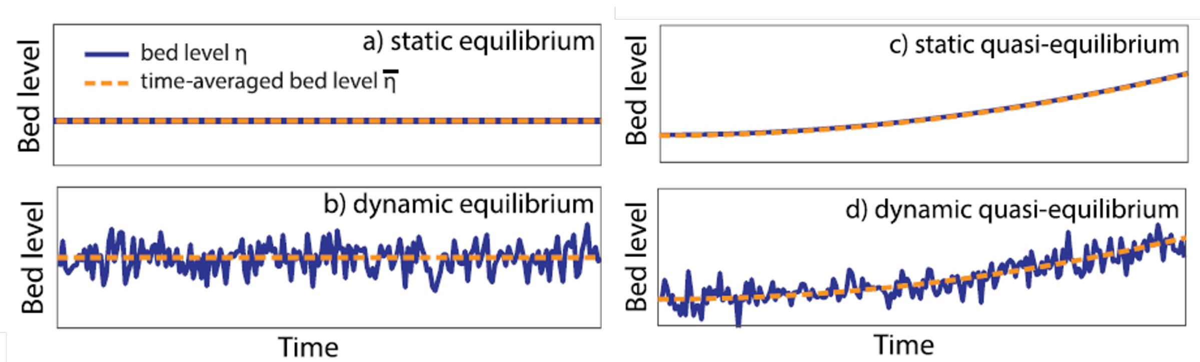


**Figure 2.2:** Schematics of the different types of equilibria (Arkesteijn et al., 2019).

## 2.2 Hydrodynamic and morphodynamic responses to sediment nourishments in rivers

When a nourishment is placed, it initiates several hydrodynamic and morphodynamic responses. Figure 2.3 gives a simplified representation of the initial hydrodynamic and morphodynamic responses to a nourishment. To understand the response of the river to such a nourishment, it is important to know that the Dutch part of the Rhine is mildly sloped, meaning that the flow is subcritical. This implies that the effects of the nourishment travel upstream. The processes that cause the behaviour as shown in Figure 2.3 are explained below the figure.

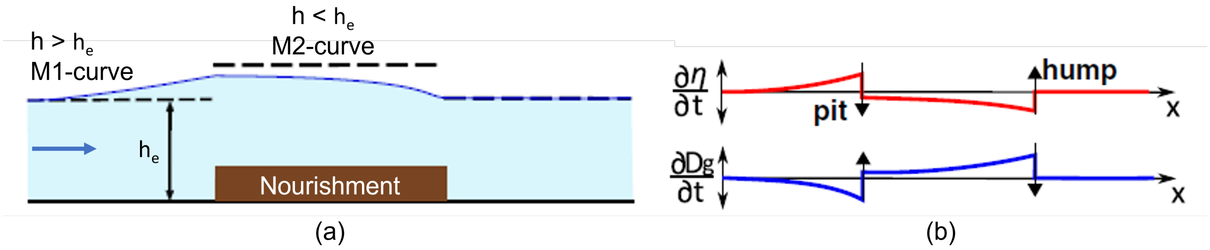


**Figure 2.3:** Initial hydrodynamic (a) and morphodynamic (b) response to a singular nourishment (adapted from Czapiga et al., 2022). The top graph in (b) shows the change in bed level, while the bottom graph shows the change in the geometric mean grain size of the bed surface.

When a nourishment is added to the river bed, this leads to a local increase in the elevation of the bed. Consequently, the water level is raised over the section in which the nourishment is implemented. Since water levels cannot jump from one level to another, backwater curves form, both upstream of the nourishment and over the nourishment itself. Upstream of the nourishment, the equilibrium water level is lower than in the section of the nourishment. Consequently, an M1 backwater curve forms upstream of the nourished section. When approaching the nourishment from upstream, the water level already increases compared to the initial situation, while the bed level is still equal. Therefore, the water depth increases. When the same discharge flows through a larger flow area, through conservation of mass, the flow velocity is lower. Hence, upstream of the nourishment the flow can transport less sediment and therefore, sedimentation occurs upstream of the nourishment. This is seen in the top graph in Figure 2.3b. Since the sediment that is transported is generally finer than the mean grain size of the bed surface, the sedimentation leads to a fining of the bed, as is shown in the bottom graph in Figure 2.3b.

Downstream of the nourishment, the equilibrium water level is also lower than over the section of the nourishment. Therefore, an M2 drawdown curve forms over the section of the nourishment. Consequently, since the nourishment thickness is initially equal throughout this section, the water depth decreases in downstream direction over the nourishment. The same discharge then flows through a smaller flow area, meaning that the flow velocity must increase. When the flow velocity increases, the sediment transport capacity increases and hence, the downstream section of the nourishment erodes faster than the upstream section of the nourishment (provided that the complete nourishment has the same sediment composition). Since fine sediment is transported more easily than coarse sediment, the bed surface coarsens over the nourished reach in downstream direction.

Moreover, the sediment composition of the nourishment may influence the flow when the sediment composition of the nourishment is coarser than the original bed surface. This has two consequences: the roughness of the bed surface increases and the mobility of the bed decreases.

Skin friction scales linearly with a representative value for the coarse fractions in the surface layer of the bed (e.g. $D_{90}$) (Parker, 1991; Czapiga et al., 2022). Therefore, a coarser bed induces a larger skin friction between the bed and the flow. When the skin friction is larger, the water level is raised. Therefore, this has a similar effect as the elevation of the bed that is caused by the nourishment. When the mobility of the bed at the location of the nourishment is decreased, this means that the flow is less able to entrain sediment from the bed in this reach. Simultaneously, the flow velocity, and thus the sediment transport capacity, does increase over the nourished reach. Downstream of the coarser nourishment, the flow can entrain sediment from the bed surface with a finer composition again. As a consequence, erosion is induced downstream of the nourishment.

As the flow acts on the nourishment, sediment is entrained and the nourishment is transported downstream. Moreover, the nourishment diffuses, meaning that its height decreases while its length increases. If the volume of the sediment is sufficiently large to significantly increase the sediment flux, the equilibrium bed slope of the river may be increased (Czapiga et al., 2022). Smaller nourishment volumes lead to more local changes in the bed level and sediment composition of the bed surface.

# 3 Methodology

In this chapter, the methodology of this research is described. Section 3.1 explains the model that is chosen to perform this research and describes how the model is set up. Thereafter, Section 3.2 describes the input that is used for the simulations in this research, consisting of the boundary conditions, the spin-up time and the schematisation of the nourishments. Finally, Section 3.3 explains the various scenarios that are examined and how these are included in the model.

## 3.1 Model choice and model description

To determine the development of the bed under various discharge conditions and to assess the effect of different nourishments, the morphological development is simulated using a 1D-model of the Rhine branches. The model used here is developed by Chavarrias et al. (2020) from Deltares for Rijkswaterstaat for use in the 'Integrated River Management' (IRM) programme. It is made for the planning phase of the IRM-programme, in which the effect of various interventions on the morphology and discharge capacity of the Dutch Rhine will be tested (Chavarrias et al., 2020). The model has been built and validated by Chavarrias et al. (2020). Paarlberg and Van Lente (2021) have tested the model on its usage for the evaluation of the long term morphological effects of side channels. Rorink (2022) also used the model for this purpose. To the knowledge of the author, no further research is available in which this model has been used.

The main reason for choosing a 1D-model is that a 1D-model requires less computational resources than a 2D- or 3D-model. Furthermore, not many studies have been done on the effect of nourishments in the Dutch Rhine under non-constant discharge conditions. A 1D-model can give a first estimation of the long-term large-scale response of the river system to nourishments and it can help to determine whether the implementation of nourishments has potential to reduce bed degradation.

This specific model of the Rhine branches is chosen because it captures the characteristics of the Rhine branches at a relatively detailed scale, compared to more conceptual models. Additionally, the model is made for the simulation of morphodynamic development. That means that sedimentation and erosion processes are captured more accurately than in models that are made for simulation of the hydrodynamic development. Another advantage is that the model covers all branches of the Dutch Rhine. Since the behaviour of one branch is strongly dependent on the behaviour of the other branches, this gives a more elaborate indication of the effect of the nourishment. When the goal is to design nourishments for real-world implementation, computations can be made using more comprehensive and more computationally expensive models. The current model is not designed for this purpose (Paarlberg and Van Lente, 2021).

The model domain is visualised in Figure 3.1. The domain of the Rhine branches model covers the main distributaries of the Dutch Rhine: the Boven-Rijn, the Waal, the Pannerdensch Kanaal, the Neder-Rijn, the Lek and the IJssel. The upstream boundary of the domain is located 48 km upstream of Lobith at the confluence of the Lippe and the Rhine, near Wesel. Consequently, also a part of the German Niederrhein is included in the model. The downstream boundaries are located at Hardinxveld for the Waal, at Krimpen for the Lek and at the Keteldiep and the Kattendiep for the IJssel.

The hydrodynamics in the model are computed by solving the 1D shallow water equations. These equations are included in Appendix A.1. The model makes use of the D-Flow FM 1D

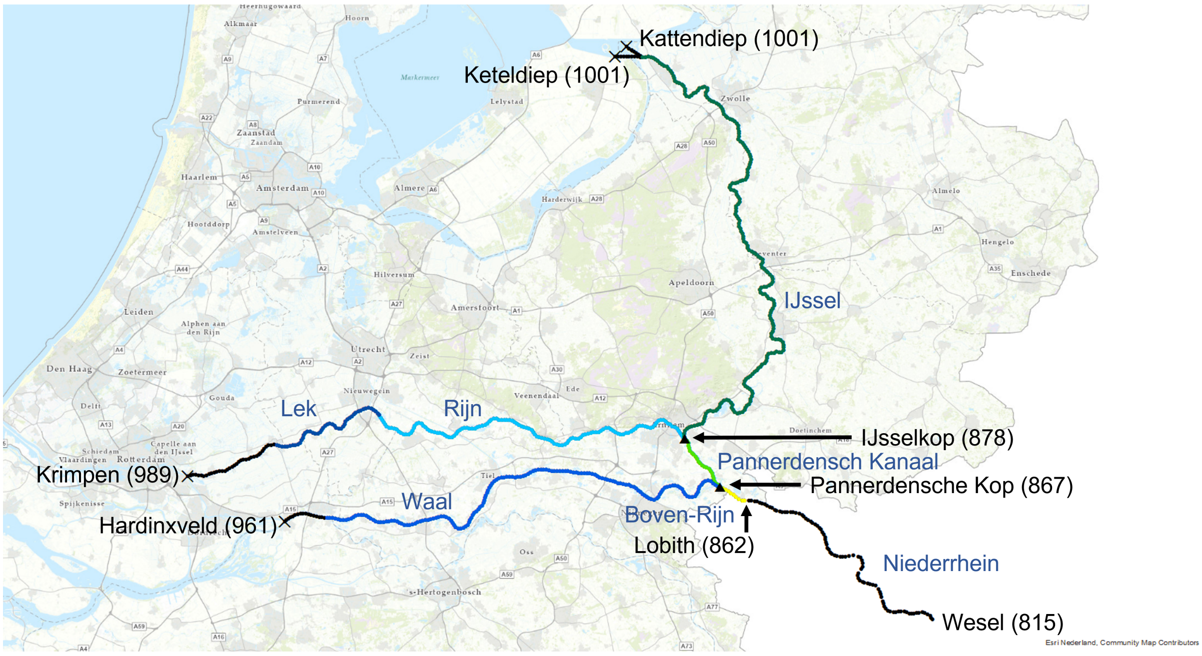


**Figure 3.1:** The model domain of the 1D-model of the Rhine branches developed by Chavarrias et al. (2020). Chainage is indicated in brackets in river-kilometres. Adapted from map made by the author in ArcGIS using a topographic basemap by Esri Nederland (2022).

computational core. The hydrodynamic model is taken from SOBEK and is converted to D-Flow FM 1D.

The model domain of the 1D Rhine branches model is straightened. D-Flow FM 1D uses a 2D numerical solver. As a consequence, energy losses occur when streamlines are curved. While energy losses also occur in reality when a river forms a bend, the curvature needs to be captured in the model with sufficient detail to model this energy loss accurately (Chavarrias et al., 2020). To prevent large and unrealistic energy losses, a small spatial step is required, which would increase the required computational resources. For the purpose of this model, this is unwanted. Chavarrias et al. (2020) therefore chose to straighten the model, such that unrealistic energy losses are prevented, while the spatial step does not have to be decreased. Moreover, the storage area in the cross-sections is removed due to problems with the advection scheme when storage is included (Chavarrias et al., 2020). Chavarrias et al. (2020) show that this has no significant influence on the model results.

The bathymetry that is included in the model is based on SOBEK-3 schematization of the bathymetry of 2019. The bathymetry of the German part of the model domain (upstream of Lobith) is based on the bathymetry of 2012. The sediment composition of the bed is based on Sloff (2006), which uses measurements from 1995. The possible effect of this discrepancy between the initial conditions for the bed level and the sediment composition is discussed in the Discussion in Section 5.1.

The model is calibrated to accurately calculate morphodynamic development. The hydrodynamics in the model are calibrated based on the flow velocities, since the flow velocity determines the sediment transport. As a consequence, the water levels that the model calculates are not necessarily the water levels that are expected in reality: they may differ by up to a decimetre

(Chavarrias et al., 2020). Moreover, the model only captures the morphodynamic development of the main channel. This means that sedimentation and erosion in flood plains is not captured.

The sediment transport that enters the model from upstream is determined by adding a fixed ghost cell to the upstream end of the domain. The sediment composition and the bed level of this cell are fixed, meaning that sediment that would be eroded from this cell enters the model through the upstream domain.

The sediment composition in the model consists of 16 different sediment fractions, ranging from fine sand to coarse gravel. The sediment fractions are divided into two categories: sand (< 2 mm) and gravel (> 2 mm). The sediment fractions that are included in the model, including their characteristic grain size and the type that they belong to, are shown in Table 3.1.

**Table 3.1:** Grain size per sediment fraction and their classification (Chavarrias et al., 2020).

| Fraction | Grain size (m) | Type | Fraction | Grain size (m) | Type |
|---|---|---|---|---|---|
| **1** | $7.529 \cdot 10^{-5}$ | Sand | **9** | $2.366 \cdot 10^{-3}$ | Gravel |
| **2** | $1.060 \cdot 10^{-4}$ | Sand | **10** | $3.346 \cdot 10^{-3}$ | Gravel |
| **3** | $1.500 \cdot 10^{-4}$ | Sand | **11** | $5.656 \cdot 10^{-3}$ | Gravel |
| **4** | $2.121 \cdot 10^{-4}$ | Sand | **12** | $1.131 \cdot 10^{-2}$ | Gravel |
| **5** | $2.979 \cdot 10^{-4}$ | Sand | **13** | $2.262 \cdot 10^{-2}$ | Gravel |
| **6** | $4.213 \cdot 10^{-4}$ | Sand | **14** | $4.525 \cdot 10^{-2}$ | Gravel |
| **7** | $7.071 \cdot 10^{-4}$ | Sand | **15** | $9.050 \cdot 10^{-2}$ | Gravel |
| **8** | $1.414 \cdot 10^{-3}$ | Sand | **16** | $1.810 \cdot 10^{-1}$ | Gravel |

Two different sediment transport formulae are used: one for the sand fractions and one for the gravel fractions. For the sand fractions, a modification of the relation by Engelund and Hansen (1967) is used, while the transport of the gravel fractions is calculated using a modification of the relation by Meyer-Peter and Müller (1948). The relations, including their parameters, are included in Appendix A.1. The possible effects of this two-fold approach in which sand and gravel are modelled differently from each other are discussed in Section 5.1. All sediment transport is modelled as bed load, therefore the deposition of sediments in the floodplains is not included. For a detailed explanation of the chosen and calibrated parameters in the relations, the reader is referred to Chavarrias et al. (2020).

The sediment in the river bed is modelled using the active layer concept by Hirano (1971). Since this way of modelling determines the way the nourishment can be implemented in the model, this concept is explained here in more detail. The active layer concept is a way of modelling that can be used when the sediment is composed of different grain sizes and sorting effects are important, as is the case when studying the morphodynamics of the river bed of the Waal. It means that the bed consists of multiple layers, of which the top layer is the active layer. The sediment in each layer is perfectly mixed and sediment can only be transported to and from the active layer. The consequences of using this active layer concept are discussed in Section 5.1.

The thickness of the active layer cannot be determined by physics, since it is a modelling approach rather than a physical phenomenon. The chosen thickness is related to the time scale of the changes in the grain size distribution: a thinner active layer means faster changes in the grain size distribution (Chavarrias et al., 2020). The thickness of the active layer is chosen to be 1 m by Chavarrias et al. (2020). They chose not to treat this value as a calibration parameter, but to base this value on the ratio of the height of perturbations of the bed to the mean bed elevation, while calibrating the sediment transport formulae, to limit the number of calibration parameters. A sensitivity analysis on the value of the active layer thickness is performed by Chavarrias et al. (2020). Since the calibration of the model was performed using an active layer thickness of 1 m, it is chosen not to alter this value in this study. The consequences of this way of modelling are further explained in Section 5.1.

Underneath the active layer, there is a maximum of 9 substrate layers, each with a maximum thickness of 0.4 m (Chavarrias et al., 2020). These substrate layers are used for bookkeeping of sediment deposition and erosion. When sediment is eroded from the active layer, the active layer is replenished with sediment from the first available substrate layer at the end of the time step, such that the active layer remains 1 m thick. When sediment is deposited on the bed, the sediment in the active layer is mixed and subsequently, the active layer is reduced to 1 m thickness and the additional sediment is pushed to the first available substrate layer. For this layer, the new well-mixed composition is calculated, after which the layer is reduced to 0.4 m and additional sediment is pushed to the next substrate layer. This process is repeated until the threshold for the thickness of a substrate layer is not exceeded. When the maximum of 9 substrate layers is exceeded, a base layer is created, in which the additional layers are merged. The base layer is not limited in thickness.

Since not enough data is available on the sediment composition of the substrate, it is assumed by Chavarrias et al. (2020) that initially, the substrate has the same composition as the bed surface, meaning that each substrate layer has the same sediment composition as the active layer.

The distribution of sediment transport at the bifurcation points of the Pannerdensche Kop and the IJsselkop is determined by a nodal-point relation, defined by Sloff (2006), which is shown in Appendix A.1. This relation gives a distribution of the sediment load that is based directly on the distribution of the discharge at the bifurcation point. The relation makes use of a calibration parameter, which is defined separately for each bifurcation point and sediment type (Chavarrias et al., 2020). The calibration by Chavarrias et al. (2020) is done based on measurements by Frings et al. (2019).

Three regulating structures are included in the model: the three weirs in the Neder-Rijn, at Driel (rkm 891), Amerongen (rkm 922) and Hagestijn (rkm 947). The crest level of these weirs is determined by the water level at a predetermined location. The coupling of the model and the regulation of the weirs is done by the D-Flow FM module D-RTC. Unrealistic morphological behaviour was observed around the weirs by Paarlberg and Van Lente (2021). This is solved by fixing the bed level around the weirs. When comparing this to reality, this is like continuously dredging and nourishing around the weirs to counter any sedimentation or erosion. It is expected that this does not have a significant influence on the interest area of this study (the Waal).

Finally, the model includes fixed layers in the Waal, at Erlecom (rkm 873-876), Nijmegen (rkm 883-885) and St. Andries (rkm 925-928). To preserve the sediment transport over these fixed layers, the layers are modelled by a lack of sediment, which is implemented by removing the substrate layers (Chavarrias et al., 2020). At the location of the fixed layers, erosion may therefore occur of up to 1 meter, but the active layer is not replenished. As the thickness of the active layer reduces, the sediment transport over the active layer is reduced (Paarlberg and Van Lente, 2021). The bed level at the location of the fixed layers does not necessarily accurately represent the bed level that would occur in reality, but the sediment transport over the fixed layer is captured (Chavarrias et al., 2020).

The simulation period in this study is chosen to be 50 years. The Rhine branches model has been developed for the evaluation of long term morphological effects, meaning that the time scale at which the effects are evaluated has to be sufficiently large. In the studies by Paarlberg and Van Lente (2021) and Rorink (2022), a 100-year simulation period was chosen. However, Paarlberg and Van Lente (2021) conclude that it is uncertain whether the results of 100-year simulations are reliable and realistic. Moreover, both Paarlberg and Van Lente (2021) and Rorink (2022) implemented side channels; a measure of which the effect continues to exist during the complete simulation period. In this study, nourishments are implemented at the start of the simulation. Test-runs have shown that the effects of a nourishment reduce significantly in the first years after implementation of the nourishment. It is therefore decided that a 100-year simulation period is not required for evaluating the effects of non-repeated nourishments. In the IRM-programme, predictions on the future bed level are made for the upcoming 30 years (Programma Integraal Riviermanagement, 2021; Klijn et al., 2022). Other research on predicting future bed level change based in the Waal based on past trends also account for the period until 2050 (Ylla Arbós et al., 2019). It should therefore be kept in mind that comparison of the bed level beyond a simulation period of 30 years is mostly based on results from other modelling studies.

The bathymetry in the model is based on schematisations of the bed in 2019, meaning that the development of the bed is modelled from this year onward. The simulation is started at the beginning of the hydrological year. Together, this means that the 50-year simulations run from October 1, 2019 until October 1, 2069.

## 3.2 Model input

This section describes the input that is needed for a general simulation with a nourishment. The input for the specific scenarios that are studied is described in Section 3.3. In Section 3.2.1, the used boundary conditions are described. In Section 3.2.2, the required spin-up time at the start of a simulation is specified. Finally, Section 3.2.3 provides an explanation of the way nourishments are implemented in the model.

### 3.2.1 Boundary conditions

To simulate the morphological development in the Rhine branches, upstream boundary conditions need to be provided in terms of a water discharge entering the system from upstream. Furthermore, to close the system, downstream boundary conditions need to be defined at each downstream boundary of the system. The process of generating and choosing these boundary conditions is elaborated below.

**Upstream boundary conditions**

The upstream boundary conditions are derived from the historical discharge time series at Lobith as measured daily from January 1994 until March 2020. This time series was retrieved by Chavarrias et al. (2020) from the WaterInfo website of Rijkswaterstaat. The minimum, mean and maximum for each hydrological year (October 1 to September 30) is shown in Figure 3.2. The complete time series is included in Appendix A.2. This time series was also used for calibration and validation of the model by Chavarrias et al. (2020).

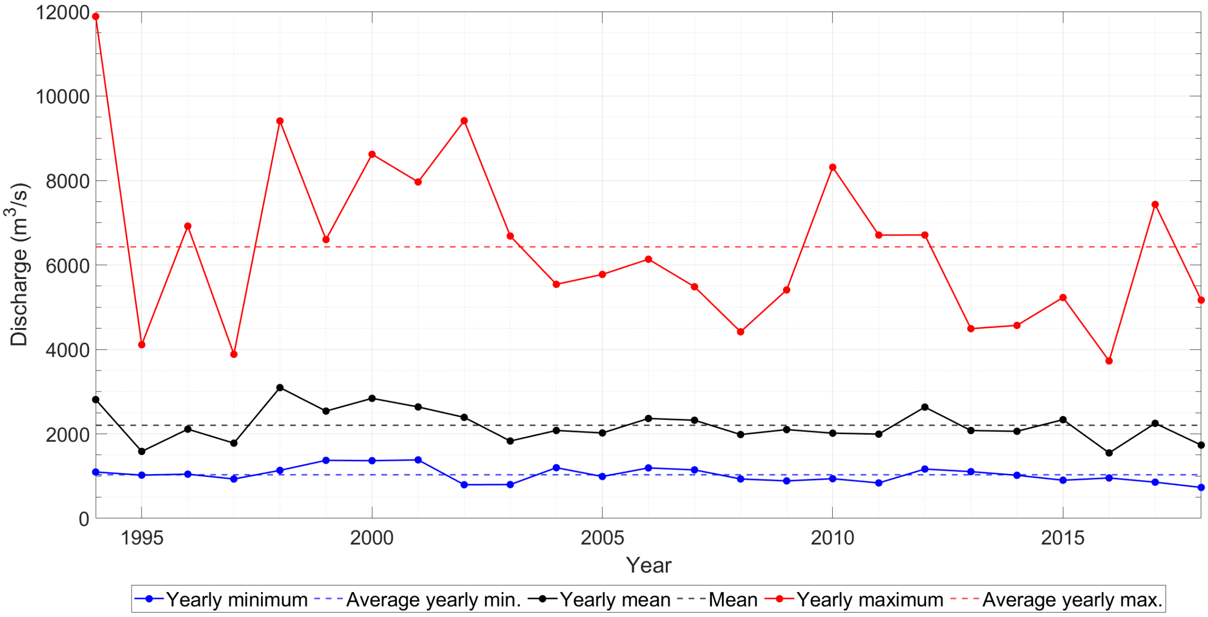


**Figure 3.2:** Yearly minimum, mean and maximum discharge of each hydrological year (October 1 - September 30) and their respective average of the historical discharge time series from 1994 until 2019.

Twenty-one data points are missing in the data set, meaning that there is no record of the discharge for those days. The interpolation method between discharges that is imposed in the model is linear, meaning that if there is no discharge data available for that point in time, the discharge is linearly interpolated between the two nearest data points. The missing data points are distributed over the time series. The longest period without discharge data is five consecutive days. Since the model is built and used for analysis of long term phenomena and not for evaluating the effect of individual discharge waves, this is assumed to have no significant effect on the outcome of the study.

It is acknowledged that the historical discharge time series is measured at Lobith (rkm 865), while the upstream boundary of the system is located 50 km upstream of Lobith in the Niederrhein (rkm 815). However, as both Chavarrias et al. (2020) and Paarlberg and Van Lente (2021) explain, this difference is not significant since the interest of this study is to simulate the long-term morphological development, rather than the development of individual flood waves moving through the system. Furthermore, the discharge data that is used is measured daily, which is already a too large time step for accurate modelling of the flood wave itself.

To be able to use the boundary conditions for simulations of 50 years, new discharge time series are generated. The discharge time series are translated to 50-year time series by using the method of bootstrap resampling (Efron, 1982). In bootstrap resampling, a new data series is constructed by drawing random data points from an original data series. For this resampling method, the underlying distribution of the resampled time series does not have to be known and it can be applied when there is no correlation between the data points (Van Vuren, 2005). However, as Van Vuren (2005) highlights, there is a seasonal dependence between discharges of the Rhine and considering that daily discharges are used here, there is also strong correlation between two consecutive data points. This problem can be omitted by following the approach by Van Vuren (2005) and sampling entire (hydrological) years of discharges instead of daily discharge values. In that way, the daily and seasonal dependence within each hydrological year is preserved. This means that the resampled time series consists of fifty randomly selected years of the original time series. Since it is allowed to select each year an arbitrary number of times, the statistics of the generated discharge time series differ from the original historical discharge time series and from the statistics of the other generated discharge time series. The historical time series is cut up per hydrological year, which runs from October 1 to September 30. At the start of the hydrological year, discharges are usually relatively low. This prevents a large jump at the cut between two years.

Using the bootstrap resampling technique, 100 50-year discharge time series are constructed. Of these discharge time series, the mean and the average yearly maximum is calculated. This is shown in Table A.3 in Appendix A.2.1. From these one hundred discharge time series, one discharge time series is selected as the reference discharge time series. It is decided to base the selection of discharge time series on the mean and the average yearly maximum and specifically on their relative difference to the mean and average yearly maximum of the historical discharge time series. It is chosen not to select based on the average yearly minimum, since morphological development is a non-linear phenomenon, in which higher discharges play a much larger role than lower discharges. There could have been many other criteria upon which the time series are selected, which may provide more information about the time series, but it is assumed that these selection criteria are sufficient for the purpose of this study. This decision is further reflected upon in Section 5.1.3.

For the reference discharge time series, the goal is to select a discharge time series that has approximately the same characteristics as the historical discharge time series. The chosen selection criteria are therefore a deviation of ± 1% from the mean and the average yearly maximum of the historical discharge time series.

From the 100 generated discharge time series, discharge time series 3 (see Table A.3 in Appendix A.2.1) is selected as the reference discharge time series. The statistics of this discharge time series with respect to the historical discharge time series are shown in Table 3.2. The yearly minimum, mean and maximum of the reference discharge time series as well as their respective average are shown in Figure 3.3. A plot of the complete discharge time series is included in Figure A.2 in Appendix A.2. It is verified that the differences between the end and start of a hydrological year are indeed smaller than the maximum differences that naturally occur in the historical discharge time series.

**Table 3.2:** Average yearly minimum, mean and maximum of the historical discharge time series (1994-2020) and the reference discharge time series (as retrieved by bootstrap resampling from the historical discharge time series) (2019-2069). Also the relative difference of the reference discharge time series with the historical discharge time series is given.

| **Discharge time series** | **Avg yearly min.** ($m^3/s$) | **Difference** | **Mean** ($m^3/s$) | **Difference** | **Avg yearly max.** ($m^3/s$) | **Difference** |
|---|---|---|---|---|---|---|
| **Historical** | 1033 | - | 2206 | - | 6425 | - |
| **Reference** | 1038 | +0.5% | 2221 | +0.7% | 6360 | -1.0% |

### Downstream boundary conditions

At the downstream boundaries, a $Qh$-relation is imposed, meaning that a water level (note: not a water depth) is defined for various discharges. These relations are shared by Paarlberg and Van Lente (2021), who used the relations as defined by Agtersloot et al. (2019). The $Qh$-relations are included in Appendix A.2. Following the approach by Paarlberg and Van Lente

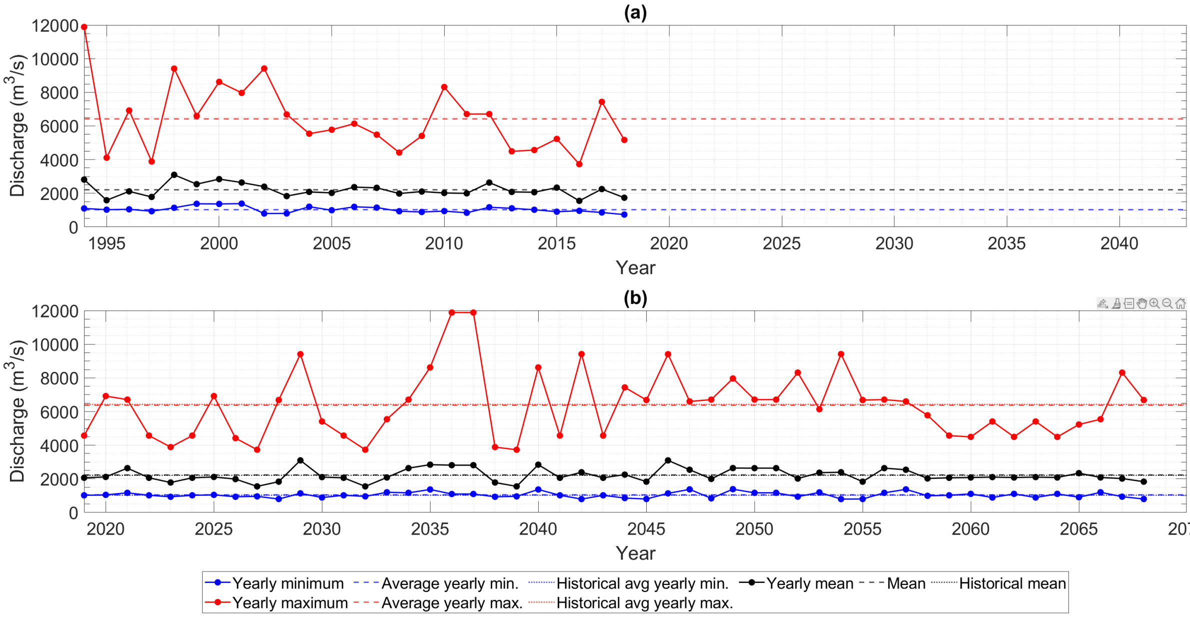


**Figure 3.3:** Yearly and average minimum, mean and maximum discharge of the historical (a) and new reference (b) discharge time series, as retrieved by bootstrap resampling from the historical time series.

(2021), lateral inflows to the system are ignored. Paarlberg and Van Lente (2021) explain that this is common in morphological simulations and that the effect of the lateral inflows is small and not visible in the results.

It is chosen to deviate from the approach by Czapiga et al. (2022), who used a water level time series at the downstream boundaries. Because the water has to travel through the system, there is a lag between the upstream discharge and the downstream water level. The exact duration of this lag is unknown. When the upstream boundary conditions are resampled, this leads to unrealistic values at the cut of each hydrological year. By using a $Qh$-relation, this is omitted.

It should be noted that by defining a water level for a certain discharge, rather than a water depth, the effect of a difference in bed level is ignored. This leads to an overestimation of the flow depth in case of degradation at the downstream boundary and an underestimation of the flow depth in case of aggradation at the downstream boundary. As a consequence, this leads respectively to an underestimation and an overestimation of the flow speed at the downstream boundary. This should be accounted for when interpreting the results. The implications of using this type of boundary condition is further discussed in the Discussion in Section 5.1.

### 3.2.2 Spin-up time

The model starts 'empty', meaning that there is no water in the system at the start of the simulation. That means that the system has to warm up before the morphological development is calculated. To determine the required spin-up time, a simulation is performed with a steady discharge of 2,221 $m^3/s$, which is the mean discharge of the reference discharge time series. When the upstream discharge is constant, the discharge in the downstream parts of the system must also converge to an almost constant value. The value is likely not completely constant over time, since the system is not in equilibrium and therefore the bed level changes in response to the flow. However, since the spin-up time is expected to be in the order of several days to a week and bed level changes occur on a larger timescale, this is assumed to be no problem. The time it takes for the discharge to converge to this 'constant' value is the required spin-up time of the system.

The simulation with a discharge of 2,221 $m^3/s$ is run for a year and the output is saved daily. The maximum change in discharge between two consecutive days in each river branch is shown in Figure 3.4. It is found that the Boven-Rijn and the Waal converge to a nearly steady value within three days. The Neder-Rijn/Lek and the IJssel continue to show small fluctuations in discharge. This is caused by the presence of weirs in the Neder-Rijn. The response of these weirs cause different water levels around them, making them respond to these changed water levels. Their crest level is therefore not constant, even though the upstream discharge input is steady. This causes a varying discharge around the weirs and a varying discharge distribution at the bifurcation point at the IJsselkop. This is an artefact of the system settings. The validity of this is discussed in Section 5.1.2. The decision is made to base the start-up time on the behaviour of the other Rhine branches.

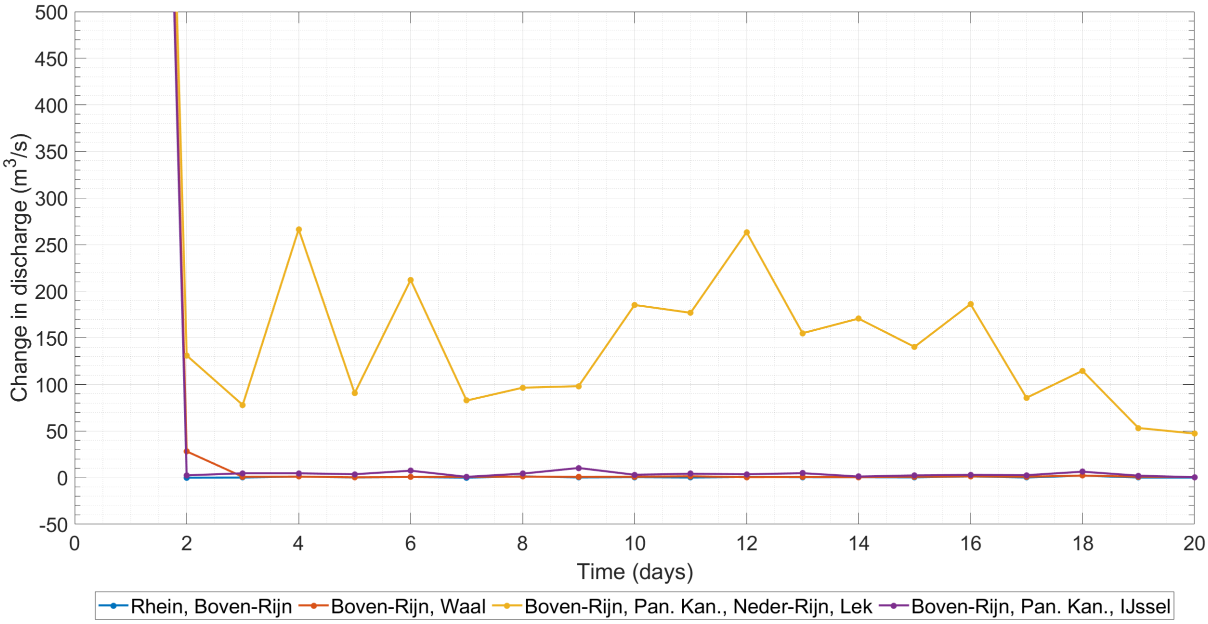


**Figure 3.4:** Maximum change in discharge compared to the previous day in each river branch for a steady discharge of 2,221 $m^3/s$.

To conclude, the minimum required start-up time is three days. For safety, a start-up time of one week is considered. That means that while the discharge time series is imposed from the start of the simulation, morphological development starts after one week. In the first week, sediment can be transported from the bed, but the bed level is not updated accordingly. That means that sediment is 'created'. In reality, there is also always already sediment in transport in a river. The 'created' sediment simulates the sediment already present in transport. Since the model is built for the analysis of long-term morphological development, rather than for the response to an individual discharge wave, it can be assumed that leaving out a week of morphological development has no significant effect on the outcome of the simulations.

### 3.2.3 Schematisation of nourishments

Nourishments are simulated by changing the initial conditions of a run. That means that the model simulates what happens when a nourishment is applied at t=0 and no further interventions are done during the run. This also implies that simulating repeated nourishments is not possible. This choice is driven by limitations of the model, as is further discussed in Section 5.1.1. A nourishment is characterised by its location, grain size and volume. First, the location of the nourishment is determined and then the corresponding the nodes and cross-sections in the model are modified to schematise the nourishment.

A nourishment can be placed such that it is either exposed or entrenched. Czapiga et al. (2022) explain that an exposed nourishment is placed on the bed, therefore forming an elevated section of the river bed, while an entrenched nourishment is placed in a hole in the river bed, therefore filling this hole up. It was found by Czapiga et al. (2022) that the behaviour and the response of the river bed to exposed and entrenched nourishments show no significant difference. Therefore, the decision is made to model the nourishments as exposed sediment humps on the river bed, since this is easier to schematise.

The volume of a nourishment is imposed by changing the cross-section definitions of the cross-sections within the nourished reach. The nourishment is applied over the complete width of the main channel. Cross-sections are defined as flow width to flow depth relations and for each cross-section, the width of the main channel is given. Only the bed levels that are defined at a flow width that lies within the main channel are updated. The bed level is raised by the thickness of the nourishment. An example of such an original and updated flow width - flow depth relation for a cross-section within a nourished reach is provided in Figure 3.5.

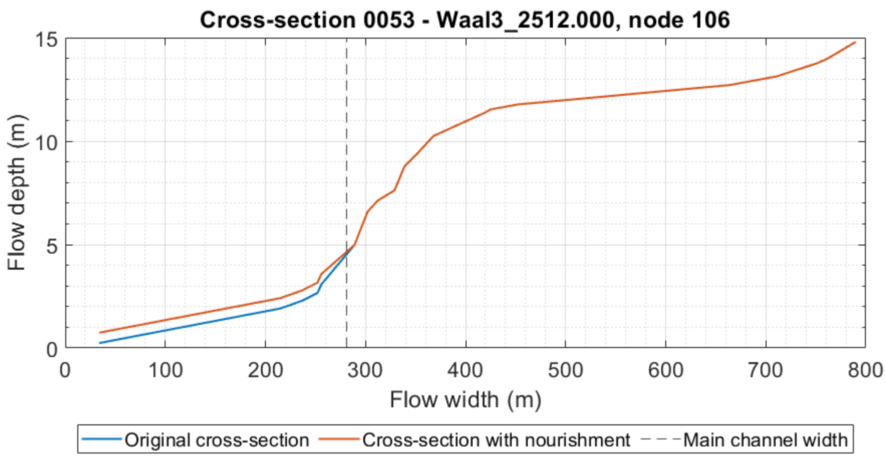


**Figure 3.5:** Example of the adapted flow width - flow depth diagram for a cross-section within a nourishment area.

In case the sediment composition of the nourishment differs from the sediment composition of the bed, also the sediment composition initialisation files are adapted. That means that for the coordinates that lie within the nourishment area, the proportion of each fraction in the surface layer of the bed is changed.

As explained in Section 3.1, the active layer concept is used in the model. The active layer is by definition perfectly mixed and all sediment that is in the active layer, can be entrained. The behaviour of the nourishment partially relates to the thickness of the nourishment compared to the thickness of the active layer, as is schematised in Figure 3.6 (Czapiga et al., 2022). When the nourishment is thicker than the active layer of 1 m (left case in Figure 3.6), the nourishment completely replaces the sediment in the active layer and the composition of the surface layer of the bed is fully determined by the composition of the nourishment. In case of a nourishment that is coarser than the bed, it can form an armor layer on top of the bed. However, when the nourishment thickness is smaller than the active layer of 1 m (right case in Figure 3.6), the nourished sediment is mixed with sediment from the active layer. This is a consequence of the use of the active layer concept. Since adapting the usage of the active layer or adapting the thickness of the active layer is outside of the scope of this research, this difference cannot be eliminated and therefore it should be accounted for when implementing the nourishments and interpreting the results.

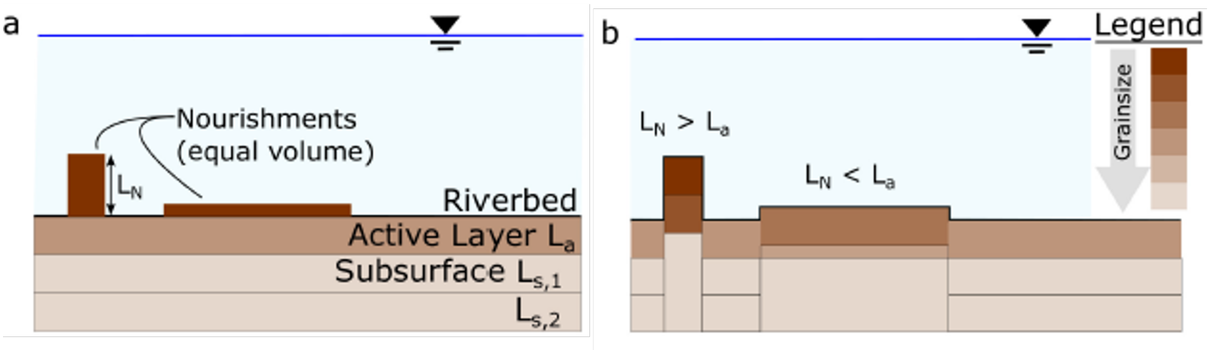


**Figure 3.6:** Schematisation of how the nourishment is added to the river bed (a) and how the nourishment is implemented in the layered bed in the initial conditions of the model after mixing with the active layer (b), in case the nourishment thickness is larger than the active layer (left) and in case the nourishment thickness is smaller than the active layer (right). $L_N$ is the thickness of the nourishment [m]; $L_a$ is the thickness of the active layer [m]; and $L_{s,j}$ is the thickness of substrate layer $j$ [m]. Figure taken from the supplementary materials by Czapiga et al. (2022).

Since the chosen nourishment thickness (0.5 m, see Section 3.3) in this study is smaller than the thickness of the active layer, there are two options for schematising the nourishments. The first is to 'mix' the sediment of the nourishment and the sediment of the present bed, as shown in the right case in Figure 3.6. The composition of the nourishment then contributes for $L_N/L_a \cdot 100\%$, in which $L_N$ is the thickness of the nourishment $[m]$ and $L_a$ is the thickness of the active layer $[m]$. The original composition of the bed contributes for $(1 - L_N/L_a) \cdot 100\%$. In the case of a nourishment of 0.5 m in thickness, both the nourishment composition and the original composition of the bed contribute for 50%. The variation in grain size of the surface layer that occurs since the coarser nourishment armours the finer composition of the bed is not reflected in the model, since the active layer is by definition perfectly mixed. Consequently, the sediment transport from the bed is overestimated, since finer sediment is available, which in reality would be (partially) sheltered by the coarser sediment from the nourishment.

The second option is to completely replace the composition of the active layer by the composition of the nourishment. When a comparison to reality is made, this would be like dredging away a part of the bed before filling this hole back up and adding a layer of sediment with a coarser composition. This implies that there is more coarse sediment present in the bed than it would in reality (when a regular nourishment is executed on top of the bed surface). However, the sediment transport as calculated by the model is likely more in line with reality than it is for the previously described approach, since the sediment composition of the sediment available for transport is equal to the sediment composition of the nourishment.

When sediment is picked up from the bed at the nourishment location, the active layer is replenished with sediment from the substrate layers. Since the substrate layers initially have the same sediment composition as the active layer before nourishing (see Section 3.1), finer sediment becomes available in the active layer again. That means that the armouring effect of the nourishment decreases with time and this decrease occurs faster than it would in reality. This counters the effect from replacing the complete active layer with coarser sediment.

It is chosen to take the latter approach, in which the complete active layer is replaced by the sediment composition of the nourishment. It is expected that this results in a better representation of the sediment transport over the nourishment.

## 3.3 Scenarios and simulations

Table 3.3 gives an overview of the various simulations that are performed in this research. The simulations are explained below. In Section 3.3.1 until 3.3.5, the selection of the nourishment volume & dimensions, nourishment location, sediment composition of the nourishment, nourishment distribution and the discharge time series are provided.

In simulation 1, the development of the bed without future human intervention under the reference discharge conditions as shown in Figure 3.3 is modelled. Simulation 1 serves as a reference for simulations 2 until 8 and is therefore also called the 'reference simulation'. This also provides the answer to research sub-question 1.

Subsequently, the effects of various nourishments are investigated in simulations 2 to 8. The results of these simulations provide the answer to research sub-question 2. Firstly, in simulation 2, the general effects of a nourishment are investigated by implementing a nourishment with a composition that is equal to that of the bed. In practice, this is equal to heightening the bed at a specific location. This simulation is used to explain the effects of such a heightening of the bed and to verify the model responses to this elevation. The volume and dimensions of the nourishment are given in Section 3.3.1, while the location is justified in Section 3.3.2. Thereafter, in simulation 3, the sediment composition of the surface in this reach is changed, such that the nourishment is coarser than the original bed surface at that location. The effects of a change in grain size can then be evaluated. The selection of the sediment composition of the nourishment is explained in Section 3.3.3.

In simulation 4, the nourishment location of the coarse nourishment is changed from the Midden-Waal to the Boven-Waal. The reason for this variation is that the Boven-Waal and Midden-Waal each have a different sediment composition of the bed and their degree of erosion differs. The Boven-Waal is coarser than the Midden-Waal and the Boven-Waal is eroding faster than the Midden-Waal (Programma Integraal Riviermanagement, 2021). Therefore, placing a nourishment in each of these sections may have a different effect. The choice of location is further elaborated upon in Section 3.3.2.

Simulations 5 and 6 investigate the influence of distributing a nourishment over multiple parts. When the nourishment is coarser than the bed, it is expected from the results by Czapiga et al. (2022) that erosion occurs downstream of the nourishment. This happens because the nourished sediment is less mobile than the original bed and it forms an armoured layer. That means that over the nourishment, the sediment transport is less than the sediment transport capacity, so sediment is picked up downstream of the nourishment, causing additional erosion (Blom, 2016; Becker, 2021; De Jongste and Huppes, 2021). By dividing the nourishment over multiple smaller

**Table 3.3:** Overview of simulations and the variations of different variables. 'RQ' stands for research question and indicates which research question the simulation aims to answer. 'Sim' indicates the simulation number. 'Description' provides a short description of the simulation. 'Discharge' indicates the upstream boundary condition that is imposed, with 'Ref.' being the reference discharge scenario; 'SMHM' being the discharge scenario with the same mean and a higher maximum; and 'HMHM' being the discharge scenario with a higher mean and a higher maximum. 'Location' indicates the branch in which the nourishment is initially placed, with 'MW' meaning Midden-Waal and 'BW' meaning Boven-Waal. 'Volume' indicates the volume of the nourishment. 'Grain size' indicates the sediment composition of the nourishment with respect to the sediment composition of the bed. 'Parts' indicates the number of parts into which the nourishment is split up.

| **RQ** | **Sim.** | **Description** | **Discharge** | **Location** | **Volume** | **Grain size** | **Parts** |
|---|---|---|---|---|---|---|---|
| 1 | 1 | Reference simulation | Ref. | - | - | - | - |
| 2 | 2 | Area-specific nourishment in Midden-Waal | Ref. | MW | $2.52 \cdot 10^5$ m$^3$ | Equal | 1 |
| 2 | 3 | Coarse nourishment in Midden-Waal | Ref. | MW | $2.52 \cdot 10^5$ m$^3$ | Coarser | 1 |
| 2 | 4 | Coarse nourishment in Boven-Waal | Ref. | BW | $2.52 \cdot 10^5$ m$^3$ | Coarser | 1 |
| 2 | 5 | Coarse nourishment in Midden-Waal distributed in 2 parts | Ref. | MW | $2.52 \cdot 10^5$ m$^3$ | Coarser | 2 |
| 2 | 6 | Coarse nourishment in Midden-Waal distributed in 4 parts | Ref. | MW | $2.52 \cdot 10^5$ m$^3$ | Coarser | 4 |
| 2 | 7 | Coarse nourishment of large volume in Midden-Waal | Ref. | MW | $6.93 \cdot 10^5$ m$^3$ | Coarser | 1 |
| 2 | 8 | Coarse nourishment of large volume distributed in 3 parts in Boven-Waal and Midden-Waal | Ref. | BW+MW | $6.93 \cdot 10^5$ m$^3$ | Coarser | 3 |
| 3 | 9 | Development without interventions under discharge scenario SMHM | SMHM | - | - | - | - |
| 3 | 10 | Development without interventions under discharge scenario HMHM | HMHM | - | - | - | - |
| 3 | 11 | Coarse nourishment in Midden-Waal distributed in 2 parts under discharge SMHM | SMHM | MW | $2.52 \cdot 10^5$ m$^3$ | Coarser | 2 |
| 3 | 12 | Coarse nourishment in Midden-Waal distributed in 2 parts under discharge HMHM | HMHM | MW | $2.52 \cdot 10^5$ m$^3$ | Coarser | 2 |

parts, this behaviour may be prevented (De Jongste and Huppes, 2021; Czapiga et al., 2022). To investigate this, the nourishment is divided over two and four smaller parts, respectively. The distribution of the nourishment parts is explained in Section 3.3.4.

In simulations 7 and 8, the effect of implementing a larger nourishment is investigated. Firstly, the nourishment is implemented as one continuous nourishment (simulation 7) and thereafter, the nourishment is split up into multiple parts (simulation 8). The goal of the latter simulation is to determine whether the effects that are observed in simulations 5 and 6 for the distributed nourishments also still hold when the individual parts of the nourishments are larger. The justification for the nourishment volumes is given in Section 3.3.1.

To answer research question 3, in simulations 9 and 10, a different discharge regime is used as the upstream boundary condition, so that the influence of a varying upstream discharge on the development of the bed without future human intervention can be investigated. This is used to place the effects of the nourishments in a broader context. Moreover, these simulations serve as a reference for simulations 11 and 12. The selection of the discharge time series that are used in these simulations is explained in Section 3.3.5.

Finally, in simulations 11 and 12, the same nourishment is applied as in simulation 5. However, in this case the upstream discharge conditions as used in simulation 9 and 10 are applied. In reality, it is uncertain which discharge conditions will take place in the years after nourishing. Therefore, these simulations serve to determine the influence of the discharge conditions on the development of the nourishment. This is also part of the answer to research question 3.

### 3.3.1 Volume and dimensions of the nourishment

The effects of nourishments of two different volumes are tested. An overview of the volume and dimensions of each nourishment is provided in Table 3.4. Below the table, an explanation of the choice for these values is provided.

**Table 3.4:** Volume and dimensions of the various nourishments

| **Simulation** | **Volume** ( $m^3$) | **Mass** (Mt) | **Thickness** (m) | **Total length** (km) |
|---|---|---|---|---|
| **2-6; 11-12** | $2.52 \cdot 10^5$ | 0.46 | 0.5 | 2 |
| **7-8** | $6.93 \cdot 10^5$ | 1.26 | 0.5 | 5.5 |

Firstly, the volume is determined which is used in simulations 2 until 6, 11 and 12. The nourishment is designed following the approach by Czapiga et al. (2022), which allows for qualitative comparison of the results. The volume is chosen to be approximately 100% of the yearly sediment transport at the location of the nourishment. This is equal to the relative volume of the nourishment compared to the sediment load as used by Czapiga et al. (2022). It is chosen to base the volume of the nourishment on the sediment transport at the location of the singular nourishments in the Midden-Waal (simulations 2& 3). From the results of the reference simulation (see Section 4.1), it is found that the cumulative sediment transport at rkm 889 is 23.4 Mt over 50 years, which averages to approximately 0.47 Mt per year.

To calculate the mass of sediment that is needed for a nourishment, Equation 1 is used. $V$ is the volume of the nourishment [$m^3$]; $\rho_s$ is the mineral density [$kg/m^3$], which is approximately

2,600 $kg/m^3$ (Frings et al., 2014); and $p$ is the porosity [-], which is estimated to be 0.3 (Frings, 2011). Following Equation 1, 0.47 Mt relates to a volume of approximately $2.58 \cdot 10^5$ $m^3$.

$$m = V\rho_s\,(1-p) \tag{1}$$

The thickness of the nourishment is chosen to be 0.5 m. This thickness corresponds to the thickness as chosen by Becker (2021) and Czapiga et al. (2022) in their studies. Furthermore, it is recommended by Klijn et al. (2022) to implement nourishments on the Waal of 0.35 m at minimum and 0.5 m at maximum. It is verified that this sudden change in bed level at the upstream and downstream end of the nourishment does not cause convergence errors that lead to unrealistic model results.

To obtain a nourishment of approximately 0.47 Mt and 0.5 m in thickness, a nourishment length of 2 km is required. When calculating the volume of a nourishment with a length of 2 km and a thickness of 0.5 m using Equation 1, that gives a volume of $2.52 \cdot 10^5$ m$^3$ and a mass of 0.46 Mt. Since the nourishment is schematised by adapting the cross-sections and a cross-section is defined at each 500 m, the nourishment length can only be chosen at intervals of 500 m. This is therefore the closest approximation of the upstream sediment feed that can be obtained.

The second nourishment volume, that is used in simulation 9 and 10, is chosen based on the report by Van der Deijl (2021). In this report, it is estimated how much additional sediment is needed to maintain the bed level at its current level. She concludes that to maintain the bed level at its current position, $7.36 \cdot 10^4$ m$^3$ and $6.73 \cdot 10^4$ $m^3$ of sediment would have to be supplied each year, to the Boven-Waal and Midden-Waal respectively. Unfortunately, performing yearly nourishments is not possible in the current model set-up. Therefore, it is chosen to model the first ten years of such nourishments at once to determine its effect on the system. For the Midden-Waal, this corresponds to a volume of $6.73 \cdot 10^5$ m$^3$ at once. Since the height of the nourishment is restricted to 0.5 m, as is explained above, the length of the nourishment has to be adapted to obtain the desired volume. A nourishment length of 5.5 km is required to obtain a nourishment volume of $6.93 \cdot 10^5$ m$^3$. Using Equation 1, this relates to a mass of 1.26 Mt.

### 3.3.2 Location of the nourishment

The nourishments are placed in two different sections of the Waal: in the Midden-Waal and the Boven-Waal. From solicitation with an expert, it is determined that the exact location of this nourishment in these reaches likely does not make a significant difference in the behaviour of the nourishment itself (Sieben, 2022). The location of the nourishment can therefore be chosen.

Rijkswaterstaat has defined areas in which no dredging or dumping is allowed throughout the branches of the Rhine, for example to ensure navigability or to protect pipes and cables that cross the river bed (Rijkswaterstaat Oost-Nederland, 2018). However, since the nature of this study is exploratory and the goal is to assess the general effects of different types of nourishments and not to design specific nourishments, the decision is made that compliance with these restrictions is not necessary. Consequently, a nourishment may be located in a part of the river where no dredging or dumping activities are allowed.

An overview of the locations of the various nourishments is shown in Table 3.5. Maps showing the locations of the nourishments and the exact nodes that are adapted are included in Appendix A.3. Below, the argumentation for the choice of these locations is provided.

**Table 3.5:** Locations of the various nourishments

| Simulation | Description | Branch | River-km |
|---|---|---|---|
| **2** | Area-specific nourishment in Midden-Waal | Midden-Waal | 889-891 |
| **3** | Coarse nourishment in Midden-Waal | Midden-Waal | 889-891 |
| **4** | Coarse nourishment in Boven-Waal | Boven-Waal | 878-880 |
| **5** | Coarse nourishment in Midden-Waal distributed in 2 parts | Midden-Waal | 889-890; 901-902 |
| **6** | Coarse nourishment in Midden-Waal distributed in 4 parts | Midden-Waal | 889-889.5; 895-895.5; 901-901.5; 907-907.5 |
| **7** | Coarse nourishment of large volume in Midden-Waal | Midden-Waal | 889-894.5 |
| **8** | Coarse nourishment of large volume distributed in 3 parts in Boven-Waal and Midden-Waal | Midden-W. + Boven-W. | 878-880; 889-891; 901-902.5 |
| **11** | Coarse nourishment in Midden-Waal distributed in 2 parts under discharge SMHM | Midden-Waal | 889-890; 901-902 |
| **12** | Coarse nourishment in Midden-Waal distributed in 2 parts under discharge HMHM | Midden-Waal | 889-890; 901-902 |

Firstly, the nourishment location in the Midden-Waal for simulation 2 and 3 is selected. The nourishment location that is selected for the Midden-Waal is between rkm 889 and 891. This location is chosen since it is located at a distance upstream from the transition between the eroding and aggrading reach of the Waal (rkm 915, see Section 4.1). After application, the nourished sediment is transported downstream and by placing it in the upper section of the Midden-Waal, it is expected that the nourishment can help in reducing erosion throughout the Midden-Waal. If the nourishment is placed further downstream, the nourished sediment is soon transported to the Beneden-Waal, where aggradation takes place instead of erosion. Furthermore, this location is approximately 6 km downstream of the fixed layer at Nijmegen (rkm 884). Since the fixed layer behaves differently than the regular bed surface, it is preferred to have some distance between the fixed layer and the nourishment to be able to study the effects upstream of the nourishment.

Secondly, the nourishment location for simulation 4 in the Boven-Waal is selected. In the Boven-Waal, two fixed layers are present: at Erlecom (rkm 873-876) and at Nijmegen (rkm 883-885). It is objectionable to place the nourishment directly over such a fixed layer. Firstly, because in practice the fixed layer at Nijmegen already forms the shallowest section of the river branch during low discharges (Programma Integraal Riviermanagement, 2021) and nourishing over such a fixed layer is undesirable. Secondly, because of the way the fixed layers are implemented in the model (see Section 3.1), it is expected that the behaviour of the nourishment over the fixed layer is not modelled accurately when the nourishment still has its initial thickness when going over the fixed layer. Therefore, the nourishment has to be placed either upstream of Erlecom, between Erlecom and Nijmegen or downstream of Nijmegen.

The decision is made not to place the nourishment upstream of Erlecom (rkm 874.5), since it is found in the reference run that in that section the bed level degrades with a faster rate than expected (see Section 4.1). If the nourishment is placed downstream of Nijmegen (rkm 884), it is close to the nourishment in the Midden-Waal, so this will likely generate a result that is similar to the nourishment in the Midden-Waal. For the purpose of this research, this does not have additional value. It is therefore decided to place the nourishment between Erlecom and Nijmegen. The location that is selected is from rkm 878 to rkm 880. This location is situated in a bend. Since the Boven-Waal is characterised by a chain of bends, it is not possible to prevent the nourishment from being implemented in a bend. However, it should be noted that bend effects are not effectively captured in this 1D-model and therefore the behaviour of the nourishment in the bend may not be modelled accurately. This is further discussed in the Discussion in Section 5.1.

Thirdly, the locations of the parts of the distributed nourishments in the Midden-Waal in simulation 5, 6, 11 and 12 are selected. The Midden-Waal reaches from rkm 887 until rkm 917.5. However, placing the nourishments far downstream in the Midden-Waal is unwanted since the nourishments will then travel into the aggrading section of the Waal quickly after implementation. It is chosen to distribute the nourishments in the Midden-Waal between rkm 889 and 907. The spacing between the distributed nourishment in two parts is chosen to be twice as large as the spacing between the distributed nourishment in four parts. The chosen nourishment locations for the nourishment that is distributed in two parts are therefore rkm 889-890 and rkm 901-902. The distributed nourishment in four parts is placed at rkm 889-889.5, rkm 895-895.5, rkm 901-901.5 and rkm 907-907.5.

Finally, the locations for the larger nourishments in simulation 7 and 8 are selected. The non-distributed large nourishment has a length of 5.5 km. It is chosen to keep the upstream boundary of the nourishment equal to the upstream boundary of the nourishments in simulations 2, 3, 5 & 6, so this nourishment reaches from rkm 889 until rkm 894.5. For the locations of the parts of the distributed large nourishment of simulation 10, it is chosen to base the location on previously chosen locations: the location of the nourishment in the Boven-Waal (rkm 878-880), the location of the coarse nourishment (with the original volume) in the Midden-Waal (rkm 889-891) and the location of the downstream part of the distributed nourishment in two parts (rkm 901-902). Since the nourishment is 5.5 km in length, the most downstream nourishment location is elongated by 0.5 km (rkm 901-902.5).

### 3.3.3 Grain size distribution of the nourishment

In simulation 3 until 8, 11 and 12, a coarse nourishment is applied. To be able to compare the results of the various simulations, it is chosen to use the same sediment composition for all of these nourishments. The selection of sediment fractions is based on the sediment composition and sediment transport at the location of the nourishment in simulations 2& 3. These results are taken from the reference simulation (see Section 4.1). The method of determining the sediment composition of the nourishments based on the sediment transport is shown in Appendix A.4.

Based on the analysis shown in Appendix A.4, the decision is made to compose the coarse nourishments of the fractions 8 (1.4 mm) until 13 (22.6 mm) and to choose the composition such that the $D_{10}$, $D_{50}$ and $D_{90}$ of the nourishments are larger than those of the bed after 0 and 50 years of development of the bed without future human intervention. The final sediment composition of the nourishments is shown in Figure 3.7. Figure 3.7 also shows the sediment composition of the bed in the Midden-Waal and Boven-Waal for comparison.

### 3.3.4 Nourishment distribution

The influence of distributing the nourishment over multiple smaller nourishments is investigated for both the original nourishment volume (simulation 5 & 6) and the larger nourishment volume (simulation 8).

For the original nourishment volume, the non-distributed nourishment is 2 km in length. Since a cross-section is defined at approximately each 500 metres, that means that the nourishment can be split up into either 2 or 4 parts, in which respectively 2 or 1 cross-section is adapted per part of the nourishment. Both of these options are modelled. That means that the individual nourishment parts are either 1 km or 0.5 km in length, for the distributed nourishment in 2

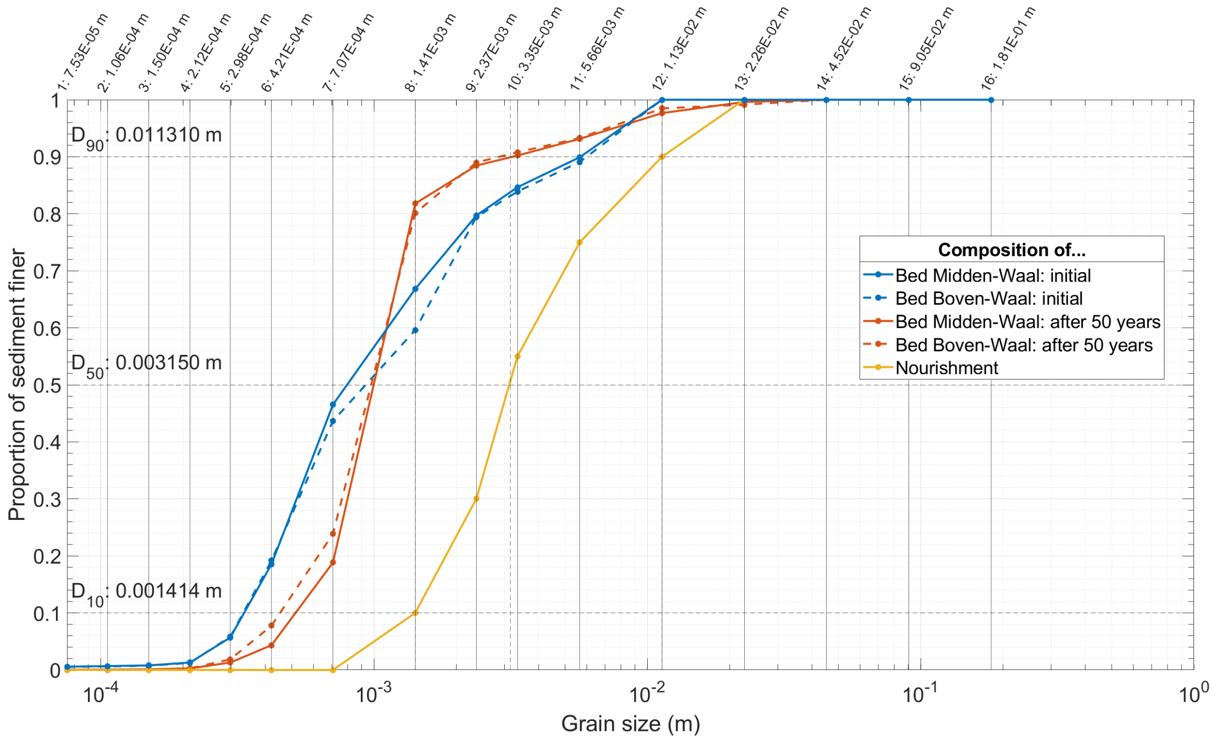


**Figure 3.7:** Sediment composition of the nourishments in simulation 3-8, 11 & 12, compared to the initial and final composition of the bed at the location of the single nourishment in the Midden-Waal (rkm 890) and the Boven-Waal (rkm 879) in the reference simulation. The values on the left correspond to the nourishment composition. The values on top show the grain size for each sediment fraction, as shown in Table 3.1.

and 4 parts, respectively. The thickness of the nourishment is kept constant with respect to the original, non-distributed, nourishment, i.e. it is 0.5 m in thickness.

The larger nourishment volume that is distributed into multiple parts in simulation 10 is divided over three parts. To be able to compare the results with the nourishments as done in simulation 5 in the Midden-Waal and simulation 8 in the Boven-Waal, the length of the parts of the nourishment is chosen to be equal to those nourishments, which is 2 km. Since the total length of the nourishment is 5.5 km, the most downstream part is only 1.5 km in length. Again, the thickness is 0.5 m.

### 3.3.5 Upstream discharge conditions

To determine the sensitivity of the system and the nourishments to discharge variability due to uncertainty in the discharge time series, the development of the bed without future human interventions as well as the development of one nourishment is also analysed under different discharge conditions. To do so, two other discharge time series are selected besides the reference discharge time series:

- SMHM (= same mean, higher maximum): A 50-year discharge time series with approximately the same mean and a higher average yearly maximum than the historical discharge time series;

- HMHM (= higher mean, higher maximum): A 50-year discharge time series with a higher mean and a higher average yearly maximum than the historical discharge time series.

Discharge time series SMHM and HMHM are selected from the same one hundred time series from which the reference discharge time series is selected. As explained in Section 3.2.1, these time series are constructed by bootstrap resampling from the historical discharge time series and their statistics are shown in Table A.3 in Appendix A.2.1. The requirements upon which the discharge scenarios are selected from these one hundred time series are:

- SMHM: Mean: ± 2%. Average yearly maximum: + 9-10%.
- HMHM: Mean: + 5-6%. Average yearly maximum: + 9-10%

Discharge series SMHM is selected directly from the one hundred discharge time series that are generated by bootstrap resampling. Time series 18 (see Table A.3 in Appendix A.2.1) meets the set requirements. None of the hundred generated series meets the requirements as set for discharge series HMHM. The decision is therefore made to alter time series 78, such that three years with lower means and maxima are replaced by years with higher means and maxima. This no longer makes the resampling method truly random, but considering the goal of this study, which is not to do a statistical analysis on the discharge of the Rhine but to investigate the effect of discharge variability on nourishments, this is assumed to be acceptable.

Above approach leads to two selected discharge time series, of which the yearly minimum, mean and average and the percentage difference to the historical discharge time series are shown in Table 3.6.

**Table 3.6:** Average yearly minimum, mean and maximum of each selected discharge time series (2019-2069) and their difference with the historical discharge time series (1994-2020).

| **Discharge time series** | **Avg yearly min.** ($m^3/s$) | **Difference** | **Mean** ($m^3/s$) | **Difference** | **Avg yearly max.** ($m^3/s$) | **Difference** |
|---|---|---|---|---|---|---|
| **Historical** | 1033 | - | 2206 | - | 6425 | - |
| **Reference** | 1038 | +0.5% | 2221 | +0.7% | 6360 | -1.0% |
| **SMHM** | 984 | -4.7% | 2241 | +1.6% | 7022 | +9.3% |
| **HMHM** | 1075 | +4.1% | 2325 | +5.4% | 7014 | +9.2% |

The yearly minimum, mean and maximum of each time series as well as their respective average are shown in Figure 3.8. Plots of the complete discharge time series can be found in Figures A.1 - A.4 in Appendix A.2. Again, it is verified that the differences between the end and start of a hydrological year are smaller than the maximum differences that naturally occur in the historical discharge time series.

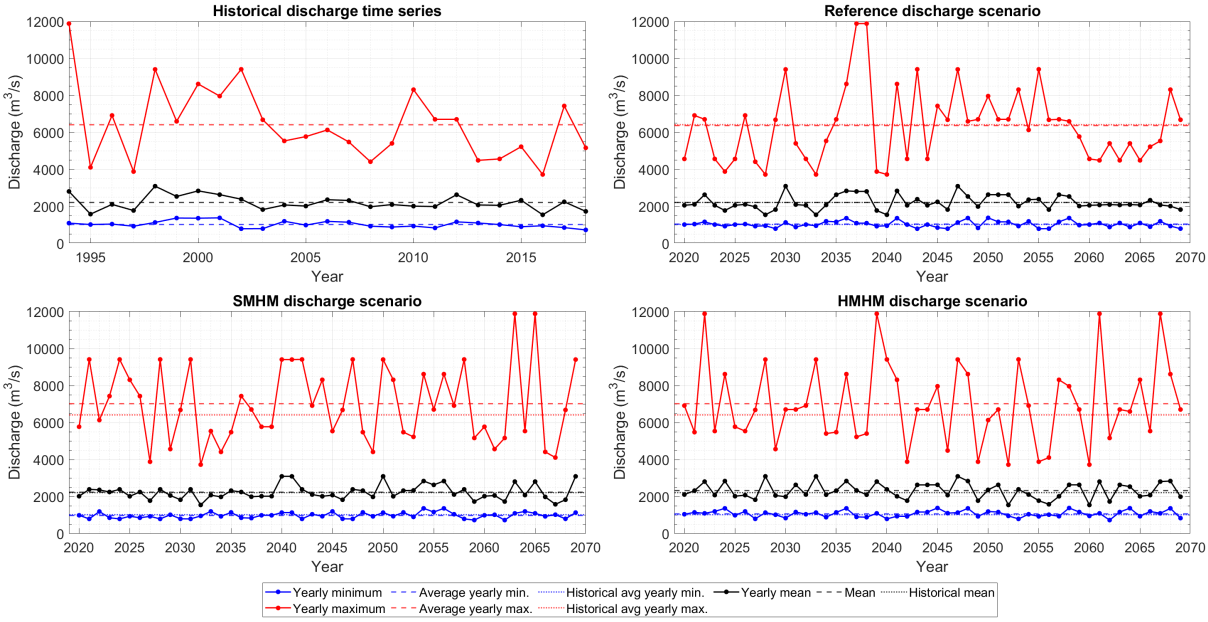


**Figure 3.8:** Yearly and average minimum, mean and maximum discharge of the historical and new discharge time series, as selected from the time series generated by bootstrap resampling from the historical time series.

# 4 Results

In this section, the results of the simulations as described in the methodology are shown, analysed and explained. Section 4.1 shows the development of the bed without future human intervention under the reference discharge conditions and provides an answer to research sub-question 1. In Section 4.2, the results from the various nourishment simulations are discussed and research sub-question 2 is answered. Finally, in Section 4.3, two additional discharge scenarios are imposed to study the development of the bed, as well as the development of a nourishment and compare this to the results under the reference discharge conditions. This answers research sub-question 3.

## 4.1 Development of the bed of the Waal without future human interventions under the reference discharge conditions

Below, the results of the reference simulation under the reference discharge conditions are shown and described. While the model domain includes all Dutch Rhine branches, only the sections relevant to the development in the Waal are discussed here, which are the Rhein, the Boven-Rijn and the Waal itself. The results are compared to the findings of other model studies by e.g. Paarlberg and Van Lente (2021), Welsch (2021) and Rorink (2022); as well as to the observations of the past trends and the predictions of the future bed level change by e.g. Ylla Arbós et al. (2019) and Programma Integraal Riviermanagement (2021).

### 4.1.1 Development of the Rhein and Boven-Rijn

Figure 4.1 shows the development of the bed level of the Rhein, from the upstream boundary of the domain (rkm 815) until Lobith (rkm 862), and the Boven-Rijn, from Lobith (rkm 862) until the Pannerdensche Kop (rkm 867). It is found that the Rhein and Boven-Rijn move to an equilibrium. This can be seen by the bed level stabilising after a certain period. Small variations occur after that, but no significant trend is visible anymore. For the most upstream part, it takes approximately 10-20 years to reach this equilibrium, while it takes approximately 30 years for the downstream part. The same timescale of moving to such an equilibrium is found by Rorink (2022).

The changes in the most upstream 7 km of the Rhein are determined by the boundary conditions. The upstream sediment influx is determined by the flow conditions in the first cell. Since the flow conditions in the first kilometres of the domain are similar to the flow conditions in the most upstream cell, the changes observed here are relatively small. Because the behaviour of this most upstream part is highly influenced by the boundary condition, the behaviour of this section is not necessarily the behaviour that would be observed in reality. It is found that this behaviour is limited to the upstream section of the Rhein, meaning that the effects of the boundary conditions do not travel into the area of interest of this study (the Waal).

The largest part of the Rhein and Boven-Rijn, downstream of rkm 822, shows a degrading trend. This is interrupted by aggradation between rkm 835 and 840. This is attributed to the presence of a side channel in this section. A part of the flow is diverted through the side channel, which leads to lower flow velocities in the main channel. As a consequence, the sediment transport capacity of the flow decreases. This leads to deposition of previously entrained sediments and thus, aggradation. The same behaviour at this location is observed by Rorink (2022).

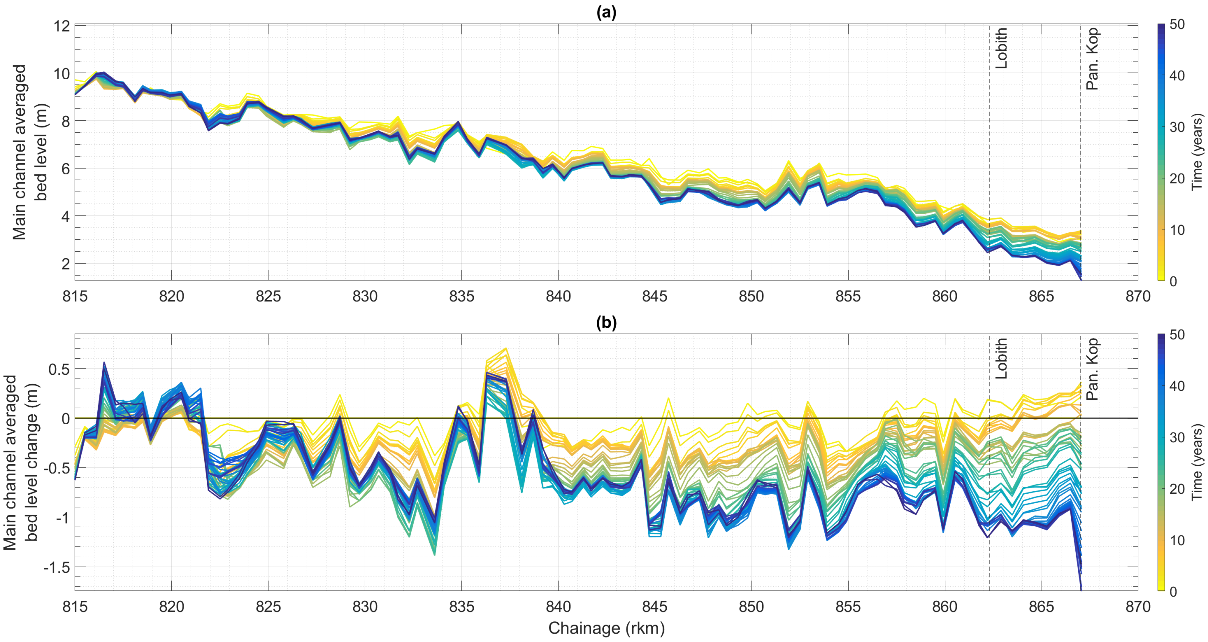


**Figure 4.1:** Main channel averaged bed level (a) and bed level change with respect to the initial bed level (b) in the Rhein and Boven-Rijn in case of development of the bed under the reference discharge conditions without future human intervention.

The bed of the Boven-Rijn, from Lobith (rkm 862) until the Pannerdensche Kop (rkm 867), shows 1.1 m erosion over 50 years. This corresponds to an average degradation rate of 2.2 cm/year. Historical measurements show that while the bed of the Boven-Rijn has degraded in the past, the bed level has been relatively stable over the past two decades (Ylla Arbós et al., 2019). According to Programma Integraal Riviermanagement (2021), experts do not completely agree on the expected behaviour of the Boven-Rijn in the future. It is uncertain whether the Boven-Rijn has already fully adapted to interventions done in the past and has therefore reached an equilibrium or whether the bed will degrade further (Programma Integraal Riviermanagement, 2021). Moreover, the behaviour of the Boven-Rijn is largely dependent on the sediment influx from upstream, so from the German reach of the Rhine. This means that how the river is managed in Germany has a large influence. The Integral River Management (IRM) programme therefore considers two scenarios: one in which the bed level stays relatively stable and one in which there is an erosional trend of 1 cm/year (Programma Integraal Riviermanagement, 2021). Compared to these scenarios, the simulated trend of 2.2 cm/year suggests an overestimation of the anticipated erosional trend.

Another important characteristic of the bed is the sediment composition of the bed surface. The geometric mean grain size of the bed of the Rhein and Boven-Rijn, as well as the change in geometric mean grain size with respect to the initial conditions, is shown in Figure 4.2. The rapid change in geometric mean grain size between year 0 and 1 indicates that the initial sediment composition of the bed surface does not match the composition as expected under the flow conditions and channel geometry that are imposed in the model. This can be explained by the initial conditions that are used in the model. The initial sediment composition of the bed is based on the sediment composition from the model by Sloff (2006), which is based on measurements from 1995. However, the initial bathymetry is based on the situation in 2019

(Chavarrias et al., 2020). The consequences of this discrepancy are discussed in the Discussion in Section 5.1.5.

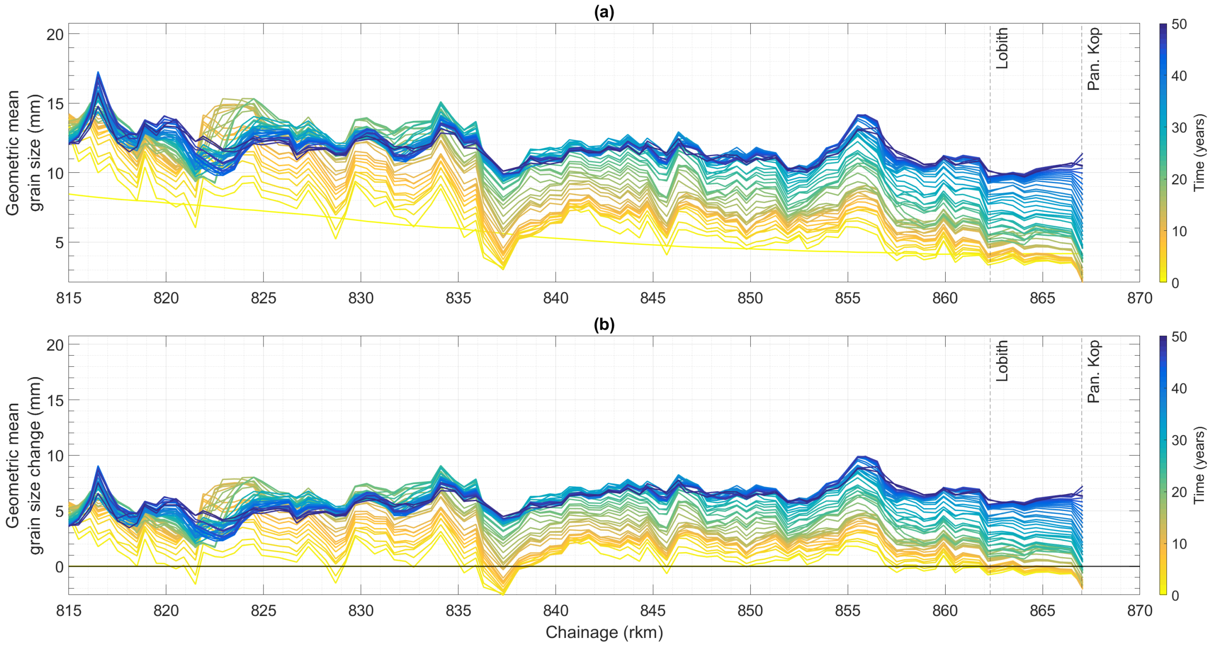


**Figure 4.2:** Geometric mean grain size (a) and geometric mean grain size change with respect to the initial composition (b) in the Rhein and Boven-Rijn in case of development of the bed under the reference discharge conditions without future human intervention.

Figure 4.2 shows that the bed coarsens over the whole reach of the Rhein and Boven-Rijn, from the start of the simulation. Since this coarsening occurs simultaneously over the whole reach from the start of the simulation, this cannot be attributed to the influx of coarser sediment through the upstream boundary, as Paarlberg and Van Lente (2021) also note. The coarsening of the bed is a direct result of the bed degradation that is found in this reach. Since fine sediment is more easily entrained than coarser sediment, fine sediment is transported from the bed surface first, which leads to a coarsening of the bed surface. In reality, an armour layer would form over time, in which the coarser sediment shields the finer sediment in the bed. This reduces the sediment transport. It is expected that the formation of such an armour layer in the model is slowed down because of the use of the active layer concept to model sediment in the bed. This is further discussed in Section 5.1.4.

The sediment transport to the more downstream branches is governed by the sediment influx from the upstream boundary and the sediment transport in the Rhein and Boven-Rijn. When the bed of the Rhein and Boven-Rijn coarsens, that means that sediment is less easily entrained, which decreases the total sediment transport. This is also seen from Figure 4.3, which shows the cumulative and yearly sediment transport: the sediment transport reduces significantly over time. It can therefore be concluded that the degradation of the Rhein and Boven-Rijn leads to a reduction in the sediment transport to the downstream sections of the Rhine, through a coarsening of the bed.

To conclude, the erosion of the bed in the Rhein and Boven-Rijn seems to be overestimated in the simulation. As a consequence of the erosion, the bed surface in this reach coarsens, which leads to a reduction in the sediment transport. This limits the sediment supply to the

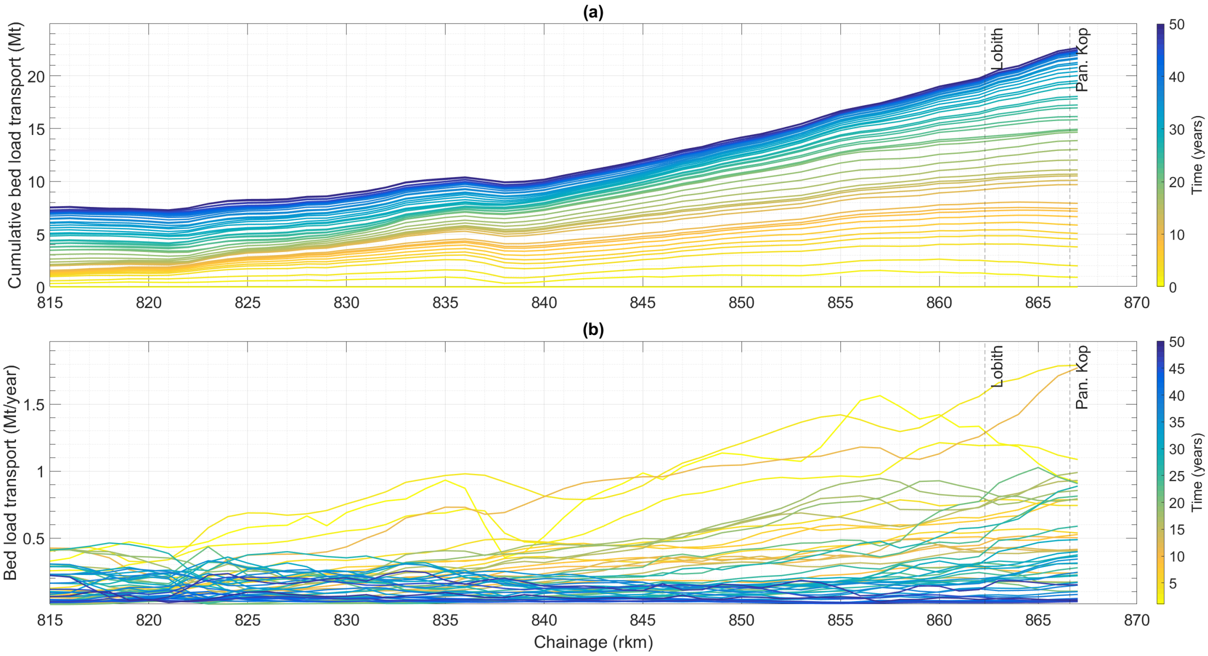


**Figure 4.3:** Cumulative (a) and yearly (b) sediment transport in the Rhein and Boven-Rijn in case of development of the bed under the reference discharge conditions without future human intervention.

downstream branches of the Dutch Rhine. The possible influence of model choices on this behaviour is discussed in Section 5.1.

### 4.1.2 Development of the Waal

The development of the bed level of the Waal under the reference discharge conditions is shown in Figure 4.4. It is immediately seen from Figure 4.4 that the bed slope of the Waal decreases over time: the upstream part, until rkm 915, is eroding, while the downstream part is aggrading. This is in line with observations from the past (Blom, 2016; Barneveld et al., 2020), with predictions of the future behaviour of the bed level of the Waal (Programma Integraal Riviermanagement, 2021) and with results from other modelling studies (Paarlberg and Van Lente, 2021; Rorink, 2022).

Between year 30 and year 50, strong degradation is observed between the Pannerdensche Kop (rkm 867) and Erlecom (rkm 874). In these 20 years, the bed degrades with 11.3 cm/year on average. It is found that after 30 years of simulation, the bed of the Rhein and Boven-Rijn has coarsened so much that the flow can hardly entrain sediment from the bed anymore. That means that the flow that enters the Pannerdensch Kanaal and the Waal carries less sediment than its transport capacity. As a consequence, the erosion wave travels downstream into the Waal and the Pannerdensch Kanaal. Consequently, the bed of the Waal downstream of the Pannerdensche Kop erodes. The same behaviour is observed by Paarlberg and Van Lente (2021) and Rorink (2022).

Predictions on the bed level development by Programma Integraal Riviermanagement (2021) only consider the period from now until 2050. Therefore, the behaviour after 30 years of development that is found in the simulation cannot directly be compared to the predictions

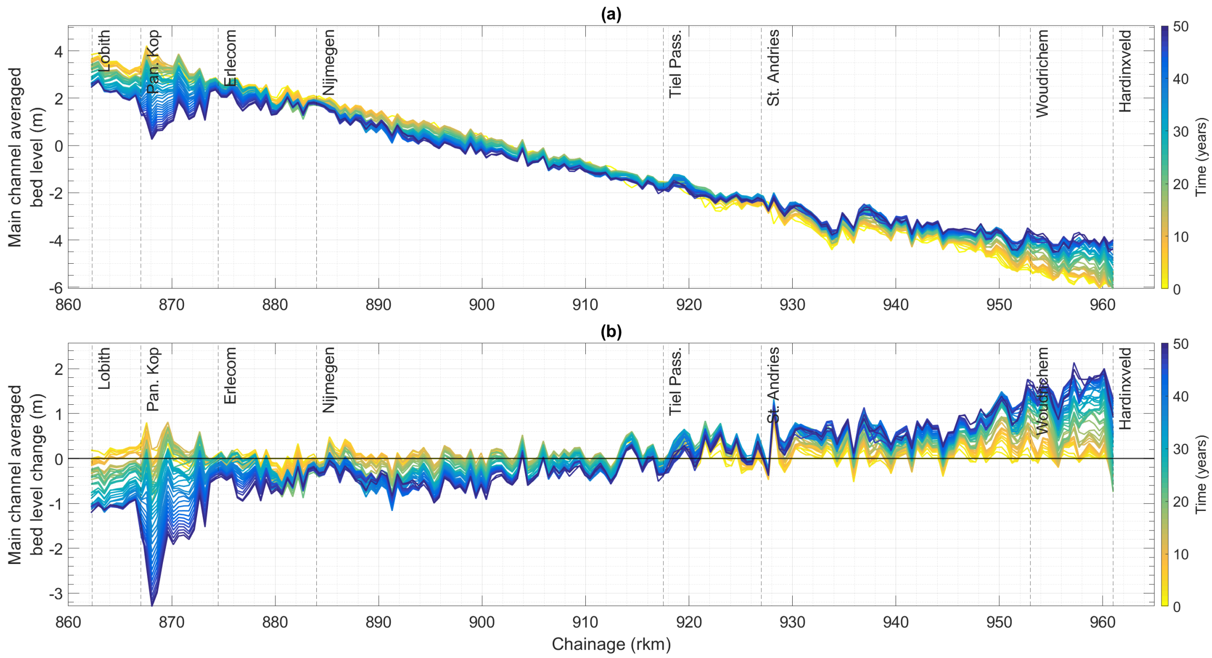


**Figure 4.4:** Main channel averaged bed level (a) and bed level change with respect to the initial bed level (b) in the Boven-Rijn and Waal in case of development of the bed under the reference discharge conditions without future human intervention.

made by Programma Integraal Riviermanagement (2021). However, since the predicted average erosion rate of the Boven-Waal (rkm 867 until 887) by Programma Integraal Riviermanagement (2021) until 2050 is 1.9 cm/year, an average erosion rate of 11.3 cm/year in the 20 years after that is likely an overestimation of the bed degradation.

When looking further downstream in the Boven-Waal in Figure 4.4, it is found that between Erlecom (rkm 874) and Nijmegen (rkm 884), the erosion is less severe. After 50 years, the bed has degraded with 0.6 m on average, or 1.2 cm/year. The bed level evolution between Erlecom and Nijmegen is more in correspondence with the expected bed degradation in the next 30 years of 1.9 cm/year (Programma Integraal Riviermanagement, 2021) than the upstream part of the Boven-Waal. In the studies by Paarlberg and Van Lente (2021) and Rorink (2022), severe degradation is found in this section of the river, but only after more than 50 years of simulation. This is further evidence that the erosional wave travels further downstream through the system over time.

At the locations of the bottom groynes at Erlecom (rkm 873-876) and the fixed layer at Nijmegen (rkm 883-885) and Sint Andries (rkm 925-928), still some erosion is found. In reality, erosion is not possible over such a fixed layer, unless sediment is deposited on the fixed layer which is later eroded again or if the fixed layer is only applied to a part of the river cross-section. The latter is the case in reality at Nijmegen and Sint Andries, but in the model these fixed layers are assumed to be applied over the full width of the main channel. In the model, limited erosion directly over such a fixed layer is possible. The fixed layers are modelled by equalling the thickness of the substrate layers to 0 (Chavarrias et al., 2020). That means that there is still an active layer of 1 m that can erode. The method of modelling of the fixed layers has as a consequence that the simulated elevation at the location of the fixed layers is not necessarily the bed elevation that would occur in the field (Chavarrias et al., 2020). This has to be accounted for when evaluating the modelling results.

The simulations show that the difference in bed level of the Midden-Waal, which reaches from just downstream of Nijmegen (rkm 887) until Tiel-Passewaaij (rkm 917.5), varies from 1.0 m of erosion to 0.2 m of sedimentation over 50 years. The average development rate is approximately 0.6 m of erosion over 50 years, which corresponds to an erosion rate of 1.2 cm/year. Programma Integraal Riviermanagement (2021) assumes an erosion rate of 1.1 cm/year on average. It can therefore be concluded that the bed level development that is found in the simulation is approximately in correspondence with the expectations by Programma Integraal Riviermanagement (2021).

Figure 4.5 shows a quantification of the bed degradation in the degrading section of the Waal (rkm 868-915). This image illustrates the size of the bed degradation problem that is to be solved according to the results of the reference simulation. Figure 4.5a confirms the overall degrading trend in the reach with an average erosion rate over the complete reach of 1.3 cm/year. Figure 4.5b shows that after 50 years, the complete reach from rkm 868-915 except for only 2 km has degraded by more than 0.05 m.

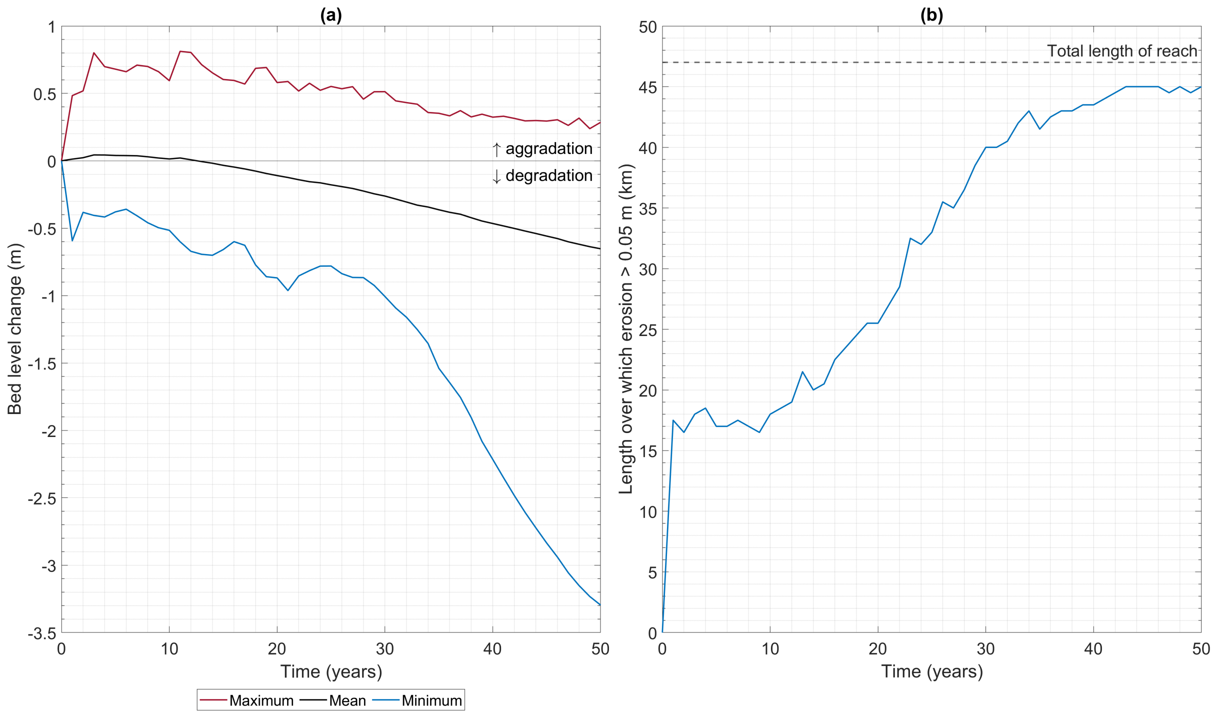


**Figure 4.5:** Summary of the bed level change in the degrading section of the Waal (rkm 868 - 915) as found in the reference simulation: the maximum, mean and minimum change in main channel averaged bed level compared to the initial bed level (a) and the length over which the erosion compared to the initial bed level exceeds 0.05 m (b).

The Beneden-Waal, which reaches from Tiel-Passewaaij (rkm 917.5) until Woudrichem (rkm 953), shows an aggrading trend. The bed level increases up to 1.5 m over 50 years, which corresponds to a sedimentation rate of 3.0 cm/year on average. Programma Integraal Riviermanagement (2021) predicts a much lower sedimentation rate: 0.1 cm/year on average. However, in the predictions by Programma Integraal Riviermanagement (2021), it is assumed that the dredging works in this section are continued. These dredging works are not included in this model, meaning that the simulated bed level is higher than the bed level that would have been expected in reality.

Figure 4.6 shows the geometric mean grain size (a) and the change in geometric mean grain size with respect to the initial conditions (b) of the Boven-Rijn and Waal. The changes in the geometric mean grain size in the Waal in both space and time are relatively small, compared to the changes in the Rhein and Boven-Rijn. Overall, the geometric mean grain size of the bed surface of the Waal decreases in downstream direction and the bed surface generally coarsens over time.

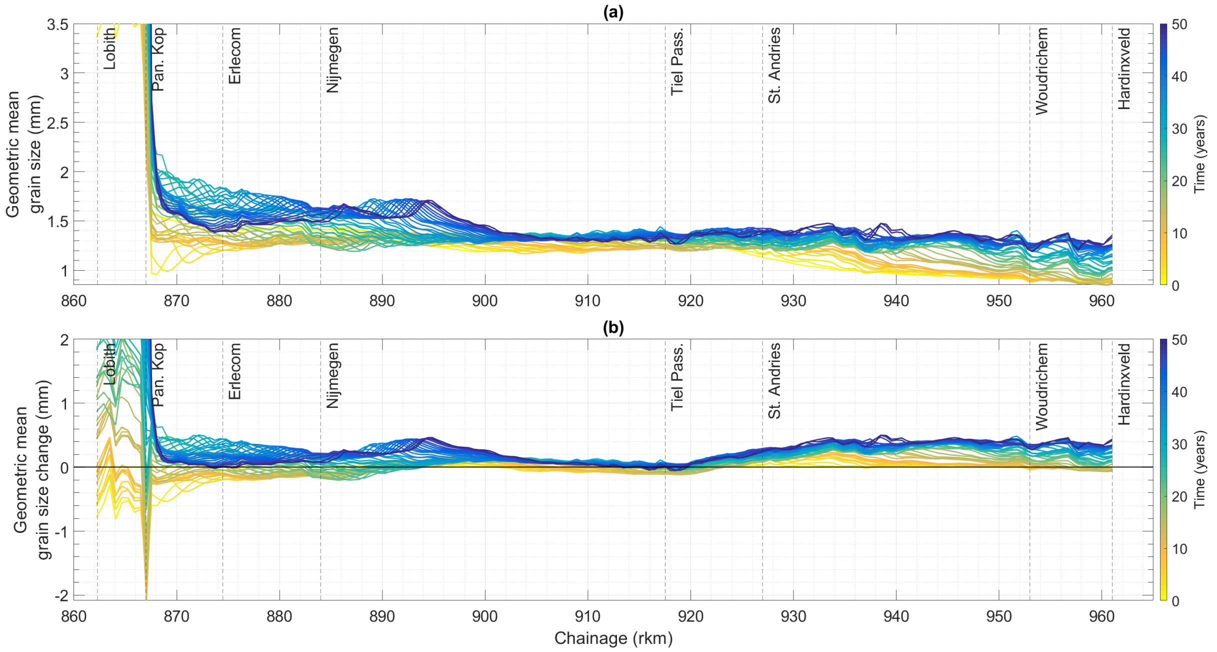


**Figure 4.6:** Geometric mean grain size (a) and geometric mean grain size change with respect to the initial composition (b) in the Boven-Rijn and Waal in case of development of the bed under the reference discharge conditions without future human intervention.

It is found that the difference in grain size between the Boven-Rijn and the Waal increases over time, which is mostly caused by the strong coarsening of the Boven-Rijn. While the geometric mean grain size of the Boven-Rijn is in the gravel range (> 2 mm) after approximately 20 years, the geometric mean grain size of the Boven-Waal remains in the sand range (< 2 mm). It can therefore be concluded that the gravel-sand transition (GST) zone is located around the bifurcation point at the Pannerdensche Kop (rkm 867) at the end of the simulation. Ylla Arbós et al. (2021) conclude from measurements that the GST becomes less abrupt. Therefore, the findings here are not in correspondence with this conclusion. In their 100 year simulations, Paarlberg and Van Lente (2021) also observe these abrupt changes in the first 50 years of the simulation, but they do observe a decrease in abruptness of the change after 50 years of simulation. It is uncertain whether the changes observed here are realistic or if they may be caused by the choice for the initial sediment composition. This is further discussed in Section 5.1.

In general, the bed of the Waal coarsens over time. In the Boven-Waal and Midden-Waal, this is caused by the degradation of the bed, in which the fine sediment is transported before coarser sediment. Moreover, exchange of sediment may exist between the flow and the bed. Sediment that is transported from upstream is coarser because the bed of the Rhein and Boven-Rijn is much coarser than the bed of the Waal. As the flow enters the Waal, its transport capacity decreases because a part of the flow is diverted to the Pannerdensch Kanaal. The nodal-point relation as shown in Equation 12 in Appendix A.1 confirms that indeed proportionally more sediment than water is diverted to the Waal. Therefore, sediment from the flow may be deposited in the upstream section of the Waal. As the transported sediment is coarser than the bed, this enhances the coarsening of the bed. In the Beneden-Waal, sediment is deposited, causing aggradation. Since the sediment is transported from a coarser part of the river, this also leads to an increase in the geometric mean grain size.

In the most upstream section of the Waal, between the Pannerdensche Kop (rkm 867) and Nijmegen (rkm 884), the geometric mean grain size of the bed surface increases until year 30 but then decreases in year 30 until 50. This is the period in which strong degradation occurs in the section from the Pannerdensche Kop and Erlecom. It is thought that this is related to the use of the active layer concept, in which the active layer is replenished from the substrate layers. The substrate layers have the same initial sediment composition as the initial composition of the bed surface and the composition of the lower substrate layers does not change because almost no sedimentation occurs in this reach throughout the simulation period. As a consequence, the geometric mean grain size decreases towards its initial value. Analysis of the thickness of the substrate layers indeed shows that substrate layers 1 until 3 are already empty at year 30 and substrate layer 4 until 9 are completely emptied between year 30 and 50. As the section between the Pannerdensche Kop and Erlecom becomes finer and sediment is eroded from this reach, the finer sediment is also transported downstream, which explains the fining of the section between Erlecom and Nijmegen in years 30 until 50 of the simulation. The use of the active layer concept is further discussed in Section 5.1.

Figure 4.7 shows the cumulative and yearly sediment transport in the Boven-Rijn and Waal. It is found that the sediment transport increases in downstream direction in the Boven-Waal and Midden-Waal, while it decreases in downstream direction in the Beneden-Waal. This explains the degradation in the first section and aggradation in the latter. Over time, the longitudinal differences in sediment transport decrease, which is related to the decrease in bed slope. As the bed slope decreases and the grain size increases, the yearly sediment transport also reduces. The fluctuations in the sediment transport over time are mainly attributed to the variable discharge that flows through the system.

### 4.1.3 Conclusion research sub-question 1

The research question that is answered by the analysis of these results is "*How do the bed level and sediment composition of the Waal develop over the next 50 years, without human interference?*".

It is concluded that the sediment influx to the Waal is governed by the behaviour of the Rhein and Boven-Rijn. In the first 30 years of the simulation, these branches erode significantly, which is paired with a coarsening of the bed. As a consequence, the sediment influx to the Waal is limited.

The Waal adapts to the deficit in incoming sediment transport by decreasing its bed slope. As a consequence, the Boven-Waal and Midden-Waal show degradation, while the Beneden-Waal aggrades. After 30 years, significant erosion of 11.3 cm/year is observed between the Pannerdensche Kop and Erlecom. This does not travel further downstream within the simulation period of 50 years. The remaining part of the Boven-Waal degrades with an average rate of 1.2

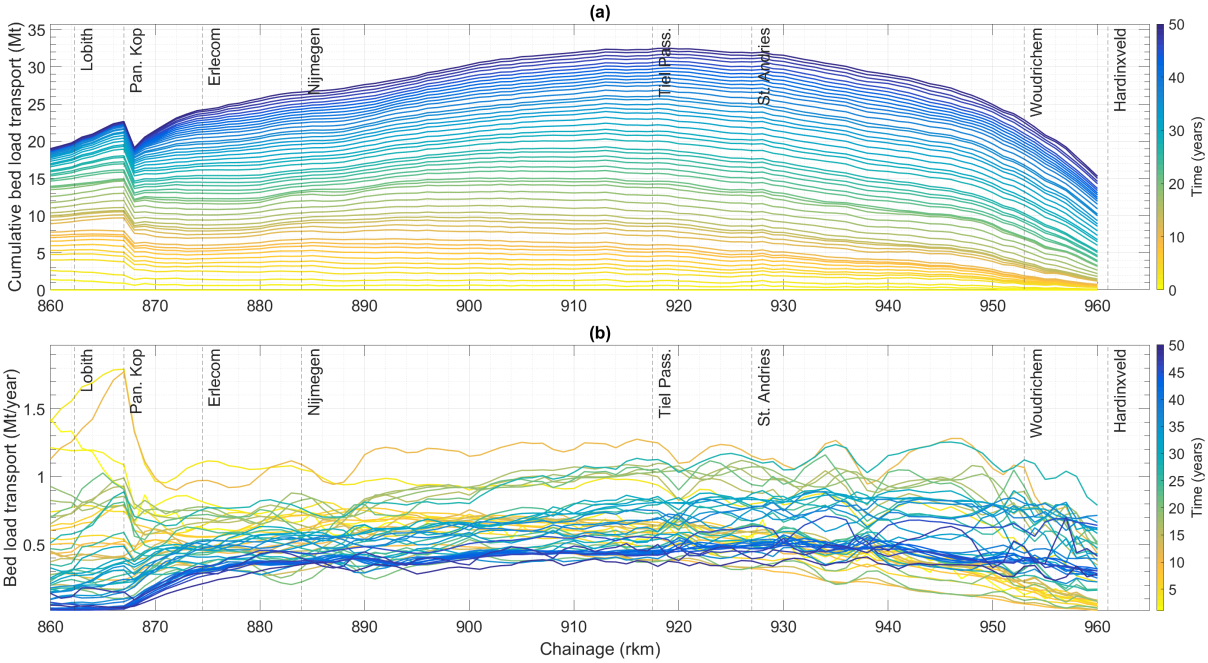


**Figure 4.7:** Cumulative (a) and yearly (b) sediment transport in the Boven-Rijn and Waal in case of development of the bed under the reference discharge conditions without future human intervention.

cm/year. The Midden-Waal shows an erosion rate of 1.2 cm/year on average, while the bed level of the Beneden-Waal increases with an average of 3.0 cm/year. It must be noted that dredging activities that currently take place in the Beneden-Waal are not included in the model.

The geometric mean grain size of the bed surface of the Waal decreases in downstream direction. Overall, the geometric mean grain size increases over time. However, the bed surface of the Waal remains much finer than the bed surface of the Boven-Rijn during the 50-year simulation period. Finally, the sediment transport increases in downstream direction until the Beneden-Waal is reached, in which the sediment transport decreases in downstream direction. Over time, the sediment transport reduces as a consequence of the reduction of the bed slope and the coarsening of the bed.

## 4.2 Effects of nourishments on the development of the bed of the Waal

In this section, the results of the simulations which are made to answer the research sub-question "*What are the morphological effects of nourishments of varying grain sizes, locations, nourishment distributions and volumes in the Waal?*" are presented. The simulations include various nourishments under the reference discharge conditions. Section 4.2.1 discusses the results from the simulations with a singular nourishment in the Midden-Waal with a composition equal to the bed surface and a composition that is coarser. These serve to analyse the effect of a nourishment in general and the effect of a varying sediment composition of the nourishment. In Section 4.2.2, the results from the simulation with a singular nourishment in the Boven-Waal is presented to determine the effects of a different nourishment location. Next, Section 4.2.3 shows the effect of distributing a nourishment in the Midden-Waal into respectively two and four smaller parts to determine the effect of the nourishment distribution. Additionally, the effect of a larger nourishment volume is shown in Section 4.2.4, which also provides more information on the effect of the nourishment distribution by dividing the nourishment into multiple parts. In Section 4.2.5, an overall comparison is made of the effects of the various nourishments that are considered. Finally, the chapter is concluded in Section 4.2.6 by answering the research sub-question.

### 4.2.1 General effects of a nourishment and the effect of the sediment composition

To determine the effect of a nourishment with a varying sediment composition on the development of the bed of the Waal, two simulations are done. Both simulations include a nourishment that is implemented at the start of the simulation between rkm 889 and 891. The first simulation includes a nourishment with a composition that is equal to the bed, while in the second simulation a nourishment is implemented with a coarser composition than the bed. From here on, these nourishments are referred to as the 'area-specific nourishment' and the 'coarse nourishment', respectively. The effects of the nourishments are evaluated by comparing the bed level and sediment composition of the bed in the nourishment simulations to the bed as simulated in the reference simulation, as described in Section 4.1. Figures showing the bed level development without comparison to the reference simulation are included in Appendix C.1.1 & C.1.2.

Figures 4.8 & 4.9 show the difference in bed level between the simulation with the area-specific (Figure 4.8) and coarse (Figure 4.9) nourishment and the reference simulation. The nourishment is present at the start of the simulation, as is seen from the difference in bed elevation of 0.5 m between rkm 889 and 891 at the start of the simulation (year 0).

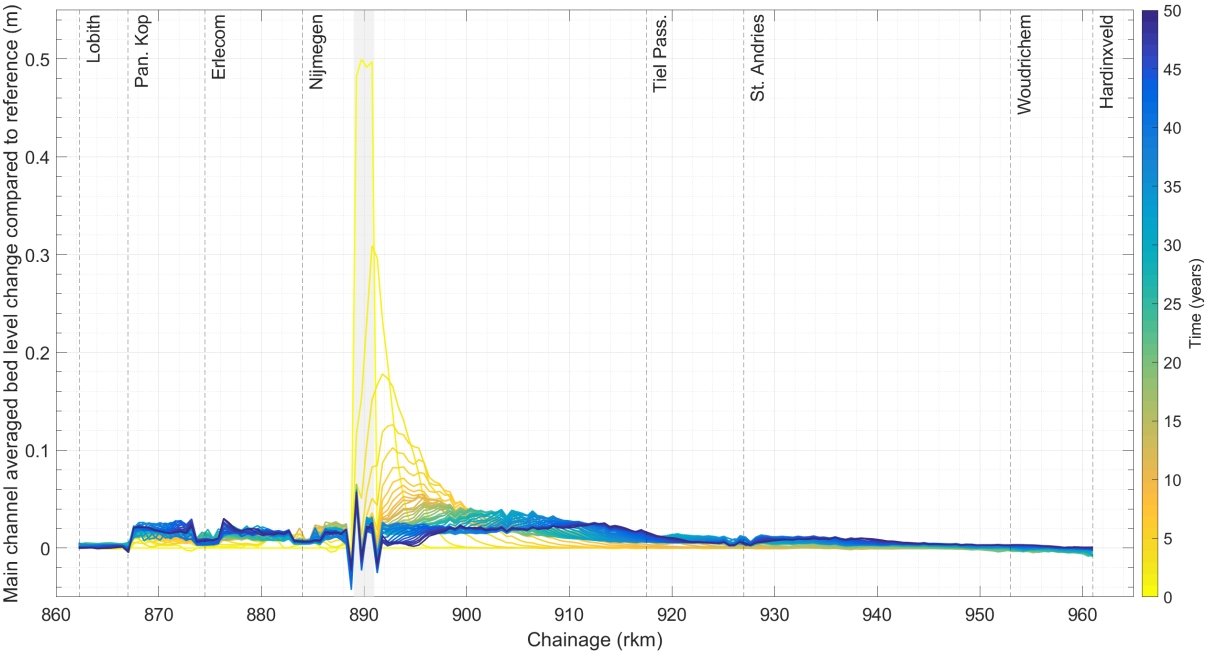


**Figure 4.8:** Difference in bed level in the Boven-Rijn and Waal between the simulation with an area-specific nourishment and the reference simulation.

The 'spike'-pattern that is seen at the location of the nourishments (rkm 889-891) in Figures 4.8 & 4.9 throughout the simulation is an artefact that is likely caused by the way at which the nourishments are implemented in the model. The peaks and troughs of the spikes each correspond to a location at which a cross-section is defined. By altering the cross-sections to implement the nourishments, the transition between the cross-sections is no longer as smooth as it used to be. It must be noted that while the pattern is also there when looking at the

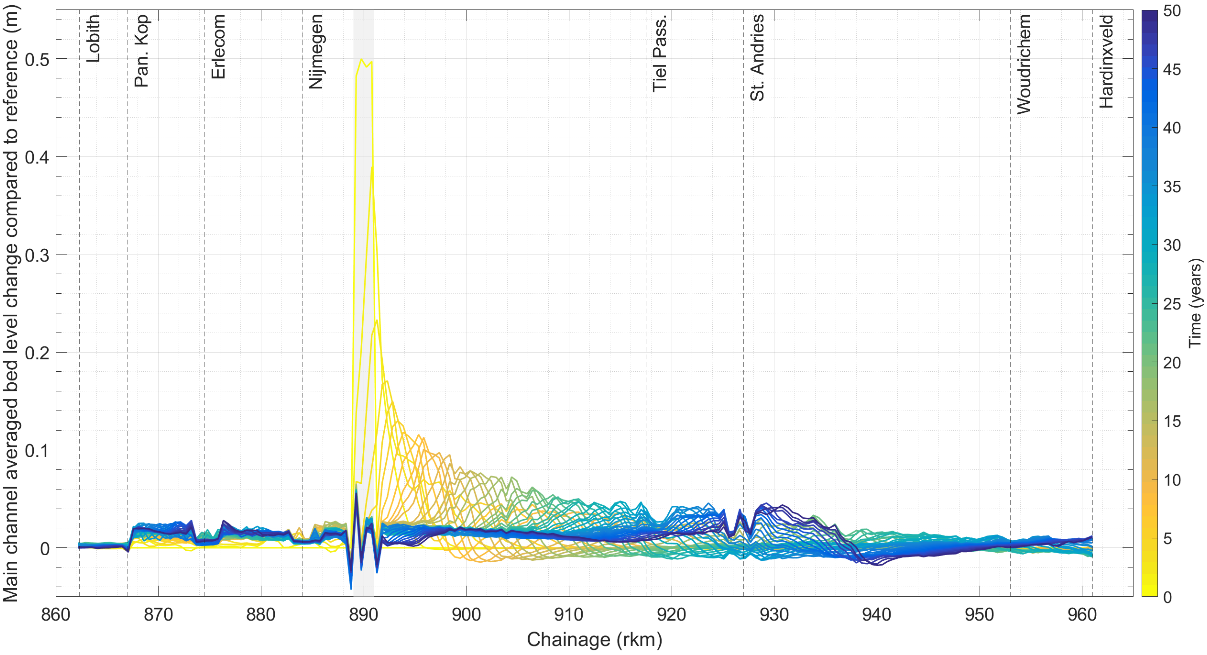


**Figure 4.9:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a coarse nourishment and the reference simulation.

bed level itself (see Figure C.1 in Appendix C.1.1 and Figure C.3 in Appendix C.1.2) instead of the difference in bed level compared to the reference situation, the pattern is less evident. The reduction in smoothness between the cross-sections may cause some numerical friction in the model, but it is assumed that this effect is negligible.

After the initial implementation of the nourishment, the sediment hump is transported downstream through advection. Moreover, the nourishment decreases in height and increases in length through diffusion. Because of the drawdown effects over the nourishment, the downstream part of the nourishment travels faster than the upstream part of the nourishment. At the location of the nourishment, the bed is elevated, which initially increases the equilibrium water level. Since the water level downstream of the nourishment is lower, an M2 drawdown curve forms over the nourishment. Consequently, the water depth decreases over the nourishment in downstream direction. By conservation of mass, the flow velocity then increases, which increases the sediment transport capacity of the flow. Consequently, the flow can transport more sediment at the downstream side of the nourishment. To facilitate a better analysis of the movement of the nourishment through the system, Figures 4.10 & 4.11 presents the information from Figures 4.8 & 4.9 in a plot with space on the x-axis and time on the y-axis. The bed level difference compared to the reference simulation is indicated by the colour.

It is found that the nourishments travel downstream at different propagation speeds. The area-specific nourishment disperses into the shape of a plume. While the effect of the area-specific nourishment on the bed level (Figure 4.10) after 50 years of simulation is largest upstream of rkm 920, the middle of the nourishment is located around rkm 940 after 40 years. The middle of the nourishment therefore travels a distance of approximately 50 km over 50 years. This corresponds to an average propagation speed of 1 km/year. This value is an expected value for the Waal, based on observations (Sloff, 2006) and findings from other modelling studies (e.g. Paarlberg and Van Lente, 2021; Welsch, 2021; Czapiga et al., 2022). Moreover, the model was

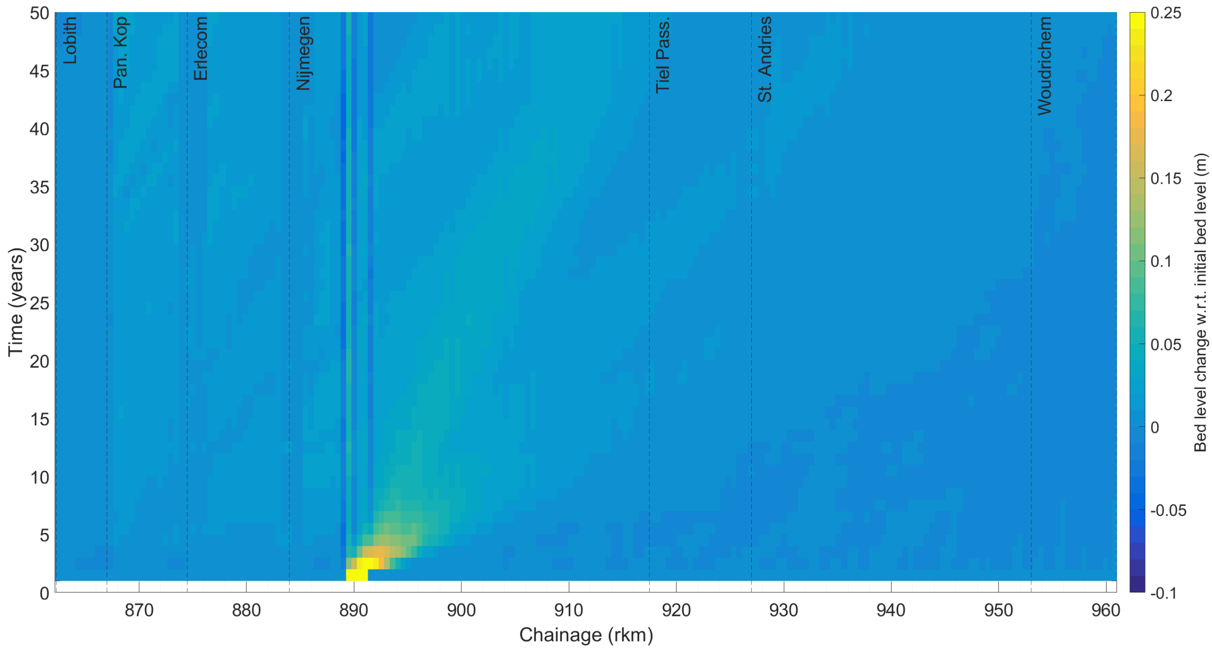


**Figure 4.10:** Difference in bed level in the Boven-Rijn and Waal between the simulation with an area-specific nourishment and the reference simulation. The large differences in the first years of the simulation are capped off.

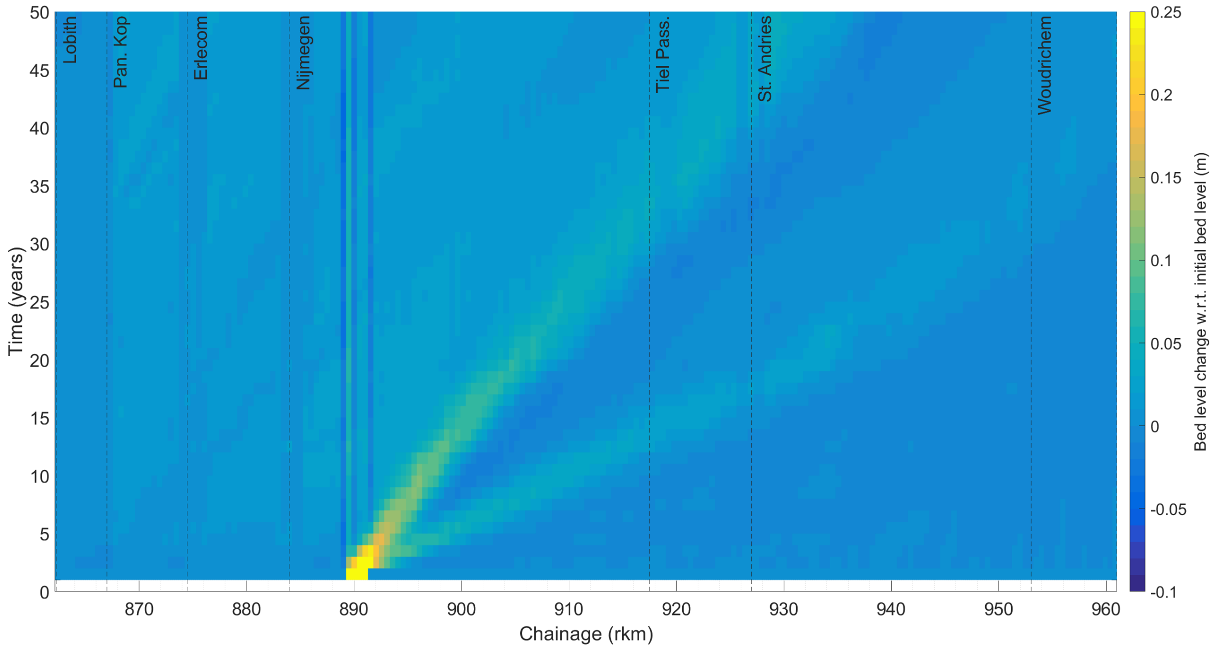


**Figure 4.11:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a coarse nourishment and the reference simulation. The large differences in the first years of the simulation are capped off.

calibrated such that perturbations travel through the system at this rate (Chavarrias et al., 2020). Since the area-specific nourishment is merely an elevation of the bed, because it has the same composition as the bed, the nourishment should indeed behave as a regular perturbation travelling through the system.

While the area-specific nourishment disperses into the shape of a plume, the coarse nourishment shows a distinct division into two parts: one part travelling until rkm 935 in 50 years and one part that leaves the system through its downstream end (at rkm 962) after approximately 40 years. The part that travels approximately 45 km in 50 years has an average propagation speed of 0.9 km/year. Since this nourishment consists of coarser, less mobile sediment than the area-specific nourishment, the nourishment propagates and disperses at a slower rate. The reduced mobility of the sediment also explains why the nourishment maintains its height for a longer period. After 5 years, the maximum height of the coarse nourishment is still 26% of its original height, while the fine nourishment reduces to 16% of its original height in 5 years. The part of the nourishment that travels from rkm 890 in year 1 to rkm 960 in year 40 and then travels out of the domain at the downstream boundary has an average propagation speed of approximately 1.8 km/year. This is likely the finer sediment in the nourishment that is being transported downstream.

It is thought that the clear distinction between the two yellow patterns in Figure 4.11 is a result of the way sediment transport is modelled. In reality, sediment consists of a continuous range of grain sizes, but in this model, there are 16 fractions with each a specific grain size. Furthermore, a distinction has been made between sand and gravel particles and for each type, a different transport formula is used. This may cause both sediment types to behave differently. Since there is only one sand fraction in the coarse nourishment and the rest of the nourishment is made up of gravel, this explains the distinct division for the coarse nourishment. This way of calculating sediment transport and its possible effect on the results is further discussed in the Discussion in Section 5.1.4. It is expected that in reality, the area between the two yellow patterns as seen in Figure 4.11 would also be an area in which a reduction in erosion is found, forming a band rather than two distinct lines.

Upstream of the nourishments, a reduction in erosion occurs. This can be seen from Figures 4.8 & 4.9, which show a positive change in bed level compared to the reference simulation in a reach that is found to have a degrading trend. This is caused by the backwater effect upstream of the nourishment. Since the bed is elevated at the location of the nourishment, the water level is raised. This induces an M1 backwater curve upstream of the nourishment, meaning that the water level is raised compared to the reference situation even though the bed level is not. Consequently, the water depth increases, which decreases flow velocities. Since the flow velocity is reduced, the flow can transport less sediment. This causes a decrease in the erosion rate. The upstream reduction in erosion caused by the two different nourishments is approximately equal. The maximum reduction in erosion upstream of the nourishment is in both cases approximately 2.5 cm.

While the area-specific nourishment induces an increase in bed level with respect to the reference simulation throughout the whole reach, the coarse nourishment also locally induces a decrease in bed level with respect to the reference simulation. Downstream of the nourishment, additional erosion occurs. This is an expected but unwanted effect in an already degrading reach. However, this effect is relatively small: the maximum additional erosion is 1.8 cm. The additional erosion occurs because the nourished sediment is coarser than the original bed surface and it therefore causes the sediment of the bed to be less mobile. This causes sedimentation at the upstream end of the nourishment and erosion at the downstream end of the nourishment (Czapiga et al., 2022). This is enhanced by the increased roughness of the bed caused by the nourishment. Skin friction scales linearly with a representative value for the coarse fractions in the surface layer of the bed (e.g. $D_{90}$) (Parker, 1991; Czapiga et al., 2022). Consequently, increased roughness induces an increase in water level. Therefore, over the section with coarse sediment, the water level is raised and just like in the case where the bed level is elevated in a specific section, backwater curves form upstream and downstream. As a consequence, a reduction of erosion occurs upstream of the coarse section and additional erosion occurs downstream of the coarse section. This erosional wave moves through the system at approximately the same rate as the nourishment.

In the reference simulation, the trend in the development of the bed level shifts from degrading to aggrading around rkm 915. After approximately 10 years, the downstream parts of the nourishments travel into the aggrading part of the river. When they do so, they contribute to additional sedimentation in an already aggrading reach. This may increase the required dredging efforts to maintain a navigable main channel. Especially at the location of the fixed layer at St. Andries, which is currently already the second shallowest part of the river during low discharges after the fixed layer at Nijmegen (Programma Integraal Riviermanagement, 2021), this may pose problems. The area-specific nourishment induces maximum additional sedimentation of 1.8 cm, while the coarse nourishment increases sedimentation by 4.6 cm at maximum. Again, this is caused by the coarse nourishment maintaining its height for a longer period.

Because downstream of the coarse nourishment additional erosion occurs, the coarse nourishment also reduces sedimentation locally in the aggrading reach. This effect is however relatively small: the maximum reduction of sedimentation is 1.8 cm. Considering the rate of sedimentation, this is assumed to form no problem and it may even reduce required dredging operations.

To facilitate the analysis of the effect of the nourishments on the mean grain size in the Boven-Rijn and Waal, Figures 4.12 & 4.13 are presented. These figures show the difference in the geometric mean grain size between the simulation with the area-specific (Figure 4.12) and the coarse (Figure 4.13) nourishment and the reference simulation in the Boven-Rijn and Waal.

As expected, the difference in mean grain size that the area-specific nourishment induces is relatively small. The area-specific nourishment induces a difference in mean grain size of $\pm$ 0.04 mm at maximum, while the coarse nourishment induces differences of up to 3.3 mm. Since the area-specific nourishment consists of the same composition as the bed, the differences in mean grain size are only caused by changes in deposition and erosion patterns. While a pattern appears to be present in Figure 4.12, this is merely a shift in the pattern of fining and coarsening that is already present in the system. Especially since the uncertainty in the calculation of the sediment composition is large, the changes in grain size with respect to the reference situation as calculated in this simulation are negligible. The changes as calculated here are expected to have no significant influence on the behaviour of the system.

The coarse nourishment does significantly influence the mean grain size in a part of the Waal. Since the nourishment is coarser than the original composition of the bed, downstream translation and dispersion of the nourishment causes a coarsening wave through the system. The difference in grain size with respect to the reference simulation is mostly restricted to the area over which the nourishment travels. This contradicts the findings by Czapiga et al. (2022). They argue that since deposition occurs upstream of a nourished reach and since the sediment that is transported as bed load is finer than the sediment on the bed, surface fining should occur

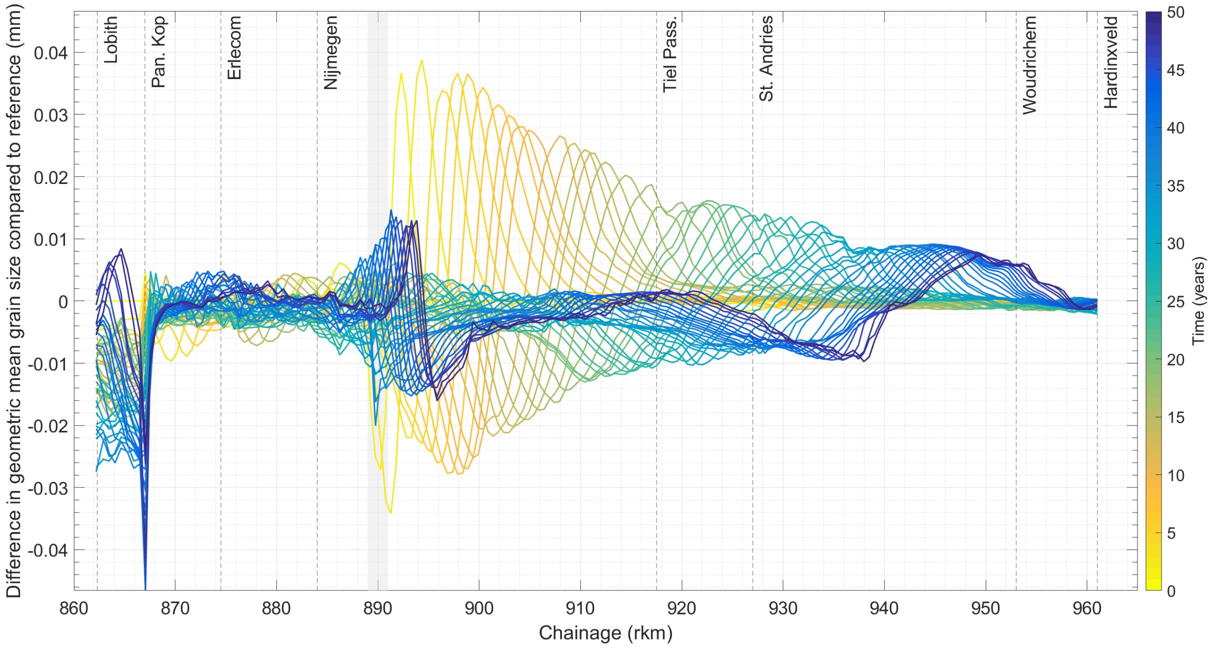


**Figure 4.12:** Difference in the geometric mean grain size in the Boven-Rijn and Waal between the simulation with a nourishment with an area-specific nourishment and the reference simulation.

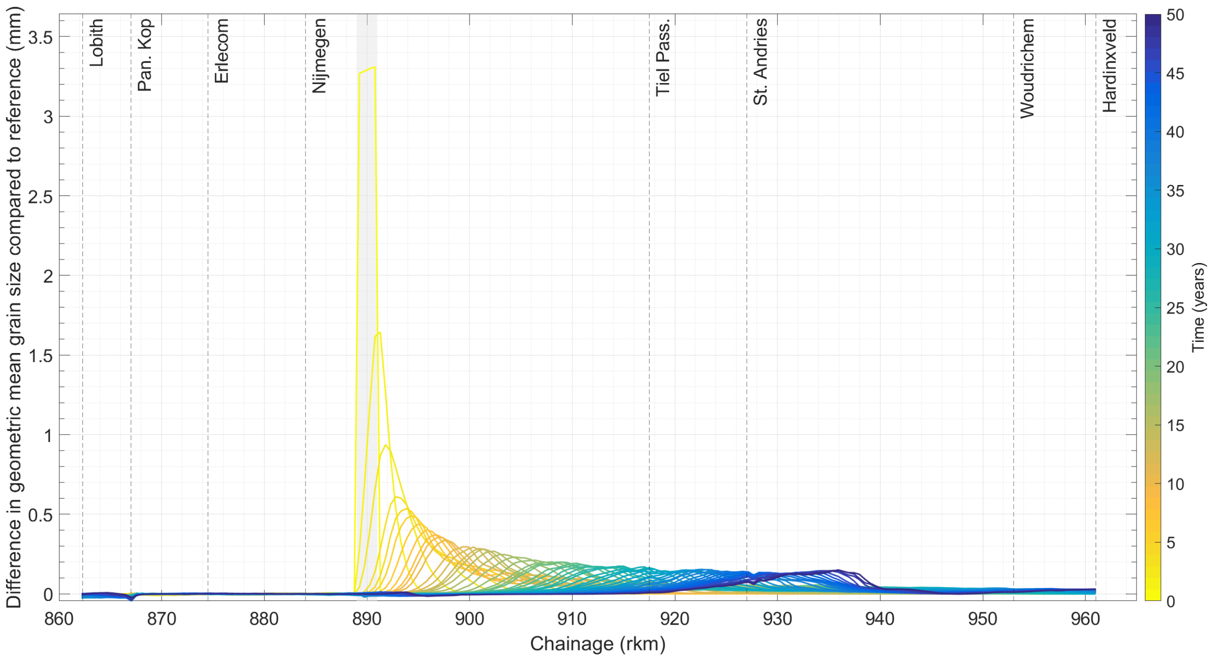


**Figure 4.13:** Difference in the geometric mean grain size in the Boven-Rijn and Waal between the simulation with a coarse nourishment and the reference simulation.

upstream of the nourished reach. However, the reduction of erosion that is caused here is small in comparison to the active layer thickness (1 m) and the reduction in grain size that would be induced is also small. Therefore, these effects are not visible here.

The nourishments add sediment to the system which is thereafter transported downstream. It is therefore expected that the nourishments influence the sediment transport in the Waal. The volume of the nourishments has been chosen such that it corresponds to approximately 100% of the yearly sediment transport at the location of the nourishment in the reference simulation. Figures 4.14 & 4.15 show the influence of the nourishments on the sediment transport in the Waal. It is found that upstream of the nourishment location, the sediment transport decreases, which explains the reduction of erosion induced by the nourishments in that section. Downstream of the original nourishment location, the volume of sediment that is transported is increased because of the additional sediment volume of the nourishment that travels downstream.

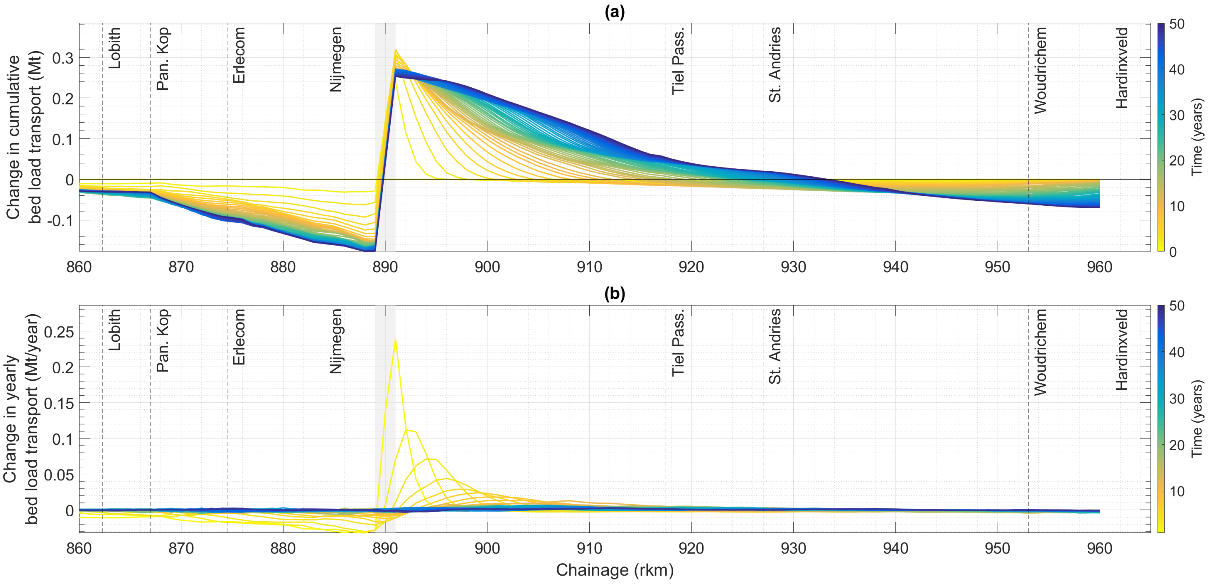


**Figure 4.14:** Difference in cumulative (top) and yearly (bottom) sediment transport in the Boven-Rijn and Waal between the simulation with an area-specific nourishment and the reference simulation.

The largest difference in yearly sediment transport with respect to the reference situation is found at rkm 891 (i.e. at the downstream end of the nourishment) in the first year of the simulations. The difference in sediment transport for the area-specific nourishment in the first year is 0.24 Mt. In the reference simulation, the yearly sediment transport averages to 0.47 Mt/year over 50 years at that location. That means that the nourishment increases the sediment load by more than 50% in the first year after the nourishment is placed. It is also seen that the effect of the nourishment on the sediment transport decreases significantly in the first 10 years after nourishing and becomes negligible after approximately 15-20 years. The difference in sediment transport in the first years after the nourishment is smaller in the case of a coarse nourishment, since the sediment is less easily entrained. The additional sediment transport in the first year is 0.19 Mt, which is approximately 40% of the original yearly sediment transport.

To conclude, it is shown that implementing a nourishment in the Midden-Waal can reduce erosion in a section of the river that is larger than the original length of the nourishment. A nourishment with a composition that is equal to the bed induces sedimentation both upstream of the nourishment through its backwater effect and downstream of the original nourishment

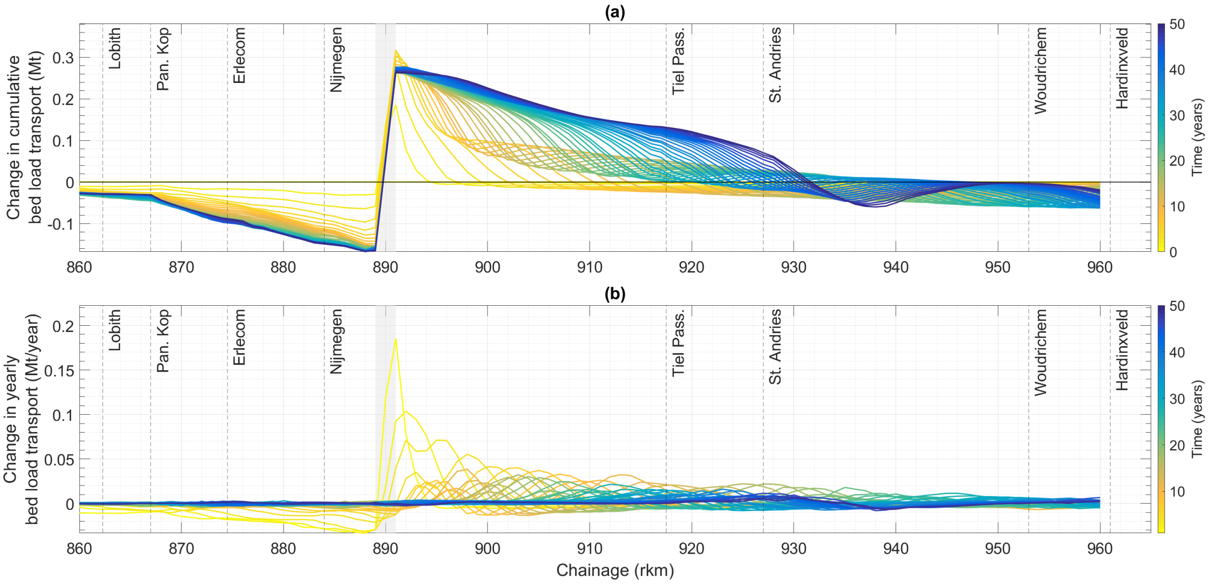


**Figure 4.15:** Difference in cumulative (top) and yearly (bottom) sediment transport in the Boven-Rijn and Waal between the simulation with a coarse nourishment and the reference simulation.

location through the downstream translation of the nourishment itself. When the sediment composition of the nourishment is coarser than the bed, the nourishment disperses slower. Moreover, it leads locally to reduced mobility of the bed, which leads to additional erosion downstream of the nourishment, in addition to the sedimentation caused by the nourishment.

### 4.2.2 Effect of the nourishment location

The previous nourishments are located in the Midden-Waal. In this simulation, a nourishment is applied in the Boven-Waal. The location is applied between rkm 878 and 880, in between the fixed layer at Erlecom and the fixed layer at Nijmegen. The nourishment has the same volume and sediment composition as the coarse nourishment in the Midden-Waal. Figures showing the bed level development without comparison to the reference simulation are included in Appendix C.1.3.

The difference in bed level between the simulation with a coarse nourishment in the Boven-Waal and the reference simulation is shown in Figure 4.16. The maximum bed level difference caused by the nourishment decreases from 50 cm when the nourishment is implemented to 4.7 cm after 50 years. This is similar to the decrease in difference in bed level that is found in the case of the coarse nourishment in the Midden-Waal (from 50 cm to 4.6 cm).

To enable a better analysis of the propagation of the nourished sediment hump, Figure 4.17 shows the information from Figure 4.16 in a time-space plot with colours indicating the bed level difference. Like for the nourishment in the Midden-Waal, it is found that the nourishment is distributed in two parts. The main part travels with a propagation speed of approximately 0.8 km/year. The second part travels faster: until the end of the domain within 50 years, which corresponds to a propagation speed of approximately 1.6 km/year. These propagation speeds are lower than the propagation speeds that are found for the nourishment in the Midden-Waal: 0.9 km/year and 1.8 km/year, respectively. Since the sediment composition of both nourishments

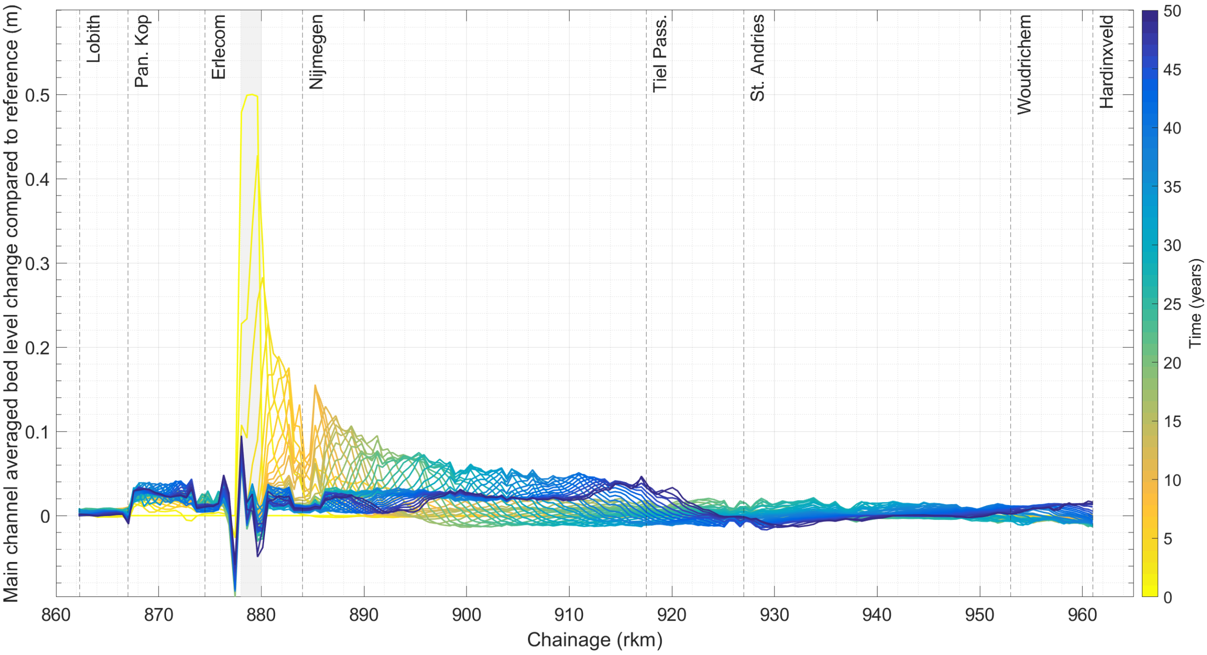


**Figure 4.16:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a nourishment in the Boven-Waal and the reference simulation.

is equal, this cannot directly be related to the sediment composition of the nourishment. It is expected that this is related to the sediment composition of the bed surface the nourishment is placed on. The Boven-Waal is coarser than the Midden-Waal, meaning that the initial composition of the substrate layers beneath the nourishment is also coarser. When a part of the nourishment is transported, the active layer is replenished with relatively coarser sediment. Since coarser sediment is less mobile, this affects the propagation speed of the nourishment.

Since this nourishment is located further upstream, it travels directly over the fixed layer at Nijmegen (rkm 883-885). It is readily seen that the nourishment is influenced by the presence of the fixed layer. From the way the fixed layer is modelled, it is known that the elevation of the bed over the fixed layer itself does not necessarily match the elevation that would occur in the field (Chavarrias et al., 2020). However, the essential morphodynamic development and thus the sediment transport over the fixed layer should be captured. When looking at Figure 4.17, this indeed seems to be true. While the bed elevation over the fixed layer is lower, the sediment is transported over the fixed layer at the same propagation speed as upstream and downstream of the fixed layer.

Figure 4.18 directly compares the effect of the nourishments in the Midden-Waal and Boven-Waal on the bed level difference compared to the reference simulation. As anticipated, the main differences in the effect caused by the nourishments are directly related to their initial location.

When starting the analysis of Figure 4.18 upstream, it is firstly found that the nourishment in the Boven-Waal causes a larger reduction of erosion in the section between the Pannerdensche Kop and Erlecom than the nourishment in the Midden-Waal. The difference is approximately a factor 1.5 after 5 years, which remains approximately the same throughout the simulation. The maximum reduction in erosion upstream of the nourishment caused by the nourishment in the Boven-Waal is 4.0 cm.

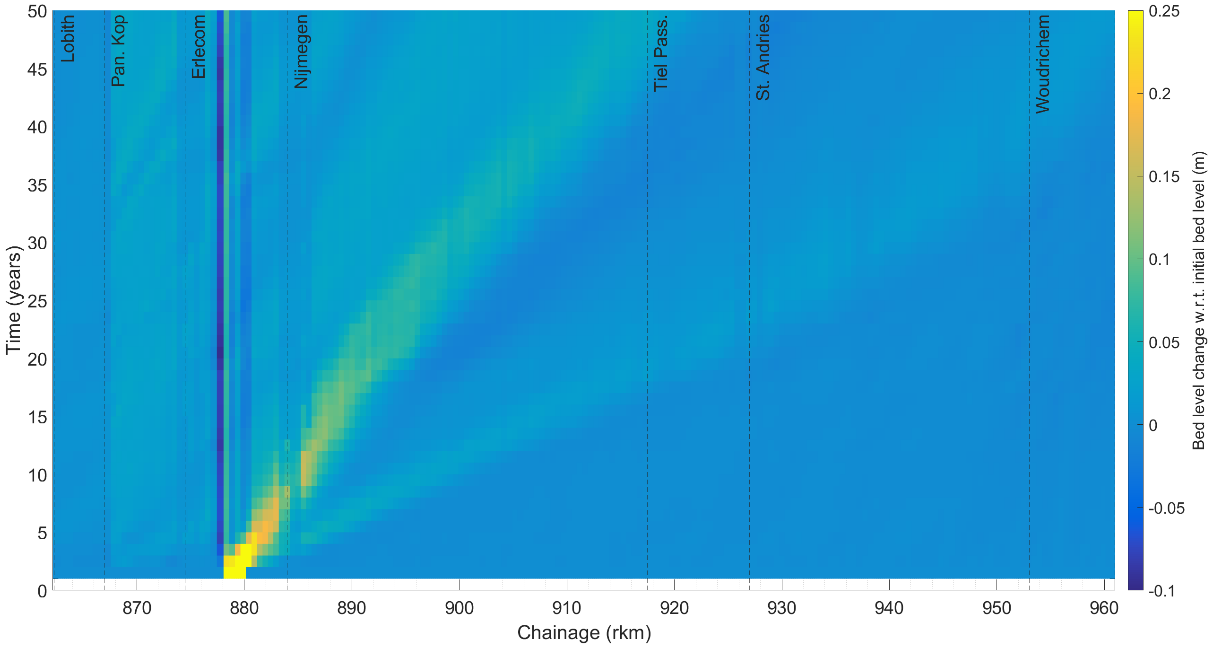


**Figure 4.17:** Difference in bed level of the Boven-Rijn and Waal between the simulation with a nourishment in the Boven-Waal and the reference simulation. The large differences in the first years of the simulation are capped off.

Since the nourishment in the Boven-Waal is located further upstream than the nourishment in the Midden-Waal, the effect of the backwater curve upstream of the nourishment is larger when it reaches the bifurcation point. The nourishment therefore has a larger influence on the discharge distribution at the bifurcation point and hence, at the development of the bed in the other branches. As a consequence, the bed level of the Pannerdensch Kanaal decreases with a maximum of 3.1 cm with respect to the bed level in the reference simulation in the first years after implementation of the nourishment, which decreases to 1.3 cm after 50 years (see Figure C.9 in Appendix C.1.3). For the coarse nourishment in the Midden-Waal, this is respectively 1.6 cm and 0.8 cm (see Figure C.5 in Appendix C.1.2).

When looking further downstream, it is found that the nourishment in the Boven-Waal decreases in height slower than the nourishment in the Midden-Waal. To determine the cause of this, the difference in mean grain size that is induced by the nourishments is examined. The development in the difference in mean grain size for the nourishment in the Midden-Waal and Boven-Waal compared to the reference simulation is shown in Figure 4.19. It is found that the nourishment in the Midden-Waal coarsens the bed slightly more than the nourishment in the Boven-Waal, although the differences are small. This is expected, since the original bed surface of the Boven-Waal is already coarser than the bed surface of the Midden-Waal. In addition, the bed surface of the Waal coarsens over time, which starts upstream and travels downstream. Consequently, the sediment available for transport in the surface layer of the bed coarsens, meaning that it is less easily entrained. Together, this causes the nourishment in the Boven-Waal to be less mobile than the nourishment in the Midden-Waal. This decreases both the advection and dispersion rate.

Like for the nourishment in the Midden-Waal, downstream of the nourishment in the Boven-Waal, there is additional erosion. At maximum, the nourishment causes 1.2 cm of additional

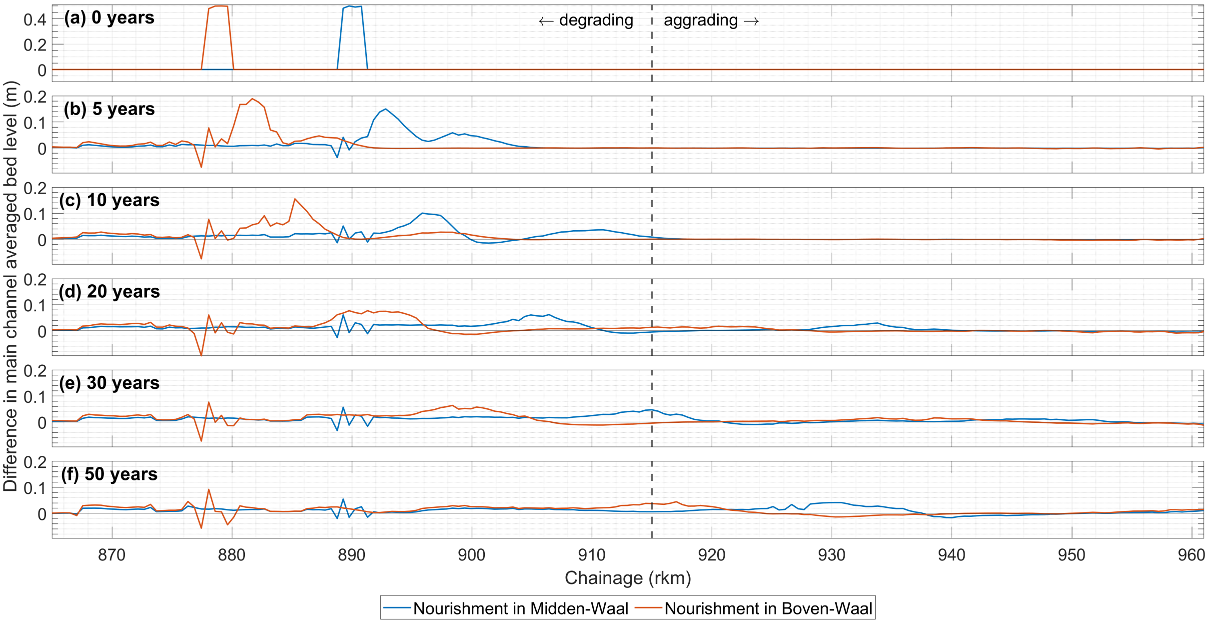


**Figure 4.18:** Difference in main channel averaged bed level in the Boven-Rijn and Waal for the different nourishment locations compared to the reference simulation at different moments in time. The approximate location at which the trend changes from degrading to aggrading in the reference simulation is indicated as a dashed line at rkm 915. Mind the difference in scaling between subfigure (a) and subfigures (b-f).

erosion. This is approximately equal to the maximum additional erosion caused by the nourishment in the Midden-Waal (1.8 cm). It takes longer before the erosion downstream of the nourishment develops. Whereas for the nourishment in the Midden-Waal this takes 8 years, for the nourishment in the Boven-Waal it takes 13 years. However, since the nourishment is located further upstream, the erosion hole stays longer in the section of the river with already a degradational trend: until year 38, compared to year 24 for the nourishment in the Midden-Waal. When the erosion hole travels into the aggrading reach of the Waal (> rkm 915), it no longer causes erosion but it causes reduced sedimentation (1.7 cm at maximum). Therefore, the erosional effect of the nourishment in the Boven-Waal is larger than that of the nourishment in the Midden-Waal.

The goal of the nourishments is to reduce erosion in the degrading section of the Waal. When the nourished sediment travels downstream of rkm 915, it contributes to aggradation, which is an unwanted effect. Because of the initial location of the nourishment, it takes longer for the nourishment in the Boven-Waal to reach the aggrading section of the Waal. While the downstream part of the nourishment does travel into this section within the simulation period (after , the upstream part of the nourishment does not fully travel into the aggrading reach, as is seen from Figure 4.18. A nourishment placed further upstream therefore contributes less to additional sedimentation within the 50-year simulation period than a nourishment placed further downstream.

To conclude, the nourishment in the Boven-Waal induces different effects than the nourishment in the Midden-Waal. This is mainly caused by the initial location of the nourishment. The nourishment reduces erosion in the degrading part of the Waal for a longer period and takes longer to travel into the already aggrading section of the Waal. This also means that the erosion

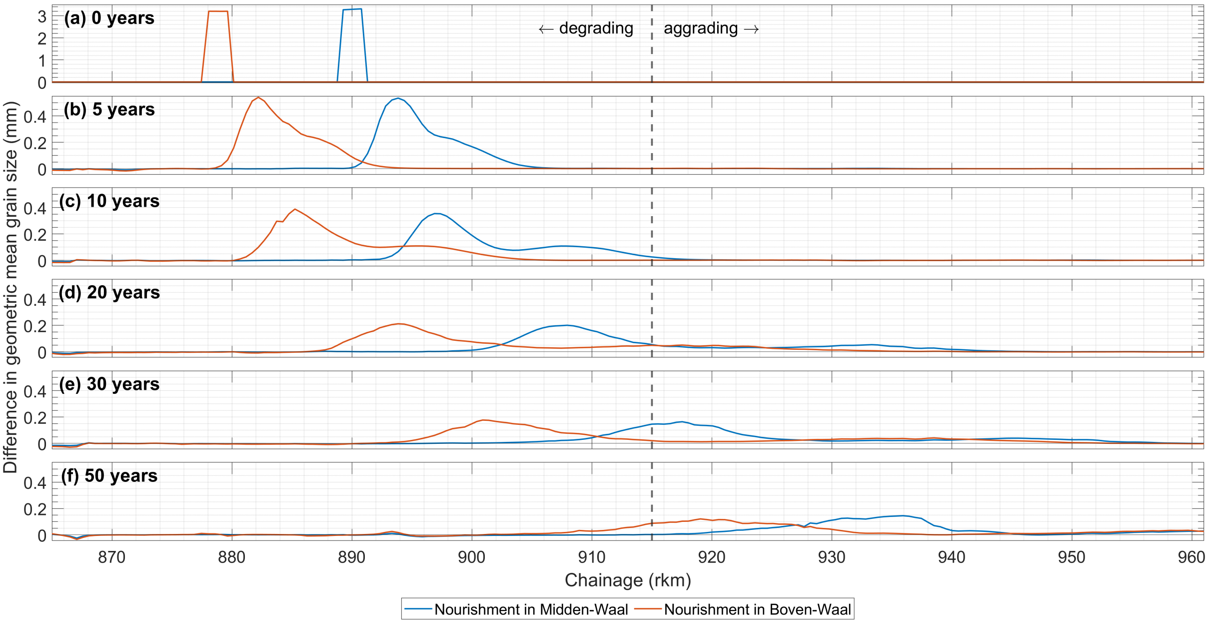


**Figure 4.19:** Difference in geometric mean grain size in the Boven-Rijn and Waal for the different nourishment locations compared to the reference simulation at different moments in time. The approximate location at which the trend changes from degrading to aggrading in the reference simulation is indicated as a dashed line at rkm 915. Mind the difference in scaling between subfigure (a) and subfigures (b-f).

hole that forms downstream of the nourishment stays in the degrading section longer, leading to more additional erosion than in the case of a nourishment in the Midden-Waal. Furthermore, since the nourishment is located further upstream, its influence on the discharge distribution and hence, on the development of the bed in the upstream section of the Pannerdensch Kanaal is larger. Finally, the coarser composition of the bed at the initial location of the nourishment in the Boven-Waal causes the sediment hump to disperse slower, meaning that it maintains its height longer and travels through the system at a slightly lower propagation speed.

### 4.2.3 Effect of the nourishment distribution

Whereas for the simulations in Section 4.2.1 the nourishment consisted of one continuous sediment hump, the nourishment in the Midden-Waal is now split up into respectively two and four parts. The total nourishment volume is the same, and so is the thickness of the nourishment, meaning that the length of the individual nourishment parts is smaller. The nourishment has the same composition as the coarse nourishment that is analysed in Section 4.2.1. The main interest is determining the differences between these results and the difference in bed level induced by one singular coarse nourishment as presented in Section 4.2.1 to determine whether applying a different nourishment distribution induces different effects. Figures showing the bed level development without comparison to the reference simulation are included in Appendix C.1.4 & C.1.5.

Figures 4.20 & 4.21 show the difference in bed level between the simulation in which the coarse nourishment is divided in two (Figure 4.20) or four (Figure 4.21) parts and the reference simulation. Like in the simulation with a non-distributed nourishment, a spike pattern is visible at the location of the nourishment, which remains at the original location of the nourishment until the end of the simulation. Again, this is considered to be a numerical artefact. However, especially in the case of four distributed nourishments, the volume of sediment that is contained in these peaks is larger than in the case of the non-distributed nourishment. It may therefore be that the effect of the additional volume of sediment is underestimated. The difference in height between the peaks and the reference simulation are omitted in the analysis of the effect of the nourishments, meaning that minima and maxima are determined without considering the peaks and troughs of the spike pattern at the nourishment locations.

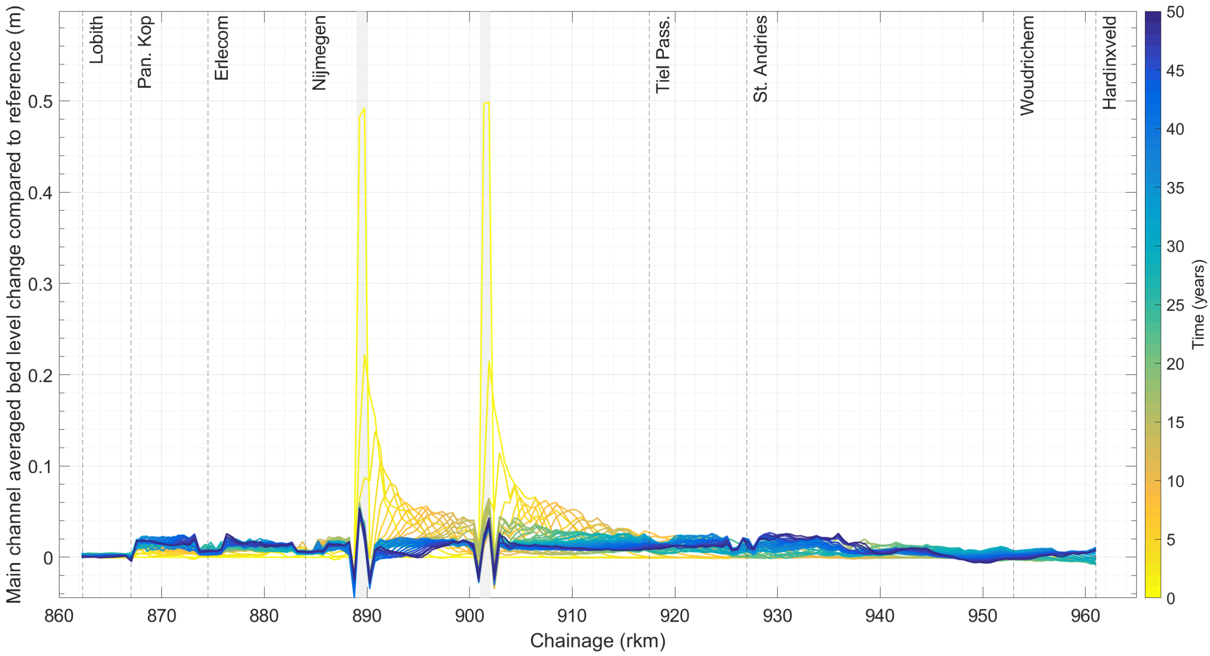


**Figure 4.20:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a coarse nourishment distributed in two parts and the reference simulation.

When comparing Figure 4.9 and Figures 4.20 & 4.21, it is found that a different nourishment distribution indeed causes different behaviour. The largest differences are directly induced by the change in the initial location and volume of the nourishment parts. The distributed nourishments decrease in height faster, but induce a reduction in erosion over a longer distance.

However, there are also changes in the response of the system to the nourishment(s). While the non-distributed coarse nourishment causes erosion downstream of the nourishment, this is not the case when the same nourishment volume is applied over multiple smaller nourishments. Using a distributed nourishment can therefore mitigate the negative effect of erosion downstream of a coarse nourishment, as is also found by Czapiga et al. (2022). By distributing the nourishment over multiple parts, the effect of the reduced mobility of the bed that is caused by placing a coarse layer over the bed surface is reduced.

To be able to make a better comparison between the three nourishment distributions, Figure 4.22 shows the difference in bed level with respect to the reference simulation for each nourishment distribution at different moments in time. Furthermore, the approximate location at which the trend in bed level development shifts from degradation to aggradation is shown. Upstream of this location, the goal is to reduce erosion, so a positive difference in bed level is desired. Downstream of this location, there already is an aggrading trend, meaning that additional sedimentation may lead to an increased need for dredging and thus, additional costs.

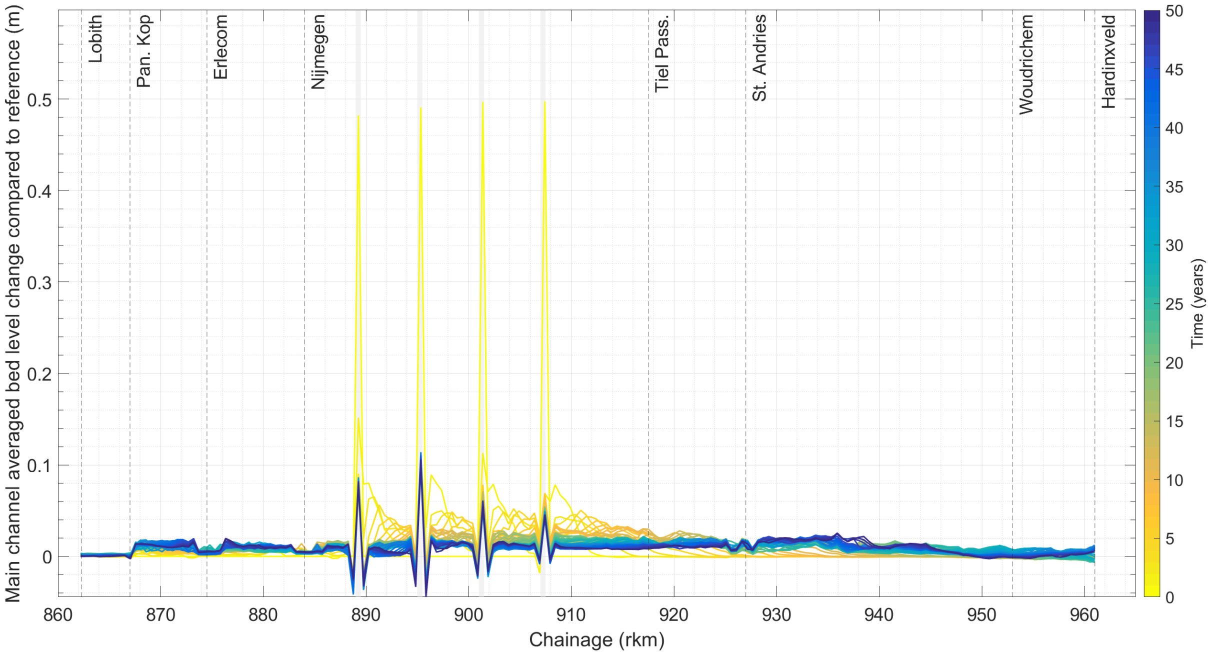


**Figure 4.21:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a coarse nourishment distributed in four parts and the reference simulation.

When looking at the section from the upstream end of the original location of the nourishments to the boundary between the degrading and aggrading reach (rkm 915), it is found that the distributed nourishments are less persistent than the non-distributed nourishment. The non-distributed nourishment causes a reduction in erosion from 50 cm at maximum initially to 15 cm at maximum after 5 years, whereas the reducing effect on erosion of the distributed nourishment in 2 parts decreases to 8 cm at maximum after 5 years and the distributed nourishment in 4 parts to 5 cm at maximum after 5 years. However, the distributed nourishments reduce the erosion over this whole reach within 5 years after the nourishment is placed, while for the non-distributed nourishment, it takes 10 years to have effect along this whole reach. Furthermore, between 6 and 25 years after implementation of the nourishment, the non-distributed nourishment causes additional erosion in an already degrading reach, while this is not the case for the distributed nourishments. It can therefore be concluded that while the reduction in erosion that the distributed nourishments induce is smaller than for the non-distributed nourishment, the distributed nourishments do cause a more spatially uniform change and they do not cause erosion in an already degrading reach.

Moreover, from Figure 4.22 it is found that the distributed nourishments induce a smaller reduction in erosion upstream of the nourishment, although the difference is small. The distributed nourishments induce approximately 0.5 cm less reduction compared to the non-distributed nourishment. As is explained in Section 4.2.1, a nourishment induces a reduction of erosion upstream of the nourishment over the length of its backwater effect. Since the non-distributed nourishment maintains a larger height for a longer period, its backwater effect is also larger. The same holds for the distributed nourishment in two parts compared to the distributed nourishment in four parts, although the difference in the reduction of erosion between these distributions is even smaller. The difference in the upstream reduction of erosion between the nourishment distributions reduces over time.

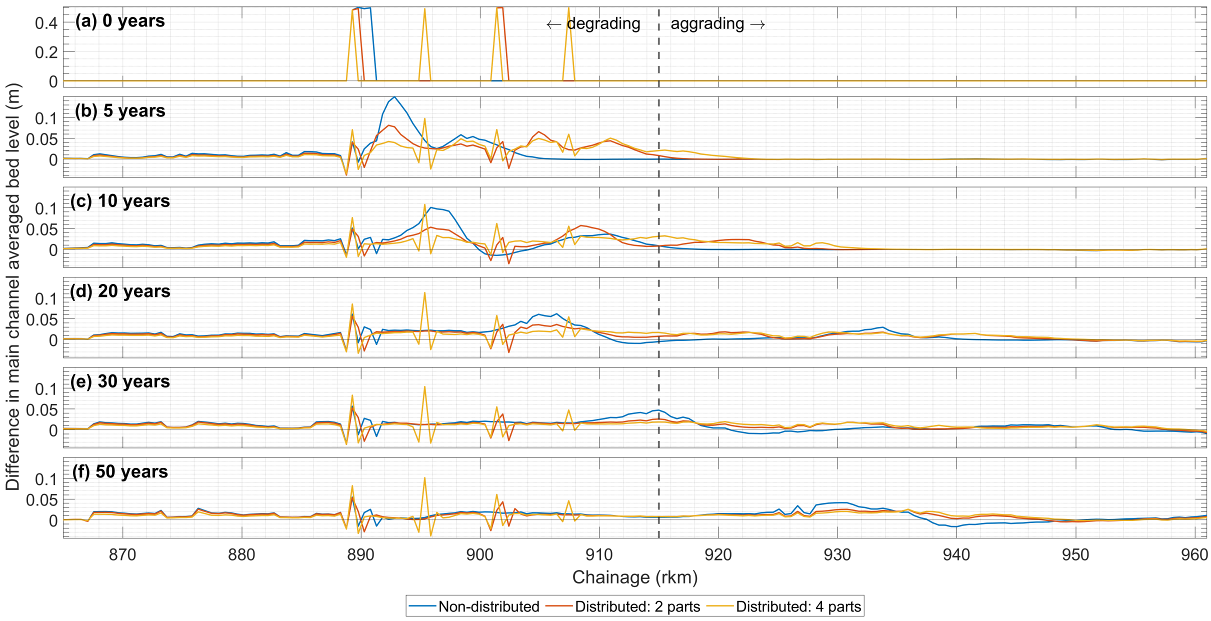


**Figure 4.22:** Difference in main channel averaged bed level in the Boven-Rijn and Waal for the different nourishment distributions compared to the reference simulation at different moments in time. The approximate location at which the trend changes from degrading to aggrading in the reference simulation is indicated as a dashed line at rkm 915. Mind the difference in scaling between subfigure (a) and subfigures (b-f).

All nourishment distributions eventually cause additional sedimentation in an already aggrading reach (downstream of rkm 915). However, the time after which this happens and the spreading of the additional sedimentation differs per nourishment distribution. In the case of the distributed nourishments, the time at which a sedimentation or erosion wave travels into the aggrading reach mainly depends on the chosen nourishment locations. The most downstream part of the nourishment of the distributed nourishments is located respectively 11 km and 16 km downstream of the most downstream part of the non-distributed nourishment. That means that their effect sooner travels into the already aggrading reach. This effect can easily be limited by choosing a different nourishment location, as is shown in Section 4.2.2. Already after respectively 3 and 5 years, additional sedimentation is observed for the distributed nourishments. After 20 years, the difference in additional sedimentation between the nourishment that is divided in 2 parts and the nourishment that is divided in 4 parts is minimal. The additional sedimentation caused by the nourishments in the aggrading part of the Waal is limited to 3.5 cm at maximum and reduces to a maximum of 2.5 cm after 50 years. Whereas the effect of additional sedimentation over 50 years is limited to the section upstream of rkm 938 for the non-distributed nourishment, in the case of the distributed nourishment, the additional sedimentation occurs over the whole downstream section of the Waal from year 30 onward.

When comparing the two distributed nourishments with each other, the differences in behaviour are relatively small. Both distributed nourishments prevent erosion downstream of the nourishment. The main differences between the distributed nourishments are caused by the initial locations of the parts of the nourishment. When the lengths of the individual nourishment parts are larger, the maximum reduction of erosion induced by the nourishment is larger because the nourishment reduces in height slower. Therefore, splitting the nourishment up in too many smaller parts is undesirable. A sensitivity analysis on the number of nourishments, their individual length and the spacing between them can help in determining the optimal distribution to prevent erosion in the Waal.

To conclude, distributing the nourishment over multiple smaller nourishments helps in preventing additional erosion downstream of the nourished reach. Since distributed nourishments disperse faster, the maximum reduction of erosion they cause is lower than for a non-distributed nourishment, but the length over which they initially reduce erosion is larger. Moreover, the locations at which the parts of the nourishment are placed with respect to the already present trend determine the effect of the nourishment for a large part. These conclusions so far only apply to the case in which the total volume of the distributed nourishment is equal to the non-distributed nourishment it is compared to. In the next section, it is investigated whether these effects still hold when the volume of the individual nourishment parts is larger.

### 4.2.4 Effect of the nourishment volume

In previous simulations, a nourishment volume of approximately $2.5 \cdot 10^5\ m^3$ is applied. In this section, it is investigated what the effect is of nourishing a larger volume of sediment ($6.9 \cdot 10^5\ m^3$). Firstly, the larger volume is applied as a continuous nourishment with a length of 5.5 km, of which the results are compared to the coarse nourishment described in Section 4.2.1. The latter is referred to here as the nourishment with the original volume. Secondly, the larger volume is also applied as a distributed nourishment in three parts of respectively 2 km, 2 km and 1.5 km. Figures showing the bed level development without comparison to the reference simulation are included in Appendix C.1.6 & C.1.7.

Figure 4.23 shows the difference in bed level between the simulations with respectively the original nourishment volume and the large nourishment volume, and the reference simulation at various moments in time. The results for the complete simulation period are shown in Figure C.16 in Appendix C.1.6 and Figure C.21 in Appendix C.1.7. It is found that the non-distributed larger nourishment induces effects that are an amplification of the effects of the original nourishment volume. The larger nourishment is more persistent, meaning that it takes longer for the nourishment to decrease in height and its effects are larger for a longer period. As a consequence, the nourishment induces a larger reduction of erosion upstream of the nourishment. The maximum reduction of erosion upstream of the nourishment for the large nourishment volume is 7.6 cm, compared to 2.5 cm for the original nourishment volume. Moreover, it has a larger influence on the discharge distribution and hence, on the bed level of the Pannerdensch Kanaal (see Figure C.18 in Appendix C.1.6). It also means that the additional erosion that is caused by the nourishment directly downstream of the nourishment is larger: 5.4 cm at maximum for the large nourishment volume, compared to 1.8 cm at maximum for the original nourishment volume. The time after which the additional erosion occurs is equal to the simulation with the original nourishment volume. Since the propagation speed of the nourishment is approximately equal to the propagation speed of the original nourishment and the downstream end of the larger nourishment is located further downstream, the main part of the larger nourishment travels into the aggrading section of the Waal approximately 2 years sooner. Since the height of the larger nourishment has reduced less when it enters the aggrading section, it leads to more sedimentation in an already aggrading section.

When looking at the difference between the non-distributed and distributed nourishment of a large volume, Figure 4.23 shows that the negative consequences of a large nourishment volume can be partly countered by splitting the nourishment volume into smaller sections. This strongly

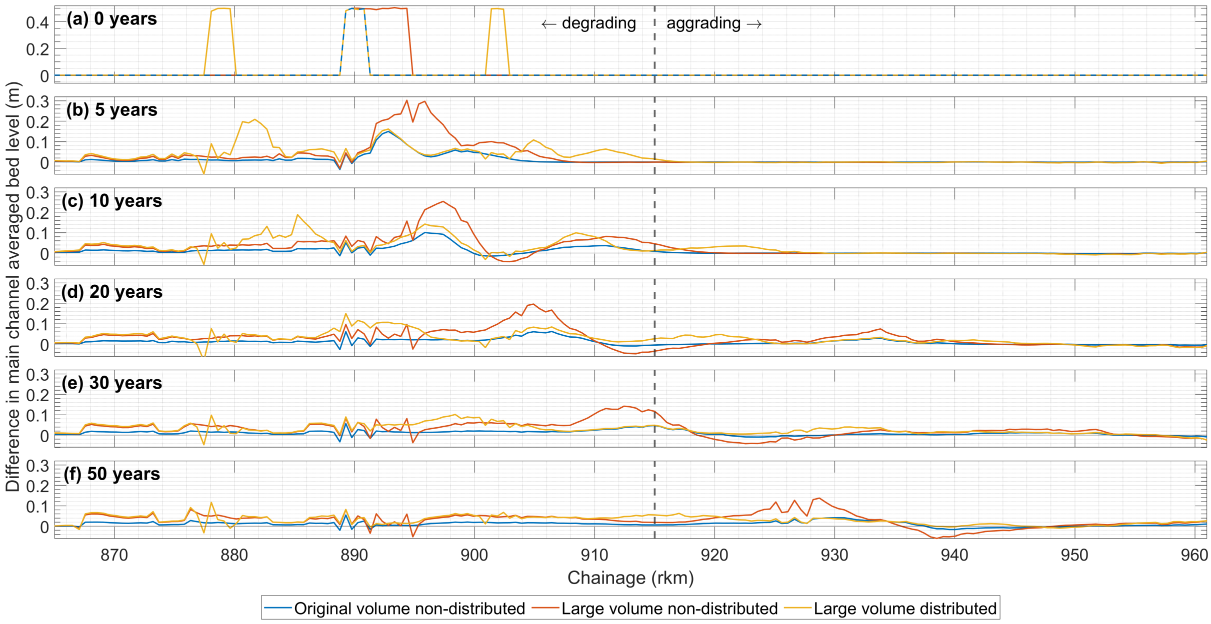


**Figure 4.23:** Difference in main channel averaged bed level in the Boven-Rijn and Waal for the different nourishment volumes compared to the reference simulation at different moments in time. The approximate location at which the trend changes from degrading to aggrading in the reference simulation is indicated as a dashed line at rkm 915. Mind the difference in scaling between subfigure (a) and subfigures (b-f).

reduces the maximum additional erosion that is induced. For a better comparison of the effects of the distributed and non-distributed large nourishment, Figure 4.24 is presented. Figure 4.24 shows a summary of the bed level change caused by the nourishments in the degrading part of the Waal (upstream of rkm 915). In the calculations, the peaks that remain at the original locations of the nourishments are omitted for the same reasons as described before.

Initially, the maximum increase in bed level compared to the reference simulation is lower for the distributed nourishment than for the non-distributed nourishment. Conversely, the increase in bed level is achieved over a larger length of the river in the case of a distributed nourishment. After approximately 8 years, both the maximum increase in bed level and the length over which the increase is more than 0.05 m are smaller for the distributed nourishment than for the non-distributed nourishment. After 35 years, the maximum increase in bed level is found to be approximately equal. Moreover, after 35 years, the length over which the increase in bed level exceeds 0.05 m is approximately twice as large for the distributed nourishment than for the non-distributed nourishment. Therefore, on the long term, the effectiveness of the larger nourishment is increased when distributing it over multiple smaller parts.

The large nourishments have a volume that is approximately 2.7 times larger than the original nourishment volume. When looking at Figure 4.24, the relative difference in the effects can be determined. Because the original nourishment height is equal in all three simulations, initially, there is no difference in the maximum increase in bed level. However, after 3 and 16 years, respectively, the maximum increase in bed level is twice as large for the non-distributed and distributed large nourishments than for the original nourishment volume. This increases to a factor 3 after respectively 18 and 34 years and remains a factor 3 until the end of the simulation period. Moreover, after 5 years of simulation, the length over which the increase in bed level

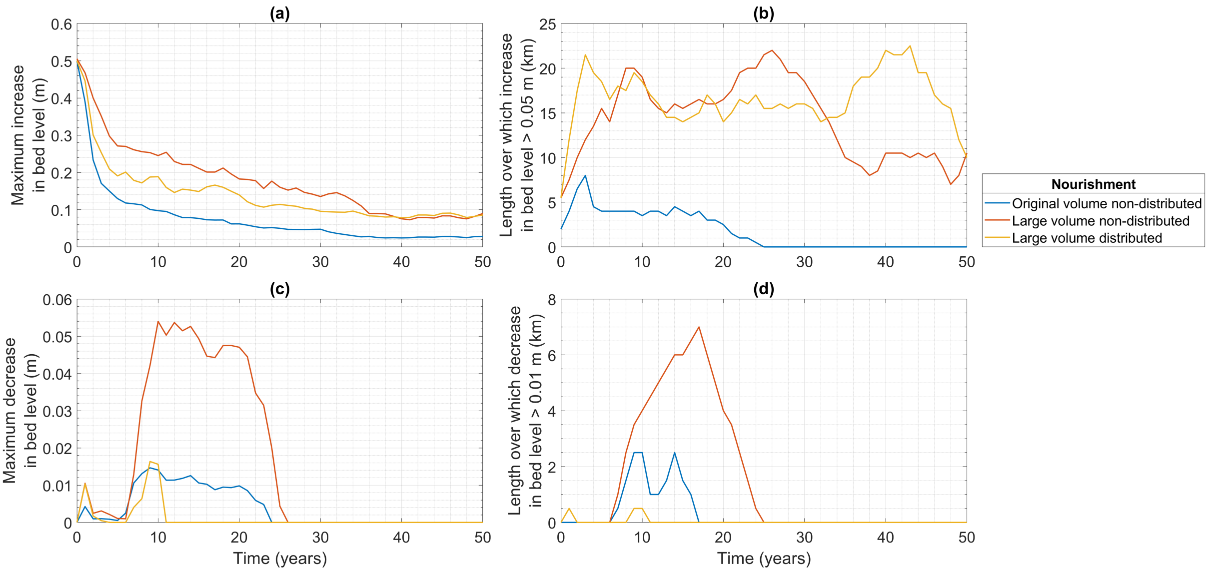


**Figure 4.24:** The maximum increase in bed level with respect to the reference simulation (a); the length over which the increase in bed level exceeds 0.05 m (b); the maximum decrease in bed level with respect to the reference simulation (c); and the length over which the decrease in bed level exceeds 0.01 m (d) for the degrading reach of the Waal, from rkm 868 until 915. Subfigures (a) and (b) show the positive effects of the nourishments, while subfigures (c) and (d) show the unwanted effects of the nourishments. The peaks that exist at the original locations of the nourishments are omitted in the calculations.

exceeds 0.05 m is more than 3 times larger for the larger nourishments than for the original nourishment volume. Between year 5 and 20, the difference is on average a factor 4. From this information, it can be concluded that while the volume of the nourishment is 2.7 times as large, the increase in bed level that is induced by the nourishment and the length over which the increase in bed level is achieved is increased by a larger factor.

To conclude, nourishing a larger nourishment volume at once enhances the effects of the nourishment by a factor that is larger than the factor with which the volume of the nourishment is increased. This means that the maximum reduction in erosion and the length over which erosion is reduced increases, but also negative consequences such as additional erosion through the formation of additional erosion downstream of the nourishment and additional sedimentation in an already aggrading section are enhanced. These negative effects can be mitigated by splitting the nourishment up into smaller parts. While the maximum reduction of erosion that is achieved is then initially smaller, the length over which the erosion is reduced is equal or larger. On the long term, the distributed nourishment induces an equal maximum reduction in erosion, while it reduces erosion over a longer length. This contradicts the findings of the distributed nourishment with the original volume, meaning that there must be some threshold volume for the parts of the nourishment above which a distributed nourishment is equally or more effective in reducing erosion than a non-distributed nourishment.

Finally, the comparison between the results of the distributed large nourishment and the nourishment with the original volume provides additional information on the effect of the nourishment distribution. It is found that the additional erosion caused by the distributed large nourishment is less than the additional erosion caused by the nourishment with the original nourishment volume. The size of the individual parts of the distributed large nourishment is equal to the size of the original nourishment. Therefore, the reduction in additional erosion cannot merely be an effect of a reduction in the size of the individual nourishment parts. The parts of the nourishment in the distributed nourishment influence each other in such a way that the sedimentation caused by one nourishment part counters the erosion caused by another nourishment part. Since sediment of an upstream part of the nourishment is transported downstream, there is sediment available for transport downstream of the coarse region, therefore limiting additional erosion downstream of the nourishment. This confirms that the spacing of nourishments can be chosen in such a way that the individual parts of the nourishment influence each other and negative effects can be mitigated.

### 4.2.5 Overall comparison of the effects of the various nourishments

In this section, an overview of the effects of the various nourishments is provided and a conclusion is drawn on which nourishment characteristics should be selected to most effectively reduce bed degradation in the Waal.

Figure 4.25 shows a comparison of the effects of the various nourishments on the degrading section of the Waal (rkm 868-915). Figures 4.25a & 4.25b provide an overview of the positive effects of the nourishment in the degrading reach of the Waal: the maximum increase in bed level that the nourishment induces and the length over which the increase in bed level compared to the reference simulation is more than 0.05 m. Figures 4.25c & 4.25d show the negative effects of the nourishments in the degrading reach of the Waal: the maximum decrease in bed level that the nourishment induces and the length over which the decrease in bed level compared to the reference simulation is larger than 0.01 m.

It is found that the effectiveness of the nourishment mainly depends on the nourishment volume. A larger nourishment volume induces both a larger maximum increase in bed level (Figure 4.25a) and a longer length over which an increase in bed level is achieved (4.25b). Thereafter, the initial location of the nourishment is of most influence on the effectiveness of the nourishment. When the nourishment is placed further upstream, it disperses slower, meaning that the maximum increase in bed level remains larger during a longer period. Initially, the length over which the nourishment causes an increase in bed level is similar to nourishments placed further downstream, but since a nourishment placed further upstream stays in the degrading section of the Waal longer, the length over which an increase in bed level is achieved is larger for a nourishment placed further upstream after a simulation period of 20 years. Moreover, Figure 4.25c & 4.25d confirm that distributing the nourishment in several parts reduces the additional erosion caused by the nourishment. Additionally, as is found in Section 4.2.3, by distributing a nourishment of a large volume into multiple parts spaced several kilometres apart, the length over which the nourishment reduces erosion even increases in comparison to the non-distributed nourishment.

To conclude, when looking at the nourishment variations that are presented in this study, distributed nourishments of larger volumes placed further upstream in the Waal are most effective at reducing erosion in the degrading part of the Waal.

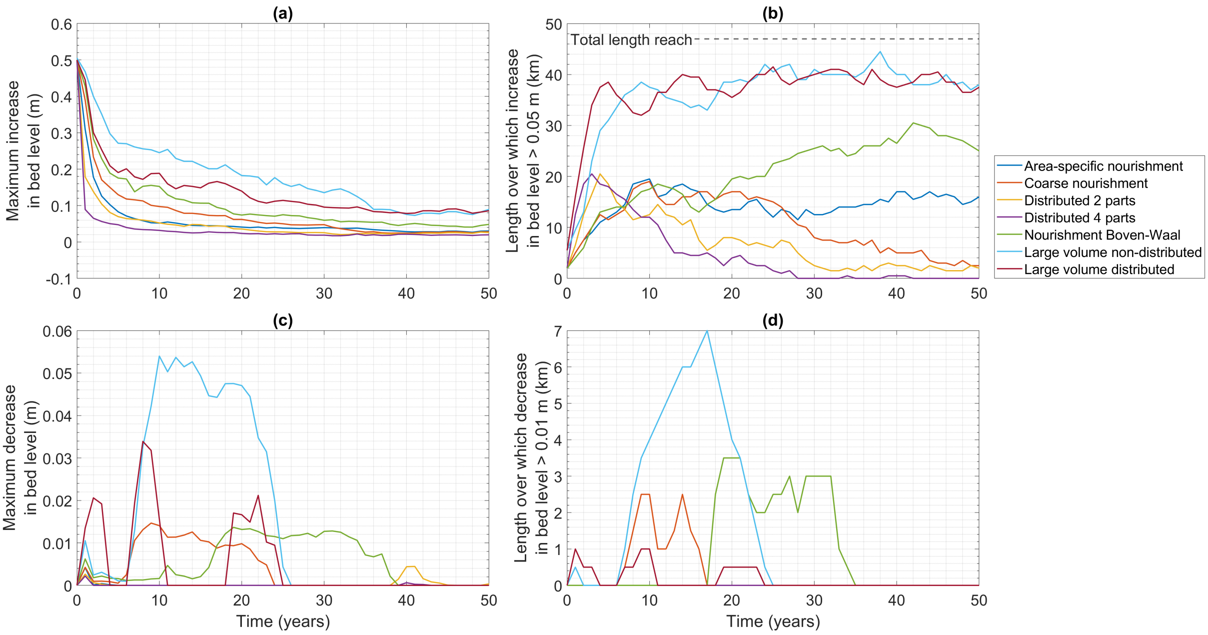


**Figure 4.25:** The maximum increase in bed level with respect to the reference simulation (a); the length over which the increase in bed level exceeds 0.05 m (b); the maximum decrease in bed level with respect to the reference simulation (c); and the length over which the decrease in bed level exceeds 0.01 m (d) for the degrading reach of the Waal, from rkm 868 until 915 for each nourishment simulation. Subfigures (a) and (b) show the positive effects of the nourishments, while subfigures (c) and (d) show the unwanted effects of the nourishments. The peaks that exist at the original locations of the nourishments are omitted in the calculations.

### 4.2.6 Conclusion research sub-question 2

The research question that is answered by the analysis of these results is "*What are the morphological effects of nourishments of varying grain sizes, locations, nourishment distributions and volumes in the Waal?*".

It is found that in general, nourishments can reduce erosion over a section of the river that is larger than the original length of the nourishment. Upstream of the nourishment, erosion is reduced through the backwater effects of the nourishment. The size of this reduction is mainly dependent on the initial location of the nourishment and the dispersion rate of the nourishment. For the nourishments investigated here, the reduction of erosion upstream of the nourishments ranges from 3 cm to 4 cm. Additionally, the downstream translation of the nourished sediment reduces erosion downstream of the original nourishment location. As the nourishment propagates downstream, it reduces in height and increases in length. Figure 4.26 provides a summary of the propagation of the various nourishments through the Waal.

By selecting a nourishment with a coarser composition than the original bed surface, the nourishment becomes more persistent. That means that it disperses slower and its propagation speed decreases. Moreover, a coarser nourishment induces a reduced mobility of the bed surface, which leads to additional erosion downstream of the main sediment hump. Besides on the sediment composition, the magnitude of additional erosion depends on the nourishment volume. For the original nourishment volume, additional erosion of 2 cm at maximum is found, while for

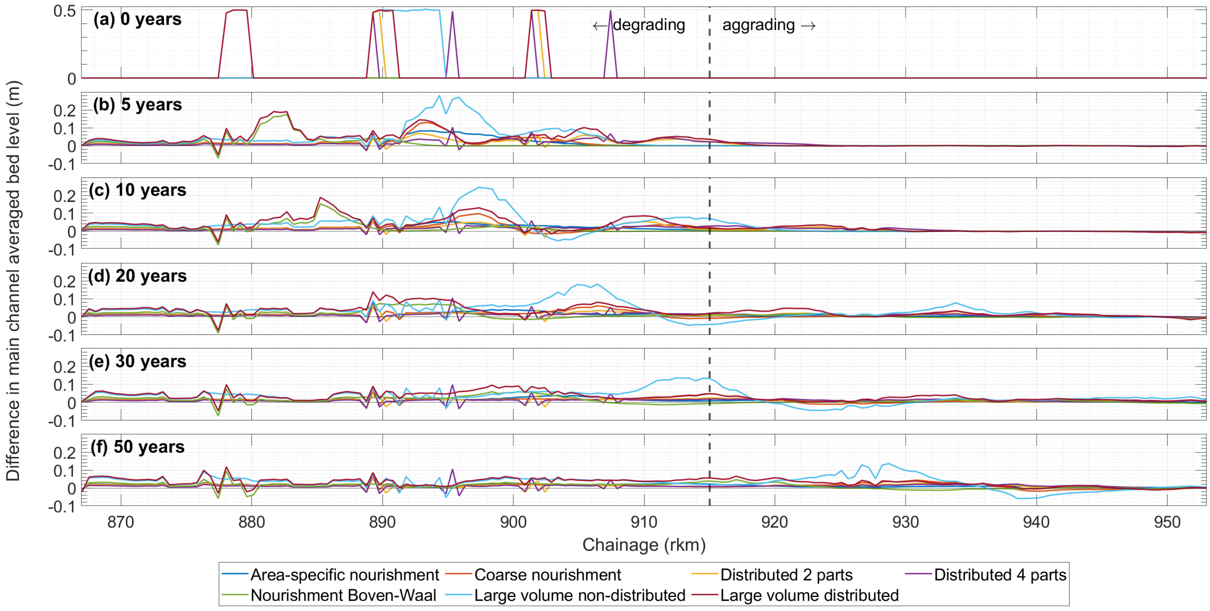


**Figure 4.26:** Difference in main channel averaged bed level in the Boven-Rijn and Waal for all studied nourishments compared to the reference simulation at different moments in time. The approximate location at which the trend changes from degrading to aggrading in the reference simulation is indicated as a dashed line at rkm 915. Mind the difference in scaling between subfigure (a) and subfigures (b-f).

the large nourishment volume, the additional erosion is 5 cm at maximum. Additional erosion is an unwanted effect in an already degrading reach.

It is found that all simulated nourishments eventually travel into the aggrading section of the Waal (downstream of rkm 915), after which they contribute to additional sedimentation instead of reduced erosion. The time after which this happens depends mainly on the initial location of the nourishment and ranges from 8 years to 15 years for the nourishments investigated here. Moreover, when the nourishment is placed further upstream, the sediment composition of the bed around the nourishment is coarser, which leads to a reduction in the dispersion and propagation speed. Finally, a nourishment placed further upstream has a larger influence on the discharge distribution at the Pannerdensche Kop and on the bed level in the Pannerdensch Kanaal.

By distributing the nourishment over multiple parts spaced several kilometres apart, the negative effect of additional erosion forming downstream of a coarse nourishment can be mitigated. This also holds when the volume of each part of the nourishment is equal to a singular nourishment. When the volume of each individual nourishment part is smaller than the non-distributed volume, the maximum reduction of erosion the total nourishment induces is smaller, but the length over which the nourishment reduces erosion is larger. However, when the volume of the individual nourishment parts is sufficiently large, the length over which the nourishment reduces erosion over the long term is larger. It is uncertain where this threshold lies. Additionally, the initial location of the nourishment parts is of large influence on the effects of the nourishment.

Finally, by nourishing a larger volume of sediment, the effects of the nourishment can be multiplied by a factor that is larger than the factor with which the volume is increased. Both the positive effect of the reduction of erosion in the degrading section and the negative effects of additional erosion downstream of the nourishment and additional sedimentation in the aggrading reach are enhanced. After 50 years, an increase in volume by a factor 2.7 results in an increase in the maximum increase in bed level compared to the reference simulation by a factor 3, while the length over which erosion is reduced increases by more than a factor 4. Again, the additional erosion downstream of the nourishment can be mitigated by distributing the nourishment over multiple parts.

## 4.3 The influence of varying discharge conditions

For all simulations that are described in Section 4.2, the reference discharge scenario is used. In this section, two other discharge scenarios are used as the upstream boundary conditions. The first is discharge scenario SMHM (= same mean, higher maximum) and the second is discharge scenario HMHM (= higher mean, higher maximum). The time series that are used are described in Section 3.3.5. The effect of these different discharge conditions on the development of the bed of the Waal without future human intervention is investigated in Section 4.3.1. The goal is to show the effect of variability in the discharge regime of the Rhine due to uncertainty, compared to the influence that nourishments may have as found in the previous section. Subsequently, in Section 4.3.2, the difference in the effect of sediment nourishments under the various discharge conditions is described.

### 4.3.1 The influence of varying discharge conditions on the development of the bed of the Waal without future human interventions

Before the development of the bed is investigated, first the direct effect of the various discharge scenarios on the flow conditions and the corresponding sediment transport is described. Figure 4.27 shows the cumulative incoming discharge and incoming sediment transport through the upstream boundary of the domain for the various discharge scenarios. Since the upstream boundary is defined as a ghost cell from which no data can be read, the data is read from rkm 815 in the Rhein, which is just downstream of the upstream boundary.

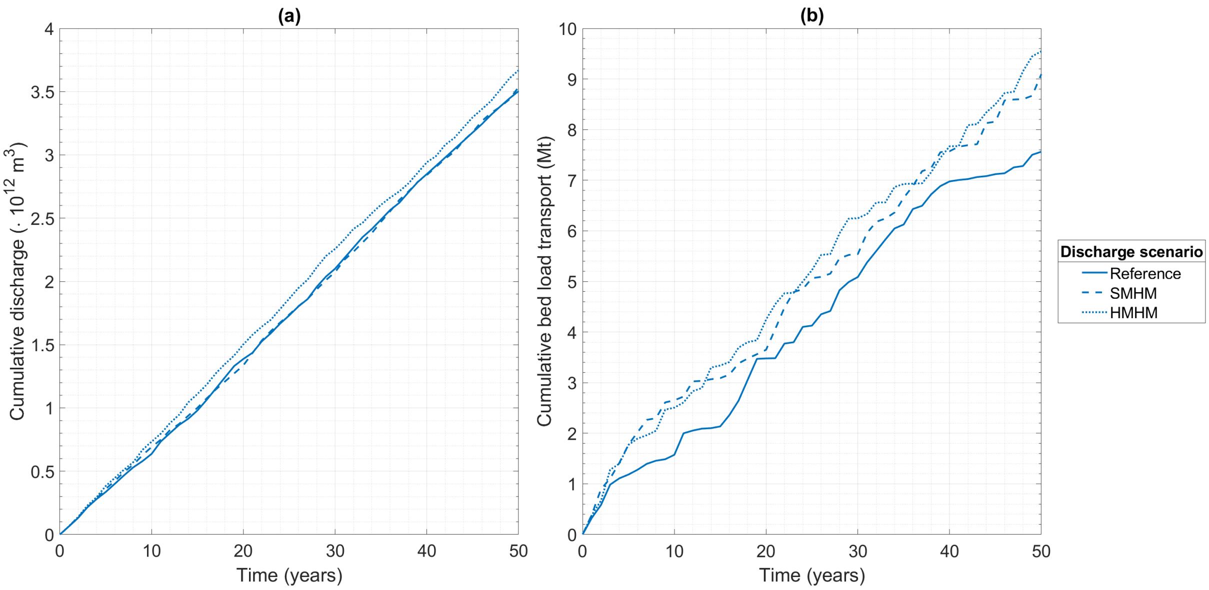


**Figure 4.27:** Cumulative discharge (a) and cumulative sediment transport (b) entering the system from upstream for the different discharge scenarios. Measured at rkm 815 in the Rhein.

By definition, the total incoming volume of water is approximately equal for the reference simulation and the SMHM scenario. However, since high discharge events occur more frequently and since sediment transport is a highly non-linear phenomenon, the sediment flux into the system through the upstream boundary is larger for the SMHM scenario than for the reference scenario. The HMHM scenario results in both a larger total volume of water in the system and a higher influx of sediment through the upstream boundary.

More often occurring high discharges through the system and a higher sediment flux entering the system both give opposite effects. The Exner equation describes the conservation of mass of the sediment in the system (Parker, 2004). According to the Exner equation, changes in bed level occur as long as there are gradients in the sediment transport capacity. When the discharge is increased, this causes an increase in the sediment transport capacity. As a consequence, to keep the mass equal, the bed erodes and the bed level degrades. However, when the sediment influx is also increased, this (partly) balances the increase in discharge. This decreases the gradient in the sediment transport capacity. Consequently, the bed level changes are smaller than when the sediment influx does not increase.

First, the influence of these changes in discharge on the Rhein and Boven-Rijn is investigated, since the behaviour of this branch largely determines what happens in the Waal. Figure 4.28 shows the difference in bed level between respectively discharge scenario SMHM and HMHM, and the reference simulation under the reference discharge conditions.

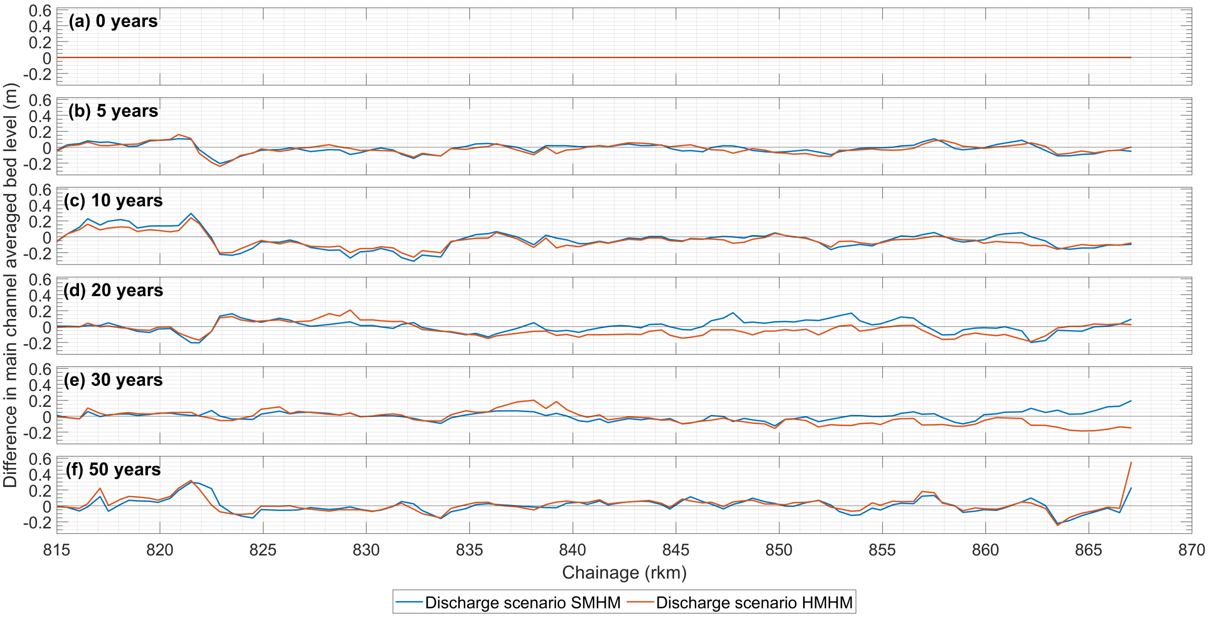


**Figure 4.28:** Difference in main channel averaged bed level in the Rhein and Boven-Rijn for the various discharge scenarios compared to the reference simulation under the reference discharge conditions at different moments in time. The values are averaged over three years to account for yearly variability (e.g. in subplot b, the average difference in bed level between year 4 and 6 is shown).

It is found that the main differences in the bed level compared to the reference situation are caused by the fact that the discharge series is composed differently. Neither the SMHM nor the HMHM discharge scenario has a consistent influence on the bed level, meaning that the difference with the reference simulation may be negative at one moment in the simulation, while it is positive at another moment in the simulation. For example, the most upstream reach of the Rhein is aggrading in the reference simulation. After 10 years, both discharge scenarios SMHM and HMHM cause additional sedimentation of up to 0.3 m. However, after 20 years, the bed level in all three discharge scenarios is approximately equal. To conclude, while the differences in bed level between the discharge scenarios are significant, there is not a clear trend following from these results.

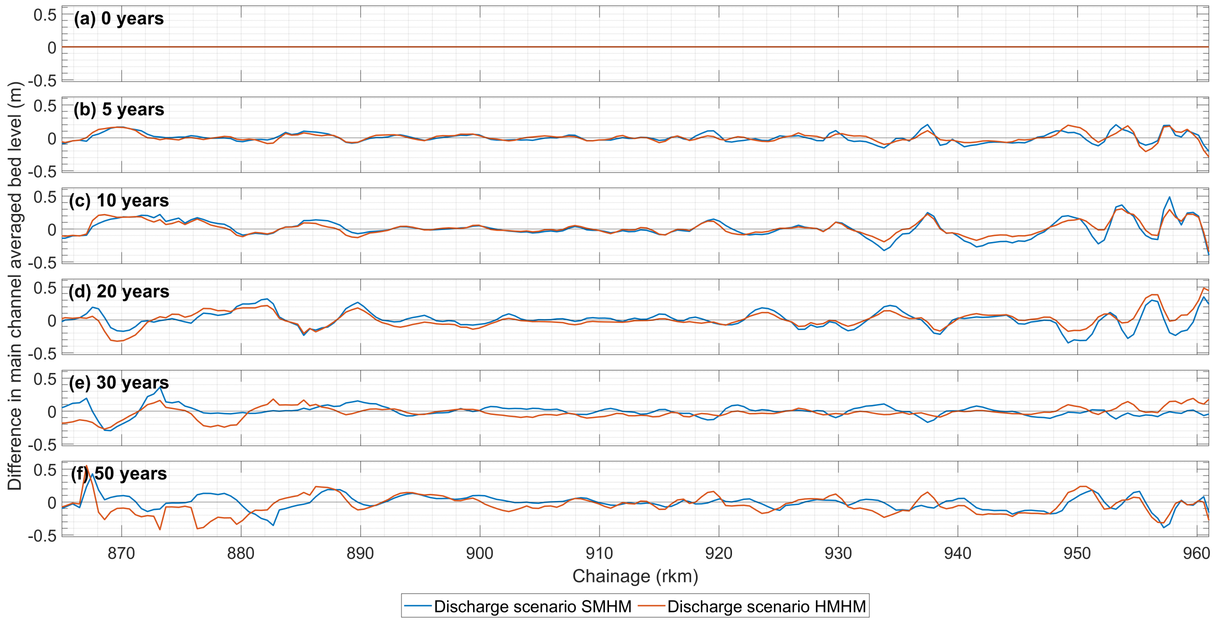


**Figure 4.29:** Difference in main channel averaged bed level in the Boven-Rijn and Waal for the various discharge conditions compared to the reference simulation under the reference discharge conditions at different moments in time. The values are averaged over three years to account for yearly variability (e.g. in subplot b, the average difference in bed level between year 4 and 6 is shown).

Figure 4.29 shows the difference in bed level of the Boven-Rijn and Waal for the discharge scenario SMHM and HMHM, compared to the reference scenario. It is seen that the largest differences in the bed level in the Waal between the various discharge scenarios occur in the most upstream and downstream sections. The most upstream section is directly influenced by the behaviour of the Rhein and Boven-Rijn. Furthermore, the discharge distribution at the Pannerdensche Kop has a large effect on this section. The changes in the most downstream section are likely caused by the boundary conditions that are imposed at the downstream boundary. There may exist a discrepancy between the calculated water level and the water level according to the imposed $Qh$-relation, which causes backwater effects to travel upstream. For this branch it also holds that there is no clear trend visible in the difference in bed level caused by the varying discharge scenarios.

While there is no trend visible caused by the differences between the discharge scenarios, locally, the discharge scenarios can make large differences. The differences between the discharge scenarios SMHM and HMHM and the reference scenario range from -0.64 m to +0.70 m. Considering that the nourishments that are treated in this research are of a maximum height of 0.5 m, it can be said that the variability in discharge can cause larger differences than the nourishments that are studied here. This is important to keep in mind when evaluating the evolution of the bed of the Waal based on one discharge scenario. Stochastic modelling can provide more information on the uncertainty range of bed level changes. When multiple discharge scenarios are evaluated, this does increase the required computational resources. Depending of the goal of the study and the available resources, the decision may be made to use a stochastic modelling approach. In Section 4.3.2, the influence of the various discharge scenarios on the development of a nourishment is investigated.

### 4.3.2 The influence of varying discharge conditions on the effect of nourishments

Whereas in Section 4.2 all nourishment simulations are compared to the reference discharge, in this section the effect of the nourishments is compared to the bed level without future human intervention under their respective discharge conditions. This then shows the difference that the nourishment makes compared to the situation in which the bed level develops autonomously. When a nourishment is designed, it is not known which exact discharge conditions will occur in the years after implementation of the nourishment. In this section, it is assumed that the nourishment is designed and the discharge conditions are given.

Figure 4.30 shows the difference in bed level between the simulations with a coarse nourishment distributed in two parts under various discharge conditions and their respective reference simulation at different moments in time. It is found that different discharge conditions can influence the propagation speed of the nourishment. Especially in Figure 4.30b and Figure 4.30c, it is seen that the nourishment travels downstream faster in the SMHM scenario and the HMHM scenario than in the reference scenario. This is expected, since higher discharges induce higher flow velocities and hence, induce more sediment transport. Moreover, a consequence of the increase in sediment transport, the height of the nourishment reduces sooner. Additionally, the nourishment travels into the aggrading section of the Waal earlier.

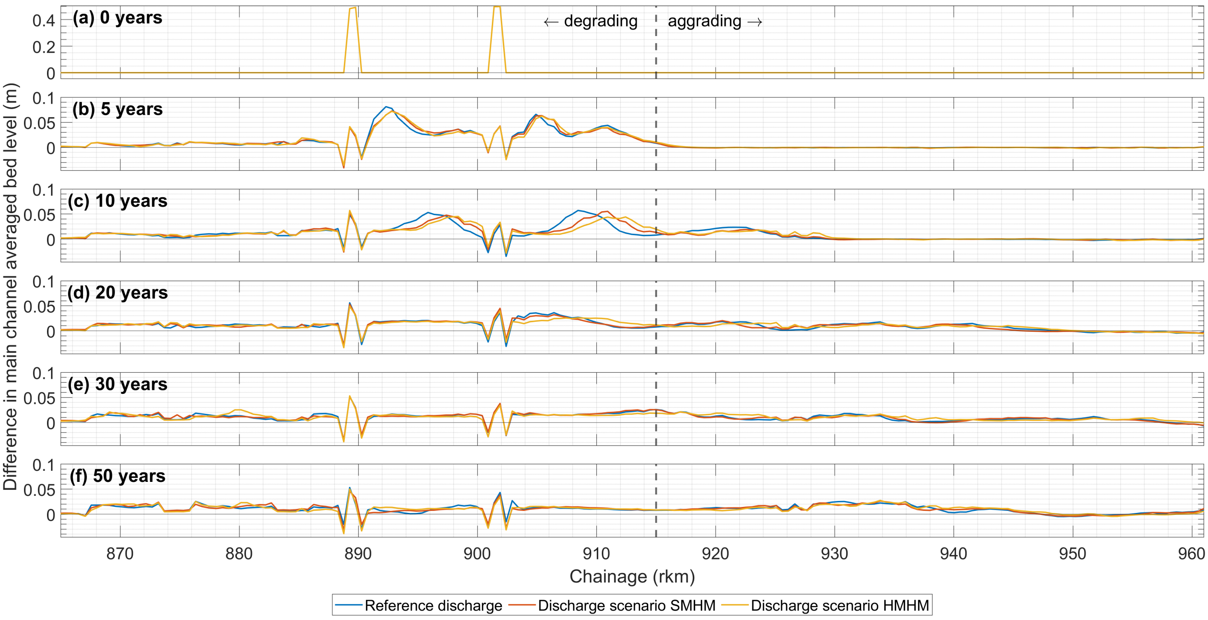


**Figure 4.30:** Difference in bed level between the nourishment simulations with a coarse nourishment distributed in two parts under various discharge conditions and the development of the bed level without future human intervention at various moments in time. Mind the difference in scaling between subfigure (a) and subfigures (b-f).

After around 30 years, the effect of the nourishment is approximately equal for all three discharge scenarios. Because the nourishment disperses, the effect of the discharge variability on the nourishment itself becomes smaller compared to the overall effect of the discharge variability on the development on the bed.

#### 4.3.3 Conclusion research sub-question 3

The research question that is answered by the analysis of these results is "*How are the development of the bed and the behaviour of a nourishment influenced by discharge variability due to uncertainty in the discharge time series?*".

It is found that by imposing different discharge conditions, differences in bed level of up to 70 cm can occur in the case of autonomous bed development. This is significant, since this is a larger difference than the maximum induced difference by the nourishments that are studied here. However, the differences do not show a significant trend and the differences are highly variable over the years. The main driver is therefore the yearly discharge variability.

The discharge conditions that are imposed on a nourishment in the years after the nourishment is placed can influence the propagation speed of the nourishment through the system, as well as the rate of dispersion of the nourishment. However, this effect decreases over time, compared to the general influence of the discharge variability on the bed level development.

Depending on the goal of the study and the available computational resources, the decision can be made to use a stochastic modelling approach to provide an uncertainty range for the changes in bed level and the effects of nourishments.

# 5 Discussion

This chapter provides a discussion on the results of this study. Section 5.1 provides a discussion on the used method and the reliability of the results. Section 5.2 elaborates on the practical implementation of nourishments and the possible differences and challenges compared to the modelling of nourishments. Finally, Section 5.3 discusses the potential of using sediment nourishments to mitigate bed degradation and provides a coupling between the results of this study and the ambitions set in the IRM programme.

## 5.1 Reflection on the used method and reliability of the results

In this section, the consequences of the methodology that is used are discussed and a reflection is done on the reliability of the results. Firstly, Section 5.1.1 reflects on the method of implementing nourishments in the 1D Rhine branches model. Section 5.1.2 presents a discussion of some aspects that are not included in the model that may cause differences between model results and the behaviour of a nourishment in reality. Section 5.1.3 reflects on the boundary conditions that are used. In Section 5.1.4, the method of modelling the sediment transport is discussed and finally, Section 5.1.5 discusses the initial sediment composition that is used in the model and its influence on the model results.

### 5.1.1 Modelling of nourishments in the 1D Rhine branches model

In this study, nourishments are modelled by raising the bed level and changing the sediment composition at the start of the simulation. Consequently, the effect of nourishing at a different time than at the start of the simulation and repeated nourishments cannot be studied. It is found that relatively large changes occur in the bed level and the sediment composition in the first year of the simulations. By implementing the nourishment at the start of the simulation, the nourishment behaviour is influenced by these initialisation effects. If the nourishment is implemented later in the simulation, this can be prevented. Moreover, since in this study it is found that the effect of a nourishment reduces over time, it is interesting to study what happens when nourishments are repeated after a certain period of time. This information can then be used to estimate how much sediment would be needed to fully counter bed degradation and maintain the current bed level of the Waal.

During this research, it was tried to implement nourishments during the simulation but this is currently not possible due to limitations of the model. Below, two methods of simulating nourishments using the 1D Rhine branches model are discussed, which may be used in case adaptations are made in future versions of the model: by using the 'dredge and dump' module and adapt the conditions during the simulation by using restart files.

One option that is evaluated is to nourish sediment by using the 'dredge and dump' module in D-Flow FM. As the name suggests, this module allows the user to define dredging and dumping activities at specific locations and during specific time periods. It is also possible to use the module just for dumping sediment from outside the system, meaning that a nourishment can be simulated. At the time of this research, however, D-Flow FM did not properly read the time series that is defined. If the reading of the time series is updated in a future version of the model, it is recommended to use this method to simulate nourishments to determine whether there are differences between the two approaches and to determine the effects of repeated nourishing.

Another option is to create restart-files in which the characteristics of the flow, the bed and the sediment transport are stored. The simulation can then be stopped after a certain period of time and the bed levels and sediment compositions can be read. The nourishment can then be added to these files, as is done in this research. Consequently, these files can be used as the initial conditions of a new simulation, which is started using the created restart-file. The desired nourishment interval can be obtained by setting a certain restart interval. This was also tried in this research, but it was found that a simulation that was run continuously and the same simulation that was restarted did not produce the same results. This is caused by different behaviour of the weirs in the Neder-Rijn, of which the crest levels did not properly adapt to the flow conditions when the simulation was restarted. While using the 'dredge and dump' module is less prone to errors and therefore recommended, this is another way in which repeated nourishments can be simulated in the 1D Rhine branches model.

### 5.1.2 Model components of the 1D Rhine branches model

By definition, a model does not capture all processes and details that occur in a system in reality. To be able to generate results while maintaining a manageable computation time, some aspects are either simplified or left out completely. However, in reality these aspects may be of importance when evaluating the influence of nourishments on the bed degradation in the Waal. Some important aspects are highlighted and discussed below.

Firstly, since a 1D model is used, 2D effects that occur in reality are not included in the model. For example, the behaviour of the flow and the consecutive sediment transport in bends is not included in the model. While in this study only the main channel averaged bed level is considered, in reality, the development of the inner and outer bend differ significantly, because of spiral flow and sorting effects (Havinga, 2016). Especially when nourishing in the Boven-Waal, which is a section of the river characterised by the presence of bends, this can significantly influence the behaviour of a nourishment (Van der Deijl, 2021). It is therefore recommended to include these effects in the model or to account for these effects at a later stage of the design by modelling in 2D.

Secondly, the effect of ships passing through the river is not accounted for in the model. In reality, the passage of ships over a nourishment may entrain the sediment through the additional turbulence caused by the propellers of the ships. This is also found in the pilot study done in the Boven-Rijn (De Jongste and Huppes, 2021). Since this is a very local and specific effect, it is often not included in models. However, especially when low discharges occur and ships are closer to the bed surface, this may have a significant effect on the propagation and dispersion of the nourishment. Niesten and Becker (2018) concluded that this is one of the two main components that causes differences between the measured and simulated effects of the nourishment pilot in the Boven-Rijn during low discharges. Including shipping effects in a model is not recommended, because the effects are local, highly variable and difficult to predict. However, such effects should be accounted for when designing a nourishment by making an estimation of these effects.

Moreover, human interventions besides the studied nourishment are not included in the model. This means that it is assumed that no training works are implemented in the river in the upcoming 50 years. This is most likely not true. This also means that current dredging activities are not included in the model. Especially in the Beneden-Waal, dredging operations occur regularly. For example, at Sint Andries, yearly 60,000 $m^3$ of sediment is dredged to maintain a navigable water depth during low flows (Programma Integraal Riviermanagement, 2021).

Moreover, while the volumes have decreased significantly over the past decades, sediment is still mined from the river bed for commercial use (Programma Integraal Riviermanagement, 2021). This leads to lower bed levels in reality than those simulated by the model. It is currently difficult to determine the effect nourishments have on the required dredging amounts.

Finally, three weirs in the Neder-Rijn are included in the model. These are controlled based on water levels using the module D-RTC, as is explained in Section 3.1. However, from the model results it appears as if the weirs do not always respond to the water levels in the way that they are expected to. To determine the spin-up time of the model (see Section 3.2.2), the model was run for one year using a constant discharge at the upstream boundary. The expectation is that when a constant discharge is imposed, after a few days the water levels stabilise and therefore, the crest levels of the weirs stabilise. However, it is found that within the simulation period of one year, this does not happen. The weirs therefore seem to be overly sensitive to small changes in water levels which are caused by either the weirs themselves through backwater effects or by small changes in bed levels. Another reason to critically evaluate the functioning of the weirs is that the crest levels of the weirs do not change in the case of a restart, while the water levels do, as is explained in Section 5.1.1. It is therefore recommended to review the functioning of the weirs.

For the simulations done in this study, it is verified that the crest levels of the weirs do change throughout the complete simulation period. It is uncertain what the influence of the uncertainty in the functioning of the weirs is on the model results in the Waal. On one hand, the weirs mostly influence the water levels in the Neder-Rijn, IJssel and Pannerdensch Kanaal. However, the weirs are originally designed to regulate the discharge distribution over both bifurcation points (i.e. the IJsselkop and the Pannerdensche Kop). Therefore, they also influence the water levels in the Waal. It is therefore expected that possible errors in the functioning of the weirs may affect the study area, but it is uncertain if there are indeed errors and if there are errors, to what extent they influence the study area.

### 5.1.3 Boundary conditions

The various scenarios for the upstream boundary conditions (the reference discharge scenario and discharge scenarios SMHM & HMHM) were selected based upon their mean and average yearly maximum and their difference with respect to the mean and average yearly maximum of the historical discharge time series. The choice for these selection criteria is fairly arbitrary. It is assumed that for the purpose of varying the discharge conditions in this study, which is to investigate the influence of an uncertainty in discharge, this is sufficient.

However, there are other criteria based upon which the discharge time series may be selected which may provide more information. For example, a threshold for high discharges may be defined, after which the time series is selected in which high discharges (i.e. discharges above this threshold) occur most frequently. Another option is to impose a range of different discharge scenarios. In this study, three scenarios are selected, but by increasing this number, an uncertainty range can be defined for the model results. Since the number of simulations is then greatly increased, this does require a lot of computational resources. Another scenario that could be explored without adding too much simulation time is a scenario with the same mean and the same maximum as the reference discharge scenario. The results from that simulation then show the sole influence of yearly varying discharge conditions.

The boundary condition that is imposed for the water level at the downstream boundaries is a Qh-relation, meaning that a specific water level is defined for a discharge. This relation does not change over time. However, the bed level does. In the downstream section of the Waal, sedimentation of up to 2 meters occurs over 50 years. Since the downstream condition is defined as a water level, rather than a water depth, an increase in bed level means that the water depth decreases over time. As a consequence, the same discharge has to flow through a smaller flow area, meaning that the flow velocities increase. Higher flow velocities induce erosion. In conclusion, the sedimentation at the downstream boundary may be underestimated due to the choice of downstream boundary conditions.

Additionally, Chavarrias et al. (2020) describes that the model has been calibrated such that the morphological development is captured accurately, while water levels may be wrongly calculated by up to a decimetre. Considering that a water level is defined at the downstream boundary, this may cause discrepancies between the calculated water level and the imposed water level at the downstream boundary. As a consequence, backwater effects may occur in the section upstream of the downstream boundary. It is uncertain how large these effects are and how far this effect travels into the study area, since the inaccuracy in the water levels cannot be determined without performing simulations with other models that do capture the hydrodynamics accurately.

The upstream boundary condition for the influx of sediment is defined using a ghost cell with a fixed bed level and sediment composition. Sediment that would be eroded from this cell enters the system at the upstream boundary. That means that the sediment influx is fully governed by the flow conditions at the upstream boundary. In reality, the sediment influx is dependent on the behaviour of the lower part of the German Rhine. This section has coarsened over the past decades, due to a combination of bed degradation and sediment nourishments using coarser sediment (Blom, 2016). As a consequence of the coarsening of this reach, an erosional wave is formed which travels downstream, enhancing bed degradation in the Dutch Rhine (Blom, 2016). Moreover, this limits the sediment influx into the Dutch Rhine. The degree to which sediment nourishments in the German section of the Rhine influence the bed level in the Dutch part of the Rhine is unknown, since it is difficult to extract such slow trends from the highly variable bed level and sediment composition data (Blom, 2016; Frings et al., 2019). However, if the sediment nourishments in the German Niederrhein do influence the bed development in the Waal, that means that the bed degradation in the Boven-Waal and Midden-Waal as found in Section 4.1 may be an underestimation of reality. To make an estimation of the effects of changes in the upstream sediment influx, it is recommended to do a sensitivity analysis. This can be implemented in the model by changing the sediment composition of the most upstream node. Another method is to adapt the model such that an annual sediment load is specified at the upstream boundary (Chavarrias et al., 2020). If that is the case, also different scenarios for the influx of sediment can be evaluated. Considering the large uncertainty in the influx of sediment and the effect of this on the bed level development in the Dutch Rhine (see also Section 5.2.2), it is interesting to test the influence of various sediment influx conditions on the model results.

### 5.1.4 Modelling of sediment transport

The Rhine branches model makes use of the active layer concept by Hirano (1971) to model sediment transport. However, the active layer concept is not able to reproduce the behaviour around armouring layers on the bed (Chavarrias and Ottevanger, 2021). In reality, a nourishment with a composition that is coarser than the bed may shelter the finer sediment underneath.

As a consequence, the sediment in the bed underneath the nourishment is less easily entrained. This reduces erosion at the location of the nourishment and induces erosion downstream of the nourishment. However, when the active layer concept is used, here with a thickness of 1 meter, the first meter of the bed surface is fully mixed. The coarse nourishment is therefore not able to form a protective layer over the bed surface. To limit the effect of this modelling method, it is decided to model the nourishments as if they replace the full active layer, as is explained in Section 3.2.3. However, even with this approach, the armouring effect may be underestimated. When a part of the nourishment is transported, the active layer is replenished with sediment from underneath, meaning that fine sediment becomes available for transport. The model results may therefore overestimate the sediment transport at the location of the nourishment and consequently underestimate the erosion occurring downstream of the nourishment. Niesten and Becker (2018) also conclude that besides the exclusion of shipping effects, this is the second main component which causes differences between the measured results of the pilot nourishment in the Boven-Rijn during low discharge conditions and the simulated results using a numerical model.

Above effect is further enhanced by the choice of modelling the sediment transport of the two sediment types, sand and gravel, with different sediment transport formulae. In the sediment transport formula for sand, the relation by Engelund and Hansen (1967), no hiding-exposure effects are included. The relation for gravel by Meyer-Peter and Müller (1948) does include hiding-exposure effects by adjusting the critical bed shear stress. As a result, sand particles do influence the mobility of gravel, while gravel particles do not influence the mobility of sand (Chavarrias et al., 2020). In reality, sand particles are also influenced by the presence of gravel (McCarron et al., 2019) and therefore, the transport of sand particles may be overestimated by the model.

It is expected that in general, the usage of two different sediment transport formulae for sand and for gravel has an effect on the results of the model. It means that when a nourishment is composed mostly of sand or mostly of gravel, the difference in their behaviour might not only be explained by the difference in their respective grain sizes, but also by the difference in their sediment transport formulae. This creates some uncertainty. However, since there does not exist one sediment transport formula that makes the right prediction of the sediment transport in all cases (Gomez and Church, 1989), a relation has to be chosen and consequently calibrated to model realistic behaviour. It is therefore not recommended to change these relations, but their possible effects should be considered when analysing the model results. To gain a better understanding of the effect of the different sediment transport formulae, the difference between composing a nourishment completely of the coarsest sand fraction and completely of the finest gravel fraction may be investigated.

Finally, the thickness of the active layer is chosen by Chavarrias et al. (2020). They note that differences between various choices for the thickness of the active layer become smaller for a more uniform sediment distribution. When a coarse nourishment is applied, the sediment distribution of that section becomes less uniform and consequently, the thickness of the active layer is of larger influence. It is therefore recommended to determine the influence of the active layer thickness on the results. The 'correct' thickness of the active layer cannot be determined by physics, since it is a modelling artefact. However, the thickness that reproduces the best results can be determined by comparing results from the pilot nourishments with modelling results, for example.

### 5.1.5 Modelled sediment composition of the bed

The initial sediment composition in the model is based on Sloff (2006), in which the sediment composition is based on measurements from 1995. Conversely, the elevation of the bed is based on measurements from 2019. Consequently, the sediment composition of the bed is based on data that is 25 years older than the data on which the bed level is based. It is expected that this has a large influence on the system. The bed level and sediment composition are largely dependent on each other, which makes that the development of these two aspects can not be viewed separately. This makes comparison between the trends that are found in this study and trends that are predicted by e.g. Programma Integraal Riviermanagement (2021) more difficult, since the results are effectively compared to a system with different initial conditions.

In 2020, Rijkswaterstaat did measurements in the Boven-Rijn and Waal to determine the median grain size of the surface of the bed, of which the results are available on the 4TU data repository (Ylla Arbós, 2021). The data set contains measurements between rkm 849 and 952, which are taken in the center of the river and 65 m to the left and right of the center. The measurements have been done using grab samplers and are taken at 500 m to 1 km spatial intervals. The data is highly uncertain since the grain size is highly variable over both space and time and the measurements have been taken only once and at a relatively low spatial density. However, qualitative comparison of the model results with the measurements can give an indication of the reliability of the model results.

Both the simulated and measured median grain sizes are shown in Figure 5.1. To eliminate some of the noise caused by the high spatial variability in longitudinal direction a moving average is taken with a window of 10 km for both the simulated results and the measurements. When no measurement data is available at a location, this location is omitted in calculation of the moving average. To minimise the effect of the spatial variability in transverse direction, the average is taken over the measurements on the left, centre and right of the river. The individual measurements are still shown in grey in Figure 5.1.

It is found that the simulated median grain size is in the same order of magnitude as the measured median grain size. Because of the high spatial and temporal variability of the sediment composition and therefore the large uncertainty in the measurement of the median grain size, a detailed comparison of the values has little value. However, the measurements do show a more gradual decrease in the median grain size around the Pannerdensche Kop. This is also in line with findings from Ylla Arbós et al. (2021), who state that the gravel-sand transition has shifted downstream. The sudden difference around the Pannerdensche Kop as found in the simulations might be explained by the nodal point relation that is used for the distribution of sediment at the bifurcation. It is recommended to do further research on whether this behaviour is realistic. This is also one of the recommendations by Paarlberg and Van Lente (2021).

If the initial sediment composition of the Rhein and Boven-Rijn is coarser, the coarsening wave travels sooner into the Waal. As a consequence, the degradation rate of the Waal is influenced. Therefore, this would have an influence on the results presented here, although the qualitative behaviour of the nourishments does not change.

The high erosion rates in the Rhein and Boven-Rijn in the first 30 years of the simulation may be explained by an initial sediment composition that is too fine. This may also be caused by the choice of the sediment transport formulae (Gomez and Church, 1989; Kitsikoudis et al., 2014; Kitsikoudis et al., 2015) and the calibration of their parameters or by the upstream boundary

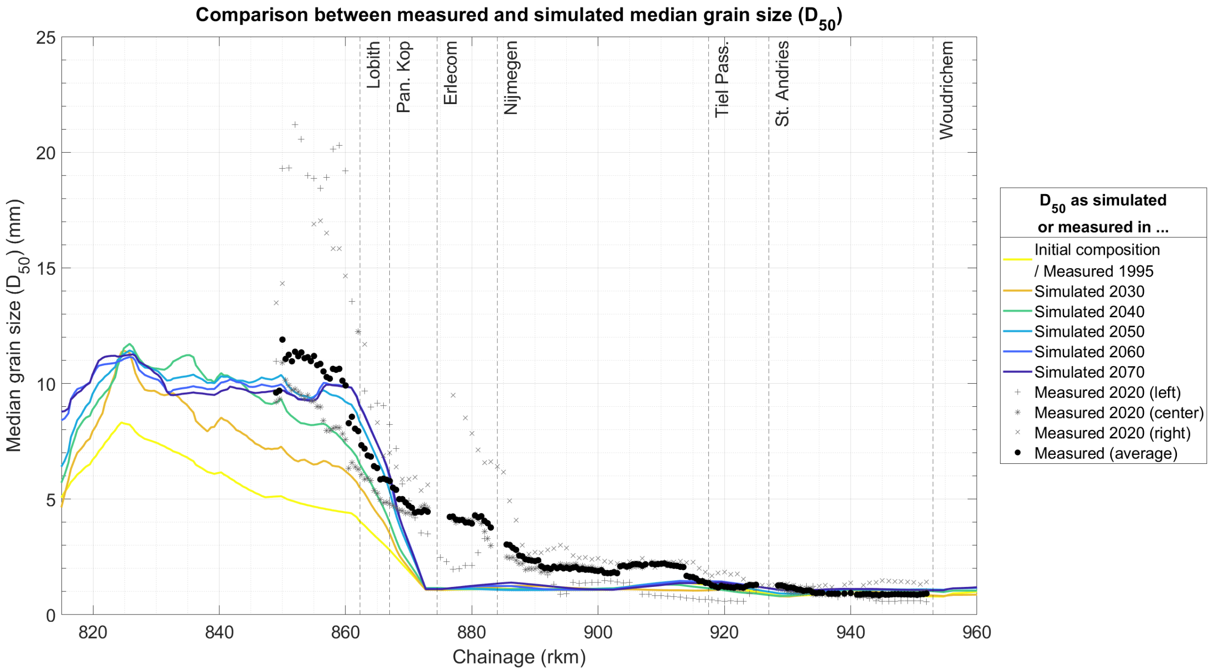


**Figure 5.1:** Comparison between the median grain size ($D_{50}$) as simulated under the reference discharge conditions and as measured in 2020 by Rijkswaterstaat (Ylla Arbós, 2021). Moving average with window size of 10 km is applied over both the measured and simulated data.

conditions for the influx of sediment. It is recommended to do further research on whether this behaviour is realistic when further analyses are done using this model. Paarlberg and Van Lente (2021) also mention this as one of their recommendations.

## 5.2 Practical implementation of nourishments

In this research, the effects of sediment nourishments are investigated. To be able to model these effects, simplifications have been made compared to reality. However, when a nourishment is to be implemented in the Waal, there are various aspects that should be considered in addition to its expected effect on the bed degradation. In Section 5.2.1, the influence of nourishments on other functions and branches is discussed. Section 5.2.2 describes the importance of gaining more insight into the upstream sediment influx.

### 5.2.1 Influence of nourishments on other parts and functions of the river

When a nourishment is implemented, it does not only have an effect on the reduction of bed degradation. Since the various functions and branches of the river depend on each other and interact with each other, the effect of nourishments on other functions and branches should be considered as well. Here, the following aspects are highlighted: navigability of the river, the effect on cables and pipes on the river bed and the discharge distribution at the bifurcation points.

**Navigability**

Currently, the fixed layer at Nijmegen is the shallowest part of the connection between the harbour of Rotterdam and the Ruhr area in Germany (Programma Integraal Riviermanagement, 2021). When the bed level around this layer degrades further, the navigability of the river during low discharges decreases even further. There are more examples of such fixed layers or structures in the river which do not degrade along with the bed around it. By reducing bed degradation the differences in bed level along the river can be minimised. Therefore, in the long term, nourishments can increase the navigability of the river through a reduction of bed degradation. However, when the nourishment is placed, it forms an obstacle on the river bed. Ships should be able to safely navigate the river after a nourishment has been executed. A requirement is therefore that the water depth may not be further reduced than 3.5 m below the agreed low water level (in Dutch: OLR = Overeengekomen Lage Rivierstand), which corresponds to the water level at a discharge of 984 $m^3/s$ (Becker, 2021). Furthermore, attention should be paid to the transition between the original bed and the nourishment. When the nourishment causes a bump on the river bed, this may pose hazard to ships due to the squat effect. The squat effect is caused by an area of low pressure that forms under a ship when it is moving over a shallow area and it causes the ship to lay deeper in the water and therefore closer to the bed (Duffy, 2008). Additionally, when a thick nourishment is placed in the vicinity of a river bend, the curvature of the channel induces a flow in the transverse direction, which may be enhanced by the sediment layer (Becker, 2021). This is also hazardous for ships. Becker (2021) found that both of these negative effects can be mitigated by gradually increasing the thickness of the nourished layer in the direction of the flow.

**Cables and pipes in and on the river bed**
In this study, the locations of the nourishments are chosen freely. However, Rijkswaterstaat Oost-Nederland (2018) has defined numerous areas of the river in which dredging and dumping of sediment is not allowed. When a nourishment is designed, the initial nourishment location has to be chosen such that it does not interfere with these areas. Moreover, when the nourishment is propagated downstream, it should be prevented that it forms an obstacle in a section where dredging is not allowed.

**Discharge distribution over the branches of the Dutch Rhine**
The current flood safety standards in the Netherlands are based on a fixed discharge distribution at the bifurcation points at the Pannerdensche Kop and the IJsselkop (Blom and Ylla Arbós, 2019). The current regulations (the 'Rivierkundig Beoordelingskader' (RKB)) prescribe that a single intervention may not induce a discharge difference of more than 5 $m^3/s$ in any Rhine branch at the bifurcation points when a discharge at Lobith of 16,000 $m^3/s$ is applied (Rijkswaterstaat, 2019). At a discharge at Lobith of 10,000 $m^3/s$, a difference of up to 20 $m^3/s$ is allowed (Rijkswaterstaat, 2019). While the nourishments in this study have not been evaluated under these discharge conditions, it is found that the nourishments studied here influence the discharge distribution and hence, the development of the bed in the Pannerdensch Kanaal. This effect becomes larger for larger volumes and for nourishments that are initially placed further upstream. It should be noted here that while there is a strict restriction with regards to the allowed change in discharge distribution, doing nothing and letting the bed further degrade also induces a change in discharge distribution, because the Waal is eroding faster than the Pannerdensch Kanaal (Becker, 2021; Barneveld et al., 2022; Klijn et al., 2022). When no interventions are done to stop bed degradation, negative consequences of a shift in discharge distribution will therefore also occur (Klijn et al., 2022).

The length over which a nourishment induces effects upstream is determined by its influence length. To check whether the results found in this study are realistic, the influence length is calculated. The full calculation is shown in Appendix B. The calculated influence length for a discharge of 2,221 $m^3/s$ and 5,000 $m^3/s$ and a reduction in influence of 50% and 5% of the original influence are shown in Table 5.1.

**Table 5.1:** Influence length as estimated for discharges of 2,221 $m^3/s$ and 5,000 $m^3/s$

| **Q** ($m^3/s$) | $L_{0.5}$ ($km$) | $L_{0.05}$ ($km$) |
|---|---|---|
| **2,221** | 15.6 | 67.7 |
| **5,000** | 26.8 | 116.3 |

Even though the values in Table 5.1 are just a coarse approximation of the influence length, it can be concluded that the bifurcation point is indeed within the influence length of the nourishments evaluated in this study, for a large range of discharges. Considering that the downstream end of the Midden-Waal (rkm 917.5) is located only 50.5 km downstream of the Pannerdensche Kop (rkm 867), a nourishment placed at any location in the Boven-Waal or Midden-Waal likely influences the bed level around the bifurcation point to some extent.

Changes in bed level around the bifurcation point can induce a shift in the discharge distribution. When the bed level of one outgoing branch degrades faster than another, that branch attracts more discharge at the bifurcation point. As a consequence, a smaller portion of the discharge goes through the other branch. The changes in discharge distribution with respect to the reference simulation are shown in Figure 5.2 for each nourishment scenario.

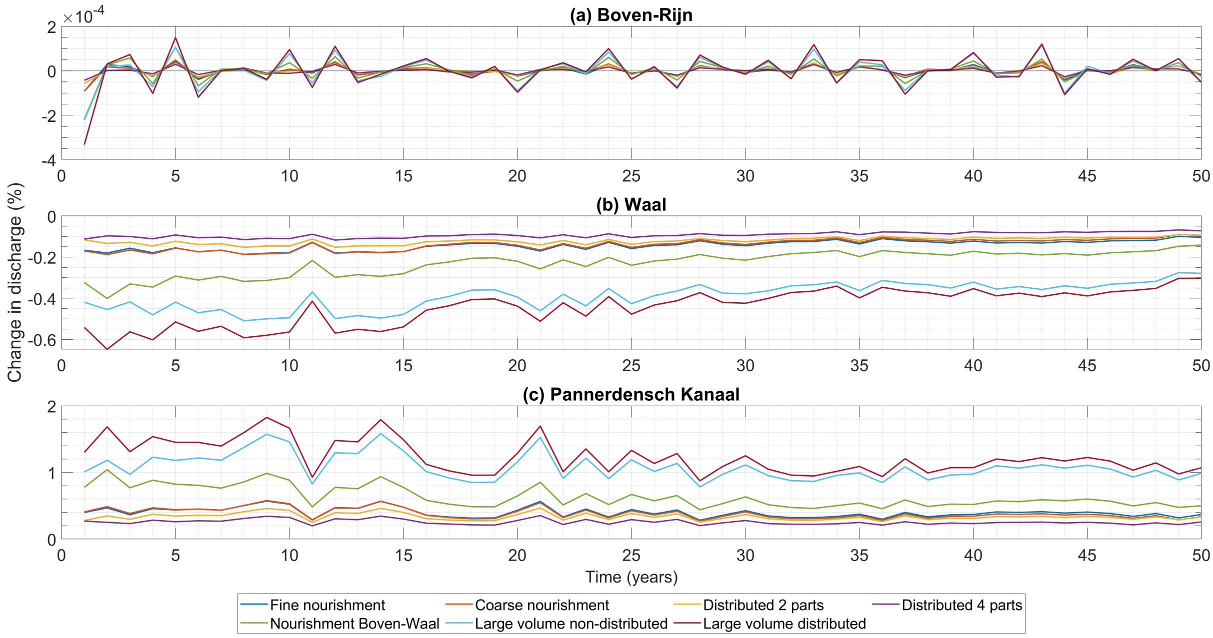


**Figure 5.2:** Relative difference in yearly cumulative discharge between the various nourishment simulations and the reference simulation. Measured at rkm 867 in the Boven-Rijn (a), at rkm 868 in the Waal (b) and at rkm 868 in the Pannerdensch Kanaal (c). Mind the difference in scaling between the subfigures.

The influence of the nourishments on the discharge in the Boven-Rijn is relatively small (the relative difference is $\pm\ 3 \cdot 10^{-4}$ % at maximum). However, the influence on the discharge distribution over the two outflow branches is significant. The absolute difference in the discharge distribution is equal, which makes sense since still approximately the same volume of water has to be distributed. However, since the total volume of water that is discharged through the Waal is higher than the total discharge through the Pannerdensch Kanaal, it makes a relative difference of ± 0.65% and ± 1.8% at maximum for the Waal and Pannerdensch Kanaal, respectively.

The difference in the discharge distribution caused by the nourishment may be enhanced by the presence of weirs in the Neder-Rijn. The weir at Driel is regulated based on water levels at Lobith and at the IJsselkop. When changes are made to the discharge distribution at the Pannerdensche Kop, this influences the discharge that arrives at the IJsselkop. The weirs may then attain a different level than in the reference situation. As a consequence, the discharge distribution at both bifurcation points is affected.

If the nourishment is found to influence the discharge distribution more than the RKB allows for a single intervention, it is possible to counter the effect of a nourishment by implementing an intervention in another branch of the Rhine (Gensen et al., 2021a). In the case of a nourishment in the Waal, this intervention should then most likely be implemented in the Pannerdensch Kanaal. Implementation of another intervention in the IJssel or the Neder-Rijn is also an option, although the influence on the bifurcation point at the IJsselkop should then also be considered and if needed, compensated. Gensen et al. (2021a) did a modelling study into compensating water level changes induced by interventions in the Waal by implementing an intervention in the Pannerdensch Kanaal and they found that this is most effective when the same type of intervention is applied in both branches. However, they also found that compensating the effect of an intervention in one branch by implementation of an intervention in another branch almost always leads to water level changes in one of the branches. Therefore, designing the nourishments in such a way that no changes in discharge occur is practically very difficult.

**Conclusion**
Bed degradation in the Waal occurs on a large scale. The problem is therefore likely not solved by implementing small interventions that only induce effects locally. It is therefore important to seek for a solution that mitigates bed degradation, but at the same time accounts for the other functions of the river system. When all functions of the river are accounted for when designing a solution, the chances that the solution will cause problems for other river functions in the future are minimised.

### 5.2.2 Gaining more insight into the upstream sediment influx

It is shown that the sediment transport to the Waal is largely dependent on the behaviour of the Rhein and Boven-Rijn. The behaviour of these sections is partly governed by the sediment influx from Germany. Frings et al. (2019) suggest that the influence of the nourishments that are done in the German Niederrhein have a larger effect on the morphodynamic development of the lower part of the Rhine than training works that have previously been implemented. Because the nourishments mostly consist of coarser sediment fractions, the nourishments cause a local coarsening of the bed level and a decrease in the volume of the sediment supply (Blom, 2016; Frings et al., 2019). This effect increases over time as the bed becomes increasingly coarse (Frings et al., 2019). Therefore, gaining more insight into the nourishments that are done in the Niederrhein can give us more insight into the behaviour of the Dutch Rhine. It is therefore recommended for river managers to seek for possibilities of cooperating with German river managers to gain more knowledge on the controls of the Dutch Rhine. If there is more knowledge available, another option could be to extend the morphological model further into Germany so that downstream effects of upstream sediment nourishments can also be modelled. It is difficult to determine these effects from measurements, because of the high natural variability in the composition of the bed surface and the difficulties in measuring this (Blom, 2016).

### 5.3 The potential of sediment nourishments to mitigate bed degradation in the Waal

Within the IRM programme, several goals are set with regards to maintaining the functions of the Dutch Rhine. Two of these goals are to stop bed degradation and to bring the bed level back to a bed level that it used to be (although which level this should be is still unclear) (Klijn et al., 2022). This research provides insight into how nourishments can be used to reach these goals. Based on the insights from this study, further direction can be given to the possible solutions that are shaped in the IRM programme.

This research shows that sediment nourishments have potential in mitigating bed degradation. However, it is also shown that the rate of bed degradation in the upper section of the Waal is large (65 cm on average over 50 years) and that singular sediment nourishments are only able to reduce bed degradation by orders of centimetres over 50 years. In order to stop bed degradation solely by repeatedly implementing sediment nourishments such as investigated in this study, very large volumes of sediment are required. The nourishment decreases exponentially in height in the first years after implementation of the nourishment. Implementing nourishments once will therefore not be enough to stop the bed degradation in the Waal.

The nourishments that are simulated in this study already have a relatively large volume. The largest nourishments studied here have a volume of approximately 690,000 $m^3$. For comparison, in the pilot studies in the Boven-Rijn that were conducted in 2016 and 2019, 70,000 $m^3$ of sediment was nourished (Blom, 2016; Becker, 2021) and the yearly sediment nourishments in the Oberrhein, Mittelrhein and Niederrhein (the German sections of the Rhine) consist of respectively 180,000 $m^3$, 100,000 $m^3$ and 75,000 $m^3$ (Blom, 2016). Therefore, to completely stop bed degradation, volumes of sediment are required that are much larger than the volumes of the nourishments that are conducted in the downstream part of the Rhine so far. While coarse sediment is present in large volumes in the river bed of the Rhine, it is uncertain whether this sediment is also available for mining (Van der Wal et al., 2019). Therefore, mining coarse sediment in for example Germany might be required, which leads to additional costs and a larger impact on the environment.

When the nourishment is driven by demand, the timing, amount and type of sediment can be chosen. However, it might be more feasible, cost-effective and sustainable to do supply-driven nourishments. That implies that nourishments are done when sediment becomes available from other projects (Van Vuren, 2022). This would be possible in the Waal, in which the downstream section is aggrading and the upstream section is degrading. The downstream section is dredged, meaning that this sediment becomes available for use within the system. That is an option that is not investigated in this research, which may have large potential for the IRM-programme. This sediment has a finer composition than the bed of the upstream section of the Waal. Therefore, it is interesting to do additional research on sediment nourishments using sediment with a finer composition than the original bed.

Following the results from the area-specific and the coarse nourishment, it is expected that a nourishment of a finer composition has a higher propagation speed and a higher dispersion rate than a nourishment with a composition equal to that of the bed. Moreover, Czapiga et al. (2022) conclude in their study that when fine sediment is nourished in small volumes, additional erosion may be induced rather than a reduction in erosion. This is because an increased sand content of the bed leads to increased exposure of particles to the flow, which leads to increased gravel transport (Wilcock, 1998; Wilcock et al., 2001). Therefore, in contrast to coarse nourishments, when fine sediment is available, it is better to apply one continuous nourishment (Czapiga et al., 2022).

When a nourishment strategy is designed, it first has to be determined what is leading in determining the design. There are multiple options for this, of which one is not necessarily better than another because they all have their advantages and drawbacks. Instead, a decision has to be made based on the possibilities and the relative importance of the set goals. However, as Czapiga et al. (2022) also stress, it is important to select one strategy and continue this strategy since changing strategies along the way increases the uncertainty of the outcome and reduces the mitigation capacity of the nourishments.

A first option is to let the optimal reduction of bed degradation be determining the nourishment strategy. Based on the results of this study it can be concluded that it is best to choose a coarse nourishment of a large volume that is placed as far upstream as possible and is distributed in multiple parts spaced several kilometres apart.

When the decision is made to let the supply of sediment be leading in determining the nourishment strategy, the characteristics of the sediment cannot be freely chosen. Therefore, the design of the nourishment has to be adapted to the characteristics of the available sediment. For example, when coarse sediment is available, the nourishment should be distributed in multiple parts. On the other hand, when fine sediment is available, it is better to apply one continuous nourishment.

Moreover, the current bed level of the river may dictate the possibilities of the nourishment strategy. The river still needs to be navigable after the nourishment has been implemented. A requirement is that the water depth may not be further reduced than 3.5 m below the agreed low water level (in Dutch: OLR = Overeengekomen Lage Rivierstand), which corresponds to the water level at a discharge of 984 $m^3/s$ (Becker, 2021). Therefore, the thickness and distribution of the nourishment may be governed by these restrictions. When only small volumes can be nourished at discontinuous locations, based on the results from this study and the study by Czapiga et al. (2022), it is advisable to choose a sediment composition that is coarser than the original bed surface.

When performing a nourishment pilot, it is logical to start by nourishing a relatively small volume of sediment to be able to assess the effects of a nourishment while keeping costs manageable. However, in this study, it is found that by nourishing a larger sediment volume, the effect of the nourishment can be enhanced by a larger factor than the factor with which the volume is increased. That means that performing pilots with relatively small nourishment volumes may not provide a complete image of the potential of sediment nourishments in mitigating bed degradation. Additionally, this research shows that by distributing the nourishment into several smaller parts, additional erosion downstream of the nourished reach can be prevented, while the length over which degradation is reduced may be increased. Therefore, by only performing singular nourishments, the full potential of nourishments in mitigating bed degradation may not be found. Therefore, if in a future stage of the IRM programme more pilot nourishments are designed, it is advised to also consider larger nourishments at various locations to be able to optimally assess the potential of using sediment nourishments.

To fully stop bed degradation, it is required to often repeat the nourishments or to combine the implementation of nourishments with other interventions which decrease the erosivity of the flow. Stopping bed degradation solely by implementing nourishments does not seem feasible, since this requires large volumes of sediment in a relatively short period of time. Therefore, it is advisable to combine the implementation of nourishments with measures that reduce the required sediment volume. Barneveld et al. (2019) conclude that the construction of side channels in the Waal may reduce the required nourishment volume in the Boven-Waal by 25,000 - 50,000 $m^3$/year (considering a degradation rate of 2 cm/year), which is a reduction of 14-33%. Besides the construction of side channels in the Waal, side channels could also be constructed in the Pannerdensch Kanaal. Rorink (2022) finds that this significantly increases the reduction of erosion. It is recommended to do further research on combining such interventions. Because of the non-linear nature of morphological development, the effect of combining the interventions is likely not just a superposition of the individual interventions.

An example in which side channels and nourishments can be combined is at the downstream end of a side channel. In the period in which the river moves to a new equilibrium state after the implementation of a side channel, local additional erosion is caused downstream of the side channel (Welsch, 2021; Rorink, 2022). Nourishments could be used in these locations to prevent large differences in the bed level. The nourishment should then have a local effect. The additional erosion is caused by an increase in sediment transport due to the increase in discharge at the downstream end of the side channel. The sediment composition of the nourishment therefore has to be sufficiently coarse to prevent the nourishment from being quickly transported downstream. Selecting the nourishment composition too coarse prevents the nourishment from being flushed away, but it also decreases the mobility of the bed. As a consequence, the sediment is not able to entrain sediment over the nourishment, leading to additional erosion downstream of the nourishment. The sediment composition of such a nourishment that is designed to locally reduce negative effects of other interventions should therefore be carefully chosen. The knowledge gained in this study on the influence of the sediment composition on the propagation speed and dispersion rate of the nourishment can be used to substantiate these choices.

Finally, one of the aims of the IRM programme is to increase the bed level to a ‘problem solving level’, meaning that it is restored to the level the bed was at a number of years ago. One of the questions that are to be answered in the IRM programme is to which level the bed should be brought back. When looking at the volume of the nourishments implemented in this study and the effect of those nourishments, it is questionable whether there is enough sediment available to bring the bed level back to the level it was at decades ago. Based on the results of this study, it is recommended to take into account the availability of sediment when making this decision.

To conclude, the nourishment strategy has to be based on the prioritised ambitions and the possibilities that are at hand to solve the problem. With the knowledge on the influence of the various characteristics of the nourishment, possible nourishment strategies can be determined. However, which strategy is the ‘best’ largely depends on which aspect the river managers determine is leading.

# 6 Conclusions & recommendations

In this chapter, Section 6.1 provides a conclusion on the answer to the main research question that is posed in this research. Moreover, in Section 6.2, recommendations for further research on the usage of sediment nourishments to mitigate bed degradation are given.

## 6.1 Conclusions

The aim of this research is to determine the morphological effects of nourishments in the Waal and to demonstrate how nourishments can be used to mitigate bed degradation in the Waal. To do this, various types of nourishments have been modelled using a 1D morphological model of the Dutch Rhine branches. Using the knowledge gained in this research and the answers to the sub-research questions that are asked, we can now answer the main research question:

**What are the morphological effects of sediment nourishments in the Waal and how can they be used to mitigate bed degradation?**

The model results show that the slope of the Waal continues to decrease in the next 50 years. Consequently, bed degradation in the Boven-Waal and Midden-Waal will continue, while the bed of the Beneden-Waal aggrades. It is found that by implementing nourishments in the Boven-Waal and Midden-Waal, erosion can be reduced over a section that is much longer than the original length of the nourishment itself. Over time, the nourishment decreases in height, increases in length and it is transported downstream. Eventually, all nourishments contribute to additional sedimentation in the Beneden-Waal. The sediment composition, initial location, nourishment distribution and the volume of the nourishment determine its propagation speed, rate of dispersion, influence on the bed level and its influence length. By adapting these characteristics, the positive effect of a reduction in erosion can be maximised, while the negative effects such as additional erosion in the degrading reach and additional sedimentation in the aggrading reach can be minimised.

It is found that to optimally reduce bed degradation by using a nourishment of a composition coarser than the bed, the nourishment should be placed as far upstream in the Waal as possible, be split into multiple nourishment parts and be composed of a large volume of sediment. Placing the nourishment further upstream causes the nourishment to have an effect on the degrading section of the Waal for a longer period. By increasing the volume of the nourishment, the maximum reduction of erosion and the length over which the nourishment reduces erosion are increased by a larger factor than with which the volume increased. Distributing the nourishment over multiple parts prevents additional erosion downstream of the nourishment and, when the nourishment parts are sufficiently large, the length over which the nourishment reduces erosion is increased in comparison to a non-distributed nourishment. Moreover, it is found that to fully stop the bed degradation, implementing a nourishment once is not sufficient. Naturally, when implementing a nourishment in practice, there are more aspects to consider besides the effectiveness of the intervention in reducing bed degradation. The knowledge on the behaviour of nourishments gained in this study can be used as a basis to define a nourishment strategy based on practical limitations and possibilities.

While the characteristics of the nourishment can be chosen for a large part, the discharge conditions that are imposed on the nourishments are a given. It is found that there is no clear trend visible in the change of behaviour of the bed level under variable discharge conditions. However, the yearly variability in discharge can induce changes in bed level larger than the height of the nourishments in this study. Moreover, the discharge conditions influence the propagation speed and the rate of dispersion of the nourishment, therefore influencing its effect on the reduction of bed degradation. This uncertainty in the discharge occurring after the implementation of the nourishment should therefore be accounted for when implementing a nourishment to mitigate bed degradation.

## 6.2 Recommendations

While the goal of this research is to contribute to the knowledge on how nourishments can be used to mitigate bed degradation, the research is limited in its scope and time resources. Therefore, various recommendations can be made on further research into the use of nourishments to mitigate bed degradation.

Firstly, to gain a better understanding of how a nourishment can be designed to obtain a maximum reduction in bed degradation, it is advised to do a sensitivity analysis on the various characteristics of the nourishment. In this study, it is found that the the nourishment volume, the dimensions, the location, the nourishment distribution and the sediment composition of the nourishment can have a significant influence on the behaviour of the nourishment. By varying these variables over a range of values, their relative effect on the effectiveness of reducing bed degradation can be determined. It is recommended not to only do this in a highly idealised setting with a constant discharge (such as in Czapiga et al. (2022)), but also to do this in a model in which a realistic river setting is modelled, with a variable discharge regime. This helps in understanding the behaviour of the nourishment in non-constant conditions.

Because of the scale on which bed degradation occurs, it is not feasible to fully counter bed degradation in the upcoming years by placing a nourishment once. While in this study only singular nourishments are studied because of the current limitations of the model, it is recommended to do research on the effect of repeated nourishments. It is expected that repeated nourishments influence each other, especially when the nourishments have a different composition than the original bed surface. Therefore, their effect is likely not just a superposition of a singular nourishment. Moreover, it is recommended to do more research on combining the effects of various interventions. For example, on combining the implementation of side channels and nourishments.

When the use of nourishments to mitigate bed degradation is further researched and the process goes to a design phase, it is recommended to also evaluate the effects of a nourishment in a more complex 2D-model. While this does increase computation times, this also allows to include 2D-effects. Currently only the main channel averaged bed level is evaluated. In reality, differences in erosion and sedimentation patterns may occur over the width of the main channel. Using a 2D-model allows to investigate these cross-sectional differences. Moreover, especially when placing a nourishment in the Boven-Waal, bend effects such as spiral flow and sorting become very important in determining the behaviour of the nourishment. In the 1D-model that is used here, these effects are not accounted for. It is then recommended to also include sediment deposition in the floodplains, since in reality, a part of the nourished sediment may be abstracted from the main channel.

In this study, a nourishment with a composition equal to that of the bed and nourishments with a composition coarser than the bed are investigated. In reality, it may be difficult to obtain coarse sediment for use in large-scale sediment nourishments. The downstream section of the Waal is aggrading. In this reach, the bed is dredged to maintain navigability of the river. This sediment may be re-used in nourishments. Since the mean grain size of the bed of the Waal decreases in downstream direction, this sediment is finer than the sediment composition of the bed in the degrading reach of the Waal. It is therefore recommended to do more research on implementing sediment nourishments with a composition finer than that of the original bed surface.

The effect of variable discharge regime on the development of the bed is considered in this research. In later stages of the design of interventions, the effects of varying discharge conditions may be further investigated by stochastic modelling. Moreover, in future studies, it is recommended to investigate the influence of other changes in the controls of the system. For example, to changes in the volume and sediment composition of the upstream sediment influx. Moreover, when longer time-scales are considered, the effects of climate change such as larger changes in the discharge regime and sea level rise also become relevant. Changes in the controls of the system may enhance or reduce autonomous bed degradation, which leads to the need for more or less interventions. Additionally, these changes may influence the behaviour of the interventions.

The focus of this research is to determine the effectiveness of nourishments on the reduction of bed degradation. However, the Waal is a river with multiple functions. When evaluating the effects of interventions to mitigate bed degradation, it is important to not solely focus on the effectiveness of the intervention on reducing bed degradation. The effect of the intervention on the other river functions should also be considered. In that way, it can be prevented that interventions that are implemented to solve one problem now, lead to other problems in the near future.

Moreover, more can be learned from research that has already started. In the past years, pilot studies have been done with sediment nourishments in the Boven-Rijn. The results from these pilot studies are currently not completely processed and published. It is advised to process the results of these nourishments and compare these with results from modelling studies. This can give an indication of the accuracy of a model in predicting the behaviour of a nourishment. The lessons learned can then be used to improve a model or to indicate the main uncertainties in the model results.

Finally, it is recommended for managers of the river system to cooperate with the managers of the German part of the Rhine. The sediment influx from upstream determines for a large part the behaviour of the Dutch Rhine. When more knowledge is gained on the sediment fluxes in Germany, this can be used to make better predictions on the behaviour of the Dutch Rhine in the future.

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# Appendices

# A Model definition and input

## A.1 Model equations

### 1D shallow water equations

The water flow is computed by solving the 1D shallow water equations: the continuity equation as shown in Equation 2 and the momentum equation as shown in Equation 3.

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

In which $u$ is the flow velocity [m$^3$/s]; $g$ is the gravitational acceleration [m/s$^2$]; $h$ is the water depth [m]; $z_b$ is the bed level [m+NAP]; and $C$ is the Chézy coefficient [m$^{1/2}$/s].

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} = 0 \tag{3}$$

### Sediment transport formulae

The relations as described below are taken from Chavarrias et al. (2020).

The sediment transport of the sand fractions is modelled using the relation by Engelund and Hansen (1967), given in Equation 4.

$$q^*_{\mathrm{b}k} = \alpha\frac{0.05}{C_\mathrm{f}}\left(\theta_k\right)^{5/2} \tag{4}$$

In which $q^*_{\mathrm{b}k}$ is the non-dimensional sediment transport rate [-] as determined by Equation 5; $\alpha$ is a calibration parameter [-], of which the values are shown in Table A.1; $C_\mathrm{f}$ is the non-dimensional friction coefficient [-] as determined by Equation 6; and $\theta_k$ is the Shield stress on size fraction $k$ [-] as determined by Equation 7.

$$q^*_{\mathrm{b}k} = \frac{q_{\mathrm{b}k}}{F_{\mathrm{a}k}\sqrt{g\Delta d_k^3}} \tag{5}$$

In which $q_{\mathrm{b}k}$ is the sediment transport rate [m$^2$/s]; $F_{\mathrm{a}k}$ is the volume of sediment of size fraction $k$ in the active layer [-]; $g$ is the gravitational acceleration [m/s$^2$]; $\Delta$ is the submerged specific density (= 1.65) [-]; and $d_k$ is the characteristic grain size of size fraction $k$ [m].

$$C_\mathrm{f} = \frac{n^2 g}{R_\mathrm{h}^{1/3}} \tag{6}$$

In which $n$ is the Manning friction coefficient [s/m$^{1/3}$] and $R_\mathrm{h}$ is the hydraulic radius [m].

$$\theta_k = \frac{\tau_b}{\rho g \Delta d_k} \tag{7}$$

In which $\tau_b$ is the bed shear stress [N/m$^2$] as defined by Equation 8.

$$\tau_\mathrm{b} = \rho g R_\mathrm{h} S_\mathrm{f} \tag{8}$$

In which $S_\mathrm{f}$ is the friction slope [-] as defined by Equation 9.

$$S_\mathrm{f} = \frac{C_\mathrm{f} u^2}{g R_\mathrm{h}} \tag{9}$$

In which $u$ is the main channel velocity [m/s].

**Table A.1:** Values of calibration parameter $\alpha$ [-] of the sediment transport relation by Engelund and Hansen (1967) (Equation 4) for each branch and sediment type (Chavarrias et al., 2020).

| **Branch** | $\alpha_{sand}$ [-] | $\alpha_{gravel}$ [-] |
|---|---|---|
| **Rhein & Boven-Rijn** | 0.47 | 0.60 |
| **Waal** | 0.18 | 0.32 |
| **Pannerdensch Kanaal** | 0.22 | 0.12 |
| **Neder-Rijn & Lek** | 0.10 | 0.10 |
| **IJssel** | 0.10 | 0.10 |

The sediment transport of the gravel fractions is modelled using the relation by Meyer-Peter and Müller (1948), given in Equation 10.

$$q^*_{\mathrm{b}k} = \alpha A \left(\theta_k - \xi_k \theta_c\right)^B \tag{10}$$

In which $q^*_{\mathrm{b}k}$ is the non-dimensional sediment transport rate [-] as determined by Equation 5; $\alpha$ is a calibration parameter [-]; $A$ is an equation specific parameter (= 8) [-]; $\theta_k$ is the Shield stress on size fraction $k$ [-] as determined by Equation 7; $\xi_k$ is the hiding-exposure relation [-] by Ashida and Michiue (1971) as defined in Equation 11; $\theta_c$ is the critical bed shear stress (= 0.025) [-]; and $B$ is another equation specific parameter (= 3/2) [-].

$$\xi_k = \begin{cases} 0.843 \left(\frac{d_k}{D_m}\right)^{-1} & \text{for } \frac{d_k}{D_m} \leq 0.4 \\ \left(\frac{\log_{10}(19)}{\log_{10}\left(19\frac{d_k}{D_m}\right)}\right)^2 & \text{for } \frac{d_k}{D_m} > 0.4 \end{cases} \tag{11}$$

In which $d_k$ is the characteristic grain size of size fraction $k$ [m]; and $D_m$ is the arithmetic mean grain size [m].

**Nodal-point relation**

The discharge distribution of sediment at the bifurcation points is determined by the nodal-point relation as defined by Sloff (2006), which is shown in Equation 12 (Chavarrias et al., 2020). The calibration parameter is defined separately for each bifurcation point and sediment type (Chavarrias et al., 2020). The calibration is done based on measurements by Frings et al. (2019).

$$\frac{Q_{\mathrm{b}k1}}{Q_{\mathrm{b}k2}} = \beta_k \frac{Q_1}{Q_2} \tag{12}$$

In which $Q_{\mathrm{b}kj}$ is the sediment transport rate of sediment fraction $k$ on the outgoing branch $j$ [$m^3/s$]; $Q_j$ is the discharge on the outgoing branch $j$ [$m^3/s$]; and $\beta_k$ is a calibration parameter [-], as defined in Table A.2.

**Table A.2:** Calibration parameter $\beta$ [-] of the nodal-point relation by Sloff (2006) (Equation 12) (Chavarrias et al., 2020).

| **Bifurcation** | Outgoing branch 1 | Outgoing branch 2 | $\beta_{sand}$ [-] | $\beta_{gravel}$ [-] |
|---|---|---|---|---|
| **Pannerdensche Kop** | Waal | Pannerdensch Kanaal | 1.79 | 1.79 |
| **IJsselkop** | Neder-Rijn | IJssel | 1.35 | 0.99 |

## A.2 Boundary conditions

### A.2.1 Statistics of generated bootstrap resampled discharge time series

**Table A.3:** Statistics of the 100 synthetic discharge time series as generated by bootstrap resampling individual hydrologic years from the historical discharge time series: the mean and average yearly maximum and their respective difference to the historical discharge time series. The time series that are selected as the reference discharge scenario, discharge scenario SMHM and discharge scenario HMHM are highlighted in yellow. The selected time series are plotted in Figures A.2 until A.4.

| | **Mean** ($m^3/s$) | **Difference** | **Avg. yearly max.** ($m^3/s$) | **Difference** | **Scenario** |
|---|---|---|---|---|---|
| **1** | 2240 | 1.5% | 6726 | 4.7% | |
| **2** | 2187 | -0.9% | 6103 | -5.0% | |
| **3** | 2221 | 0.7% | 6360 | -1.0% | Reference |
| **4** | 2298 | 4.2% | 7182 | 11.8% | |
| **5** | 2212 | 0.3% | 6561 | 2.1% | |
| **6** | 2152 | -2.5% | 6365 | -0.9% | |
| **7** | 2185 | -1.0% | 6034 | -6.1% | |
| **8** | 2191 | -0.7% | 6229 | -3.0% | |
| **9** | 2363 | 7.1% | 6901 | 7.4% | |
| **10** | 2292 | 3.9% | 6472 | 0.7% | |
| **11** | 2179 | -1.2% | 6212 | -3.3% | |
| **12** | 2154 | -2.4% | 6090 | -5.2% | |
| **13** | 2132 | -3.4% | 6237 | -2.9% | |
| **14** | 2125 | -3.7% | 5986 | -6.8% | |
| **15** | 2160 | -2.1% | 6238 | -2.9% | |
| **16** | 2167 | -1.8% | 5868 | -8.7% | |
| **17** | 2329 | 5.6% | 6668 | 3.8% | |
| **18** | 2241 | 1.6% | 7022 | 9.3% | SMHM |
| **19** | 2157 | -2.2% | 6045 | -5.9% | |
| **20** | 2191 | -0.7% | 6378 | -0.7% | |
| **21** | 2310 | 4.7% | 6671 | 3.8% | |
| **22** | 2197 | -0.4% | 6288 | -2.1% | |
| **23** | 2210 | 0.2% | 6358 | -1.0% | |
| **24** | 2288 | 3.7% | 6515 | 1.4% | |
| **25** | 2123 | -3.8% | 5963 | -7.2% | |
| **26** | 2281 | 3.4% | 6765 | 5.3% | |
| **27** | 2200 | -0.3% | 6086 | -5.3% | |
| **28** | 2103 | -4.7% | 5870 | -8.6% | |
| **29** | 2193 | -0.6% | 6512 | 1.4% | |
| **30** | 2145 | -2.8% | 5861 | -8.8% | |
| **31** | 2201 | -0.2% | 6374 | -0.8% | |
| **32** | 2227 | 0.9% | 6510 | 1.3% | |
| **33** | 2193 | -0.6% | 6027 | -6.2% | |
| **34** | 2217 | 0.5% | 6290 | -2.1% | |
| **35** | 2153 | -2.4% | 6262 | -2.5% | |
| **36** | 2231 | 1.1% | 6592 | 2.6% | |

**Table A.3 continued from previous page**

| | Mean ($m^3/s$) | Difference | Avg. yearly max. ($m^3/s$) | Difference | Scenario |
|---|---|---|---|---|---|
| **37** | 2092 | -5.2% | 6059 | -5.7% | |
| **38** | 2261 | 2.5% | 6583 | 2.5% | |
| **39** | 2132 | -3.4% | 6232 | -3.0% | |
| **40** | 2251 | 2.0% | 6795 | 5.8% | |
| **41** | 2165 | -1.9% | 6244 | -2.8% | |
| **42** | 2212 | 0.2% | 6523 | 1.5% | |
| **43** | 2275 | 3.1% | 6583 | 2.5% | |
| **44** | 2203 | -0.2% | 6514 | 1.4% | |
| **45** | 2313 | 4.8% | 6892 | 7.3% | |
| **46** | 2224 | 0.8% | 6547 | 1.9% | |
| **47** | 2179 | -1.2% | 6565 | 2.2% | |
| **48** | 2138 | -3.1% | 6408 | -0.3% | |
| **49** | 2097 | -4.9% | 6203 | -3.5% | |
| **50** | 2175 | -1.4% | 6234 | -3.0% | |
| **51** | 2257 | 2.3% | 6446 | 0.3% | |
| **52** | 2178 | -1.3% | 6366 | -0.9% | |
| **53** | 2155 | -2.3% | 6262 | -2.5% | |
| **54** | 2267 | 2.8% | 6554 | 2.0% | |
| **55** | 2237 | 1.4% | 6603 | 2.8% | |
| **56** | 2209 | 0.1% | 6514 | 1.4% | |
| **57** | 2269 | 2.9% | 6515 | 1.4% | |
| **58** | 2219 | 0.6% | 6494 | 1.1% | |
| **59** | 2111 | -4.3% | 6310 | -1.8% | |
| **60** | 2235 | 1.3% | 6575 | 2.3% | |
| **61** | 2124 | -3.7% | 5964 | -7.2% | |
| **62** | 2213 | 0.3% | 6363 | -1.0% | |
| **63** | 2208 | 0.1% | 6705 | 4.4% | |
| **64** | 2266 | 2.7% | 6551 | 2.0% | |
| **65** | 2262 | 2.5% | 6618 | 3.0% | |
| **66** | 2217 | 0.5% | 6124 | -4.7% | |
| **67** | 2218 | 0.5% | 6152 | -4.2% | |
| **68** | 2231 | 1.1% | 6531 | 1.7% | |
| **69** | 2236 | 1.3% | 6761 | 5.2% | |
| **70** | 2196 | -0.5% | 6527 | 1.6% | |
| **71** | 2160 | -2.1% | 6276 | -2.3% | |
| **72** | 2280 | 3.3% | 6684 | 4.0% | |
| **73** | 2229 | 1.0% | 6412 | -0.2% | |
| **74** | 2132 | -3.4% | 6128 | -4.6% | |
| **75** | 2175 | -1.4% | 6510 | 1.3% | |
| **76** | 2154 | -2.4% | 6244 | -2.8% | |
| **77** | 2193 | -0.6% | 6242 | -2.8% | |
| **78** | 2323 | 5.3% | 6999 | 8.9% | HMHM |
| **79** | 2204 | -0.1% | 6706 | 4.4% | |
| **80** | 2225 | 0.8% | 6641 | 3.4% | |
| **81** | 2173 | -1.5% | 6486 | 1.0% | |
| **82** | 2203 | -0.1% | 5918 | -7.9% | |

**Table A.3 continued from previous page**

| | Mean (m$^3$/s) | Difference | Avg. yearly max. (m$^3$/s) | Difference | Scenario |
|---|---|---|---|---|---|
| **83** | 2323 | 5.3% | 6431 | 0.1% | |
| **84** | 2213 | 0.3% | 6691 | 4.1% | |
| **85** | 2207 | 0.0% | 6525 | 1.6% | |
| **86** | 2198 | -0.4% | 6250 | -2.7% | |
| **87** | 2188 | -0.8% | 6625 | 3.1% | |
| **88** | 2237 | 1.4% | 6534 | 1.7% | |
| **89** | 2290 | 3.8% | 6305 | -1.9% | |
| **90** | 2199 | -0.3% | 6383 | -0.6% | |
| **91** | 2205 | -0.1% | 6696 | 4.2% | |
| **92** | 2200 | -0.3% | 6448 | 0.4% | |
| **93** | 2167 | -1.8% | 6230 | -3.0% | |
| **94** | 2265 | 2.7% | 6596 | 2.7% | |
| **95** | 2172 | -1.5% | 6681 | 4.0% | |
| **96** | 2231 | 1.1% | 6474 | 0.8% | |
| **97** | 2317 | 5.0% | 6797 | 5.8% | |
| **98** | 2143 | -2.9% | 6123 | -4.7% | |
| **99** | 2154 | -2.4% | 6146 | -4.3% | |
| **100** | 2223 | 0.8% | 6402 | -0.4% | |

### A.2.2 Time series upstream boundary conditions

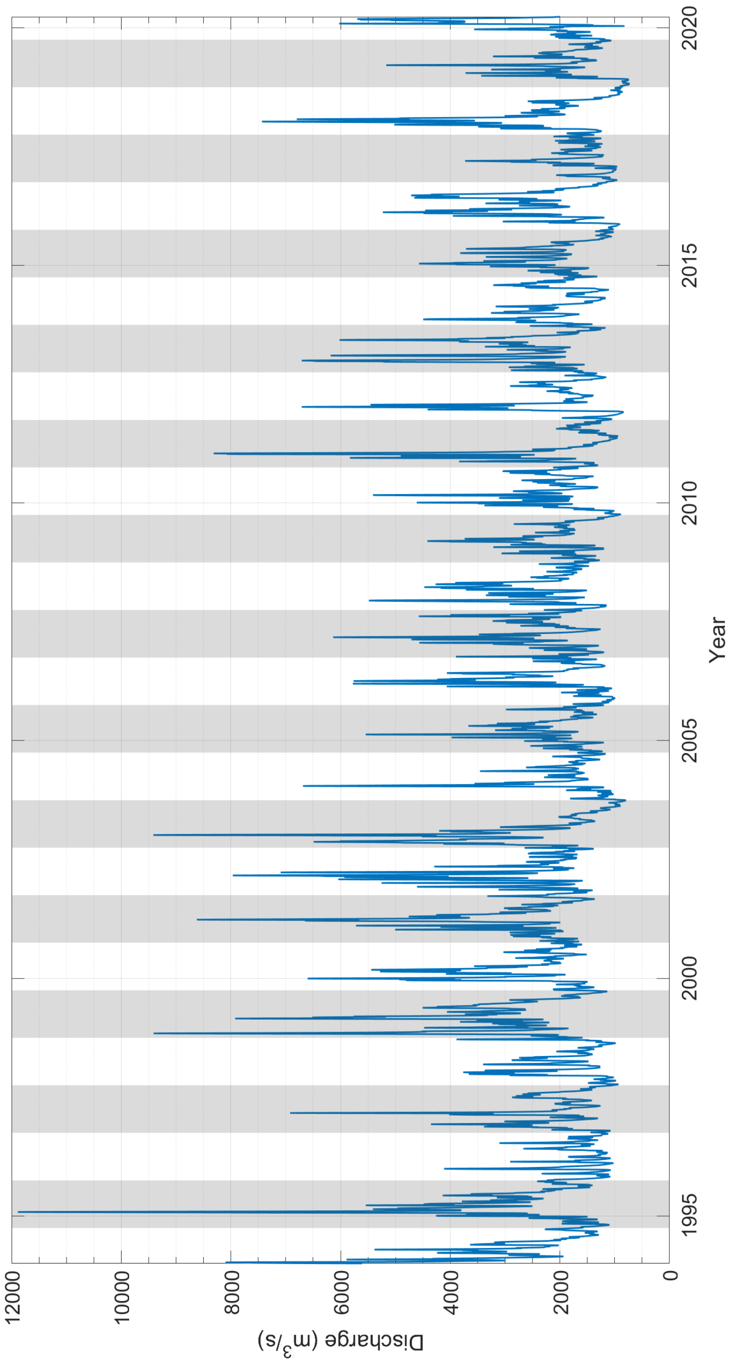


**Figure A.1:** Historical discharge time series from 1994 until 2020. The hydrological years are indicated as grey or white bands.

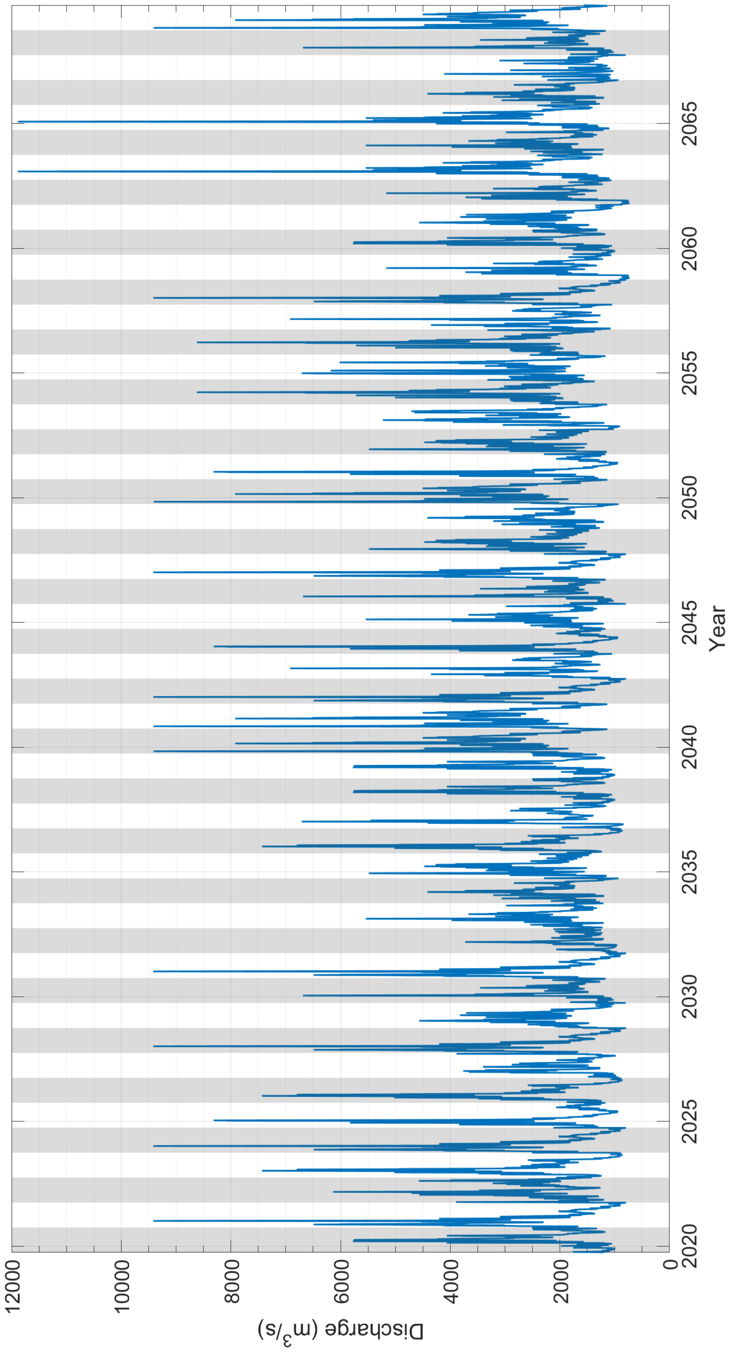


**Figure A.2:** Reference simulation discharge series from October 1, 2019 until October 1, 2069. Bootstrap resampled from the historical discharge time series as shown in Figure A.1. The hydrological years are indicated as grey or white bands.

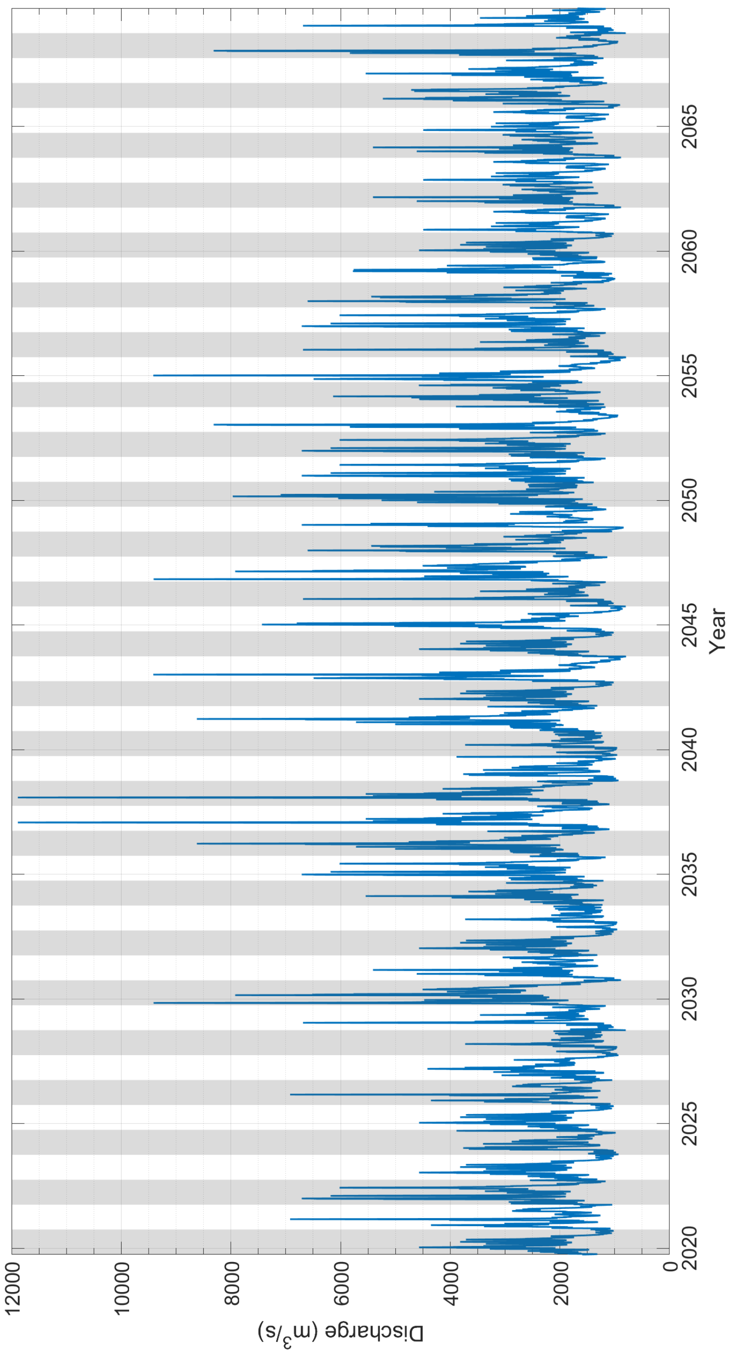


**Figure A.3:** SMHM scenario discharge series from October 1, 2019 until October 1, 2069. Bootstrap resampled from the historical discharge time series as shown in Figure A.1. The hydrological years are indicated as grey or white bands.

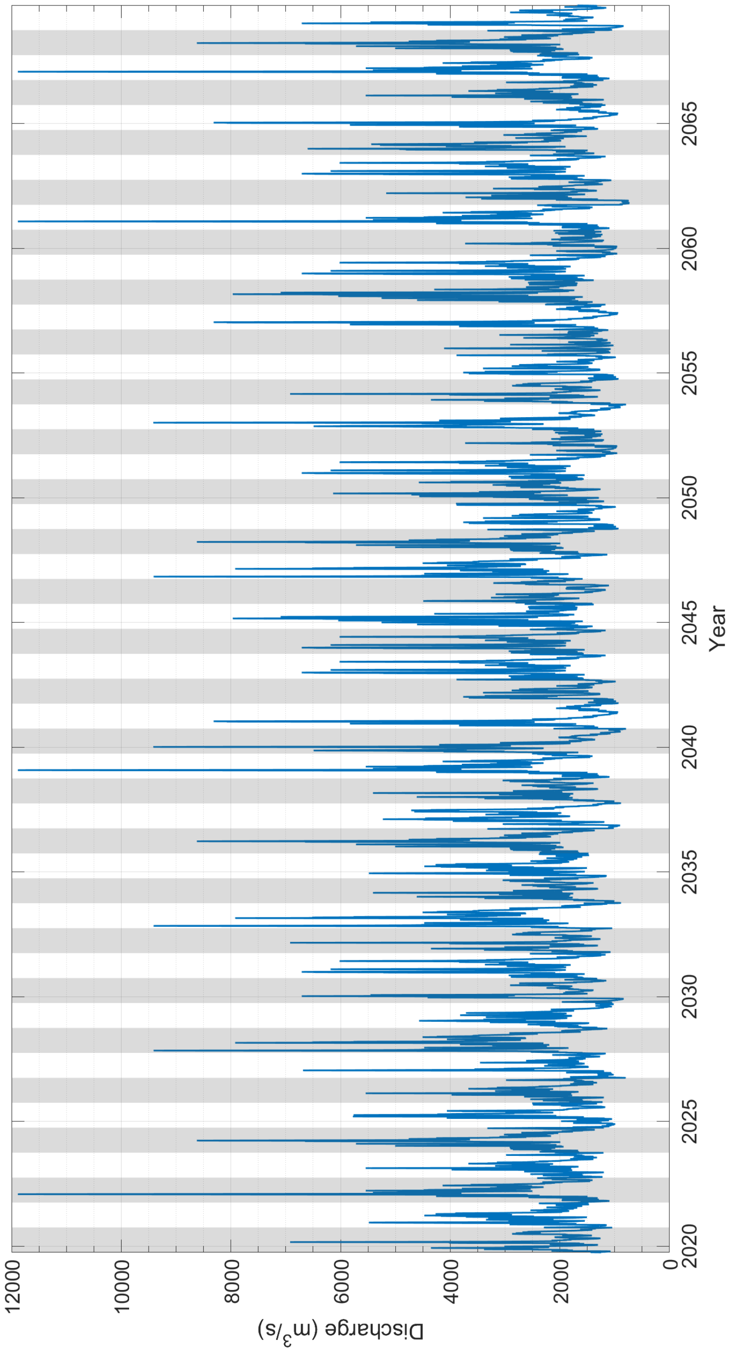


**Figure A.4:** HMHM scenario discharge series from October 1, 2019 until October 1, 2069. Bootstrap resampled from the historical discharge time series as shown in Figure A.1. The hydrological years are indicated as grey or white bands.

### A.2.3 Time series downstream boundary conditions

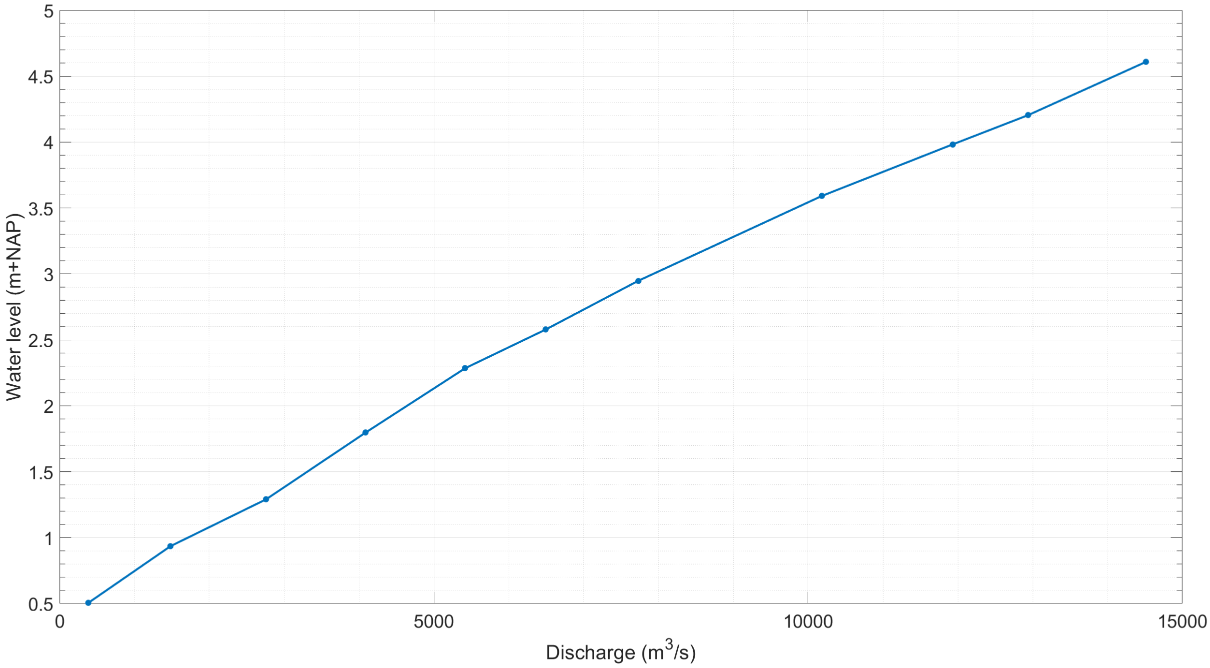


**Figure A.5:** Q-h relation imposed at the downstream boundary at Hardinxveld in the Waal. Data gotten from Paarlberg and Van Lente (2021).

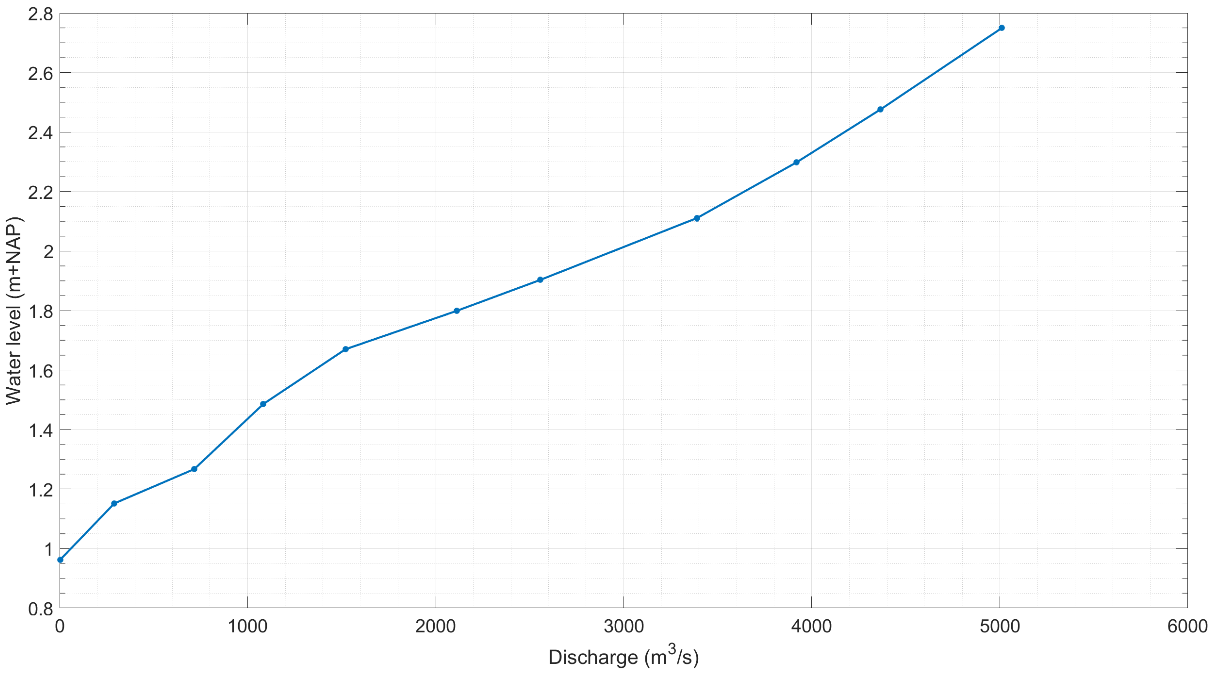


**Figure A.6:** Q-h relation imposed at the downstream boundary at Krimpen in the Lek. Data gotten from Paarlberg and Van Lente (2021).

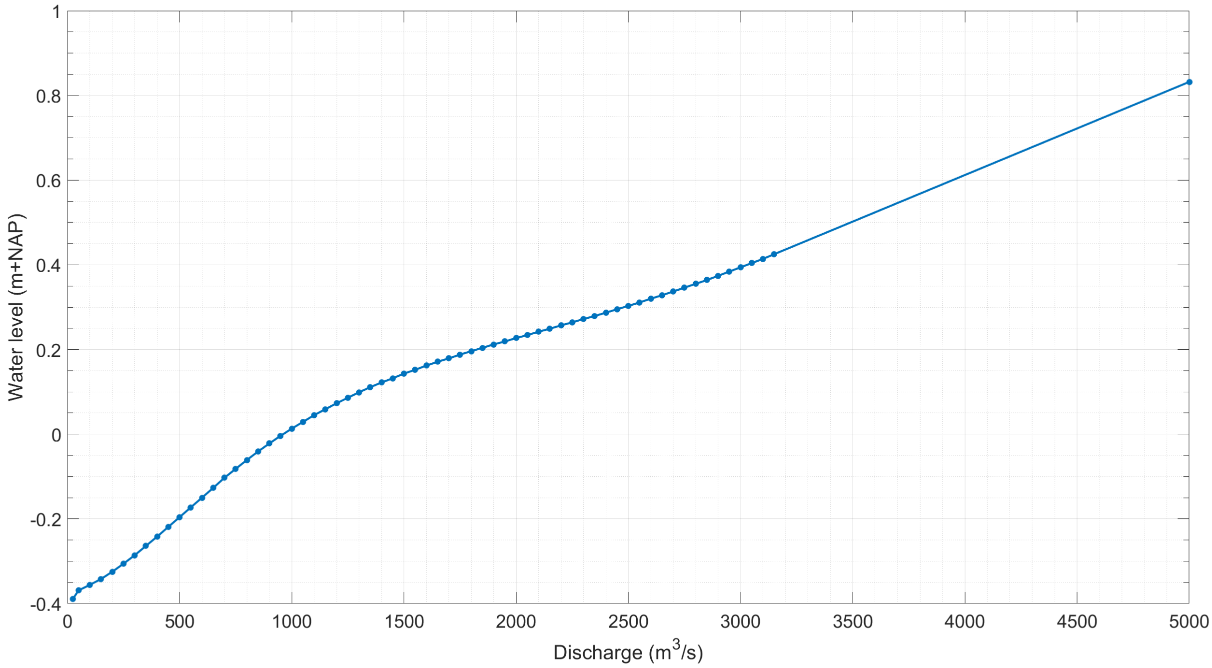


**Figure A.7:** Q-h relation imposed at the downstream boundary at the Kattendiep and Keteldiep in the IJssel. Data gotten from Paarlberg and Van Lente (2021).

## A.3 Locations of nourishments


**Figure A.8:** Simulation 2 & 3. Nourishment in the Midden-Waal; rkm 889-891. The label indicates the node ID and the chainage of the node according to the format 'ID_Chainage'.

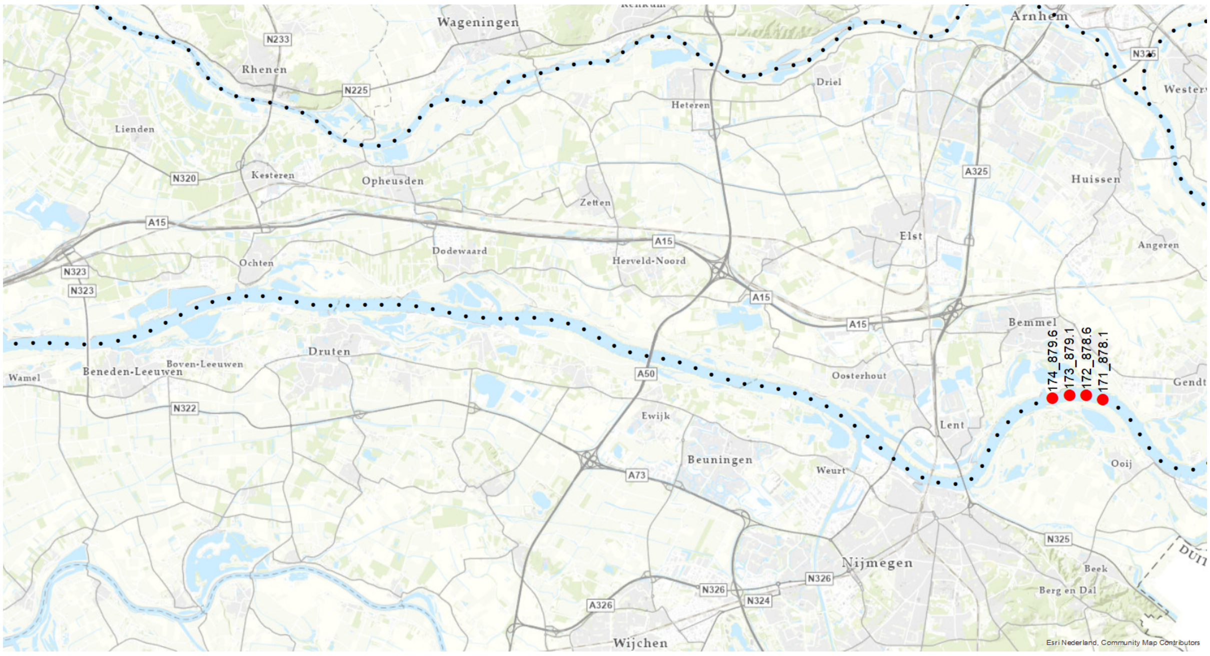


**Figure A.9:** Simulation 4. Nourishment in the Boven-Waal; rkm 878-880. The label indicates the node ID and the chainage of the node according to the format 'ID_Chainage'.


**Figure A.10:** Simulation 5, 11 & 12. Nourishment in the Midden-Waal; rkm 889-890 & rkm 901-902. The label indicates the node ID and the chainage of the node according to the format 'ID_Chainage'.

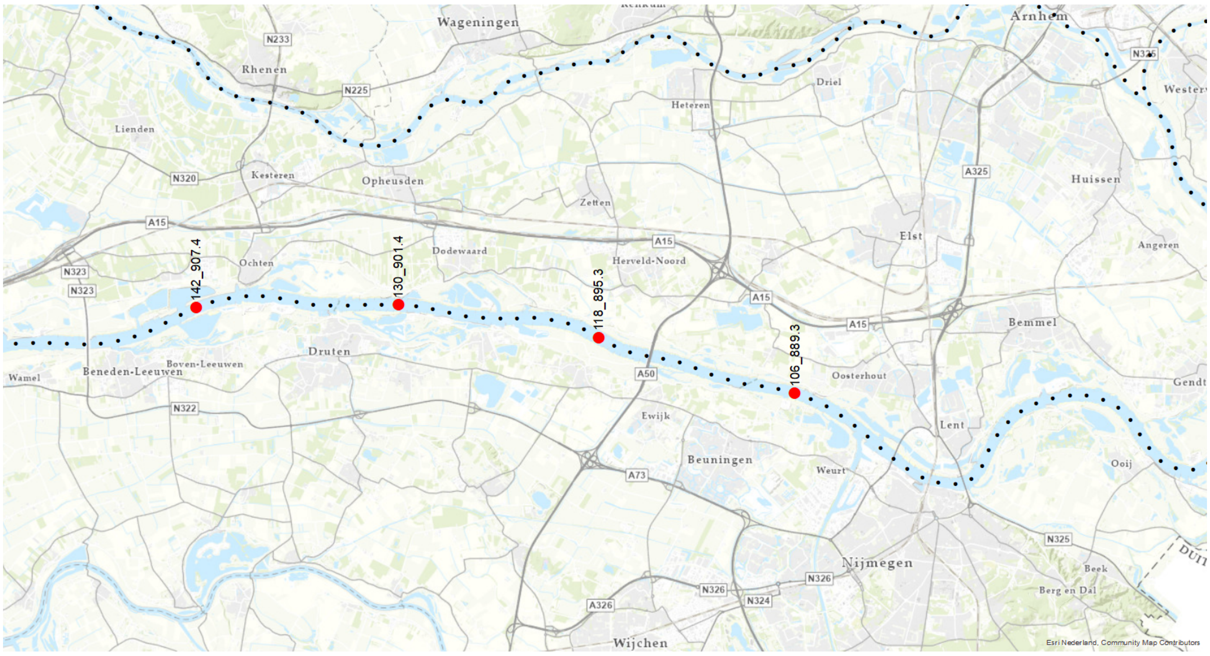


**Figure A.11:** Simulation 6. Nourishment in the Midden-Waal; rkm 889-889.5, rkm 895-895.5, rkm 901-901.5 & rkm 907-907.5. The label indicates the node ID and the chainage of the node according to the format 'ID_Chainage'.

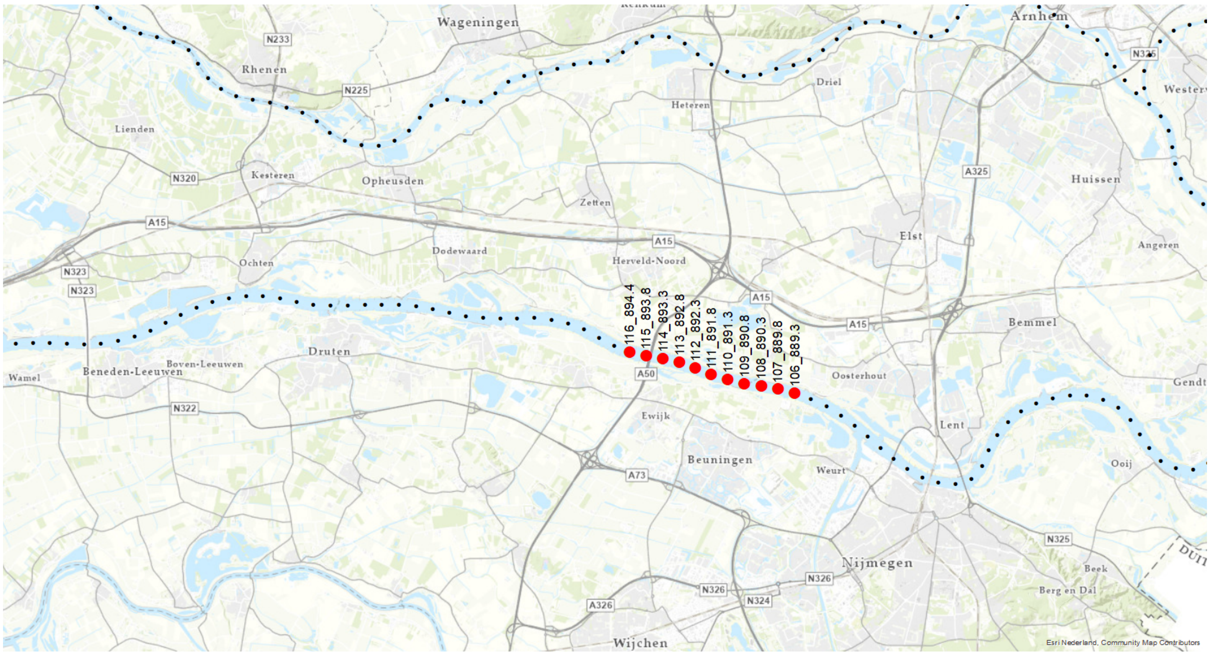


**Figure A.12:** Simulation 7. Nourishment in the Midden-Waal; rkm 889-894.5. The label indicates the node ID and the chainage of the node according to the format 'ID_Chainage'.

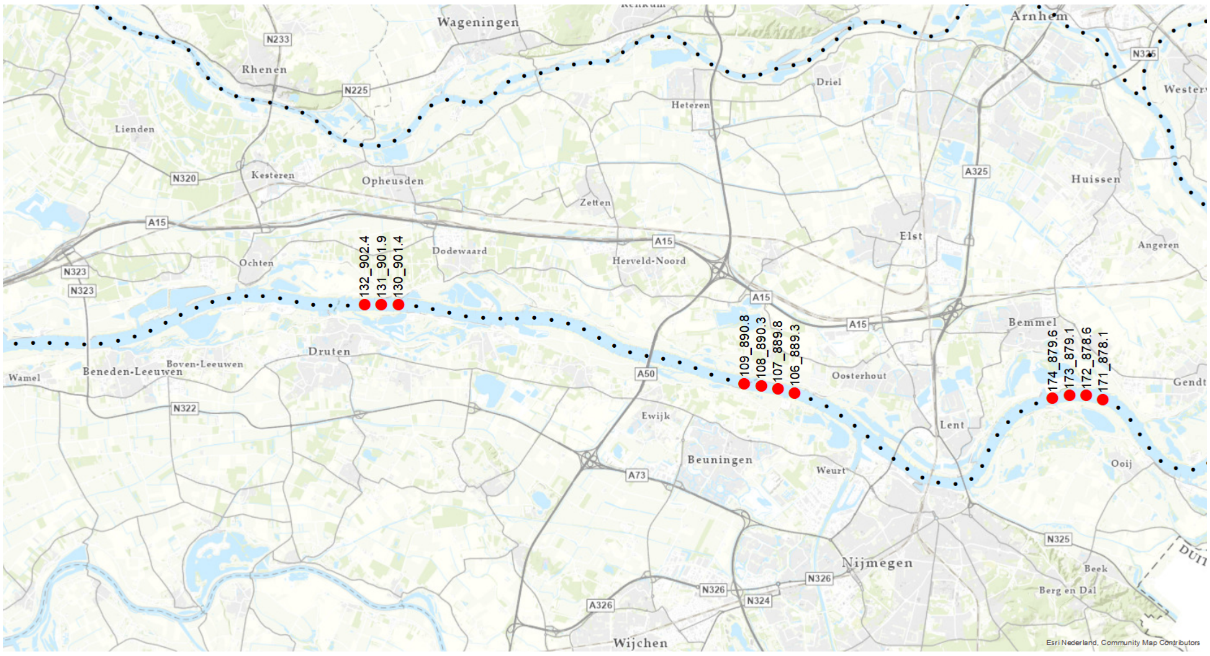


**Figure A.13:** Simulation 8. Nourishment in the Boven-Waal & Midden-Waal; rkm 878-880, rkm 889-891 & rkm 901-902.5. The label indicates the node ID and the chainage of the node according to the format 'ID_Chainage'.

## A.4 Determination of the nourishment composition

Firstly, the sediment composition of the bed at the location of the nourishment is analysed. Figure A.14 shows the initial sediment composition of the bed at the location of the nourishment in the Midden-Waal, as well as the sediment composition after 50 years in the reference simulation. This shows that the mean grain size increases over time, even though the contribution of the coarsest fractions decreases. This is seen by the lines intersecting around the sixtieth percentile and the fact that the $D_{50}$ is larger after 50 years than initially, while the $D_{90}$ is initially larger than after 50 years. The decision is made to design the nourishment such that it is generally coarser than the bed at all times during the simulation. That means that the composition is chosen in such a way that the $D_{10}$, $D_{50}$ and $D_{90}$ of the nourishment are larger than that of the bed in both its initial and final state after 50 years of development.

Secondly, it is determined which sediment fractions are included in the nourishment. Figure A.15 shows the volume fraction of each sediment fraction in the active layer at the location of the nourishment in the Midden-Waal in the reference simulation. From Figure A.15, it can be seen that the finest sediment fractions, fraction 1 to 4, are mostly flushed away within the first 20 years of the simulation. That means that they would not contribute significantly to the effect of a coarse nourishment. Furthermore, it is expected that in practice, the finest fractions will be already transported in suspension before reaching the bed during the nourishment operation (Becker, 2021). Since nourishments are modelled here as an artificial heightening of the bed, this effect cannot be accounted for. The decision is therefore made not to include the finest four fractions in the nourishment. This approach is also taken by Becker (2021) in her modelling study to the effects of nourishments in the Boven-Waal.

As is explained by Klijn et al. (2022), there are two options for choosing the composition of the nourishment. The nourishment can be fully mobile or semi-mobile. Since the goal is to

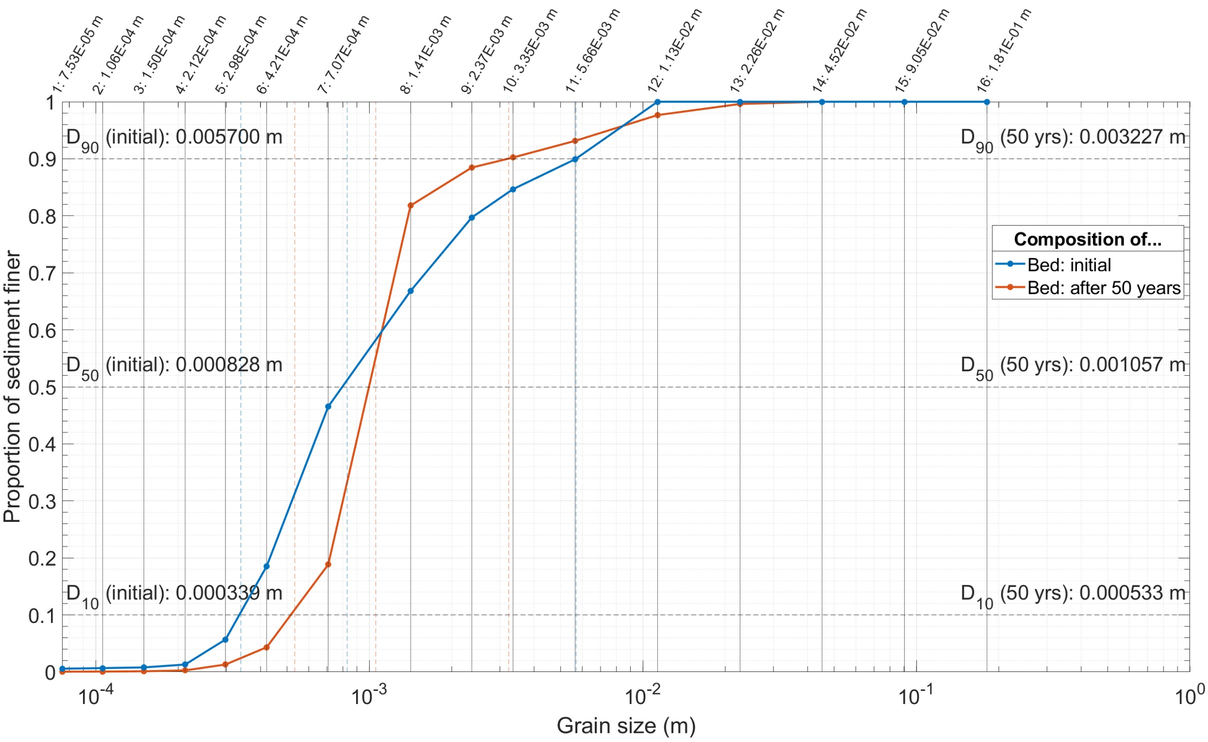


**Figure A.14:** Initial and final sediment composition of the bed at the location of the nourishment in the Midden-Waal (rkm 890) in the reference simulation. The values on the left and right correspond to the initial and final state, respectively. The values on top show the grain sizes for each sediment fraction, as shown in Table 3.1.

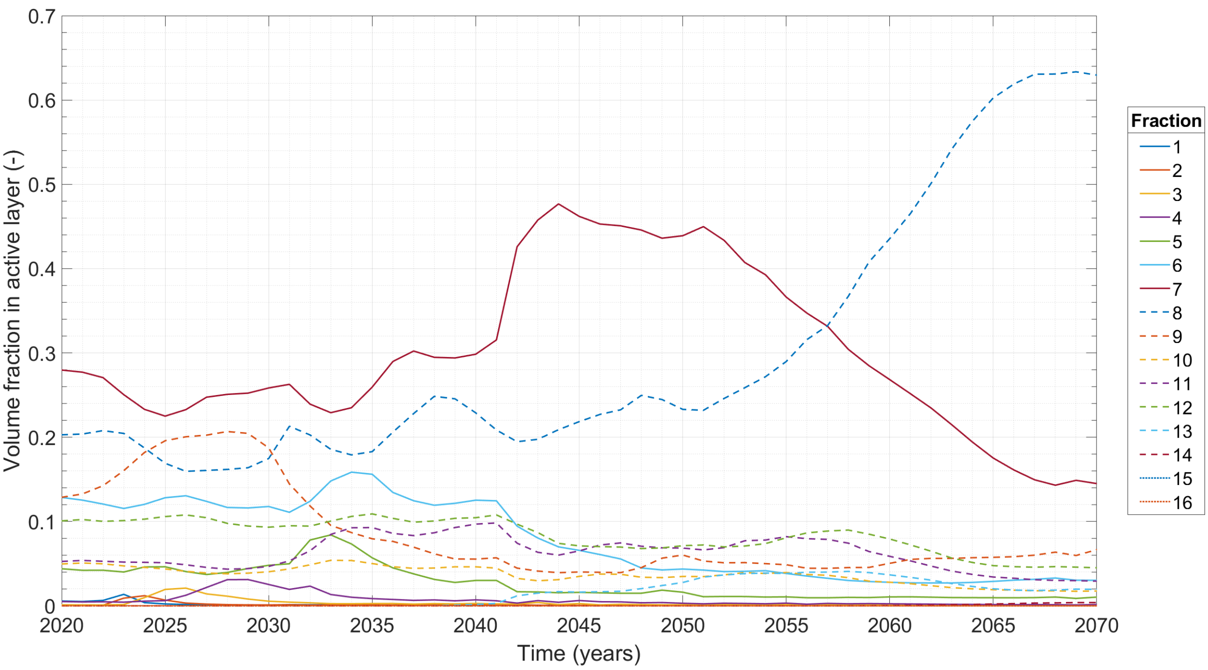


**Figure A.15:** Volume fraction of each sediment fraction in the active layer at the location of the nourishment in the Midden-Waal (rkm 890) in the reference simulation. Fraction 1 is the finest fraction, while fraction 16 is the most coarse fraction.

mitigate erosion over a larger reach, the decision is made to design a fully mobile nourishment. However, one that is coarser than the bed so that it stays in place for a certain period after nourishing. Figure A.16 shows the yearly sediment transport per sediment fraction. It is found that sediment fraction 15 and 16 are immobile throughout the simulation period. Fraction 14 is only slightly mobile at the end of the simulation period (after +/- 30 years). Based on this information, the decision is made to compose the nourishment of fractions 8 to 13. Fraction 8 is a sand fraction, while fraction 9 to 13 are gravel fractions (their characteristic grain sizes are shown in Table 3.1).

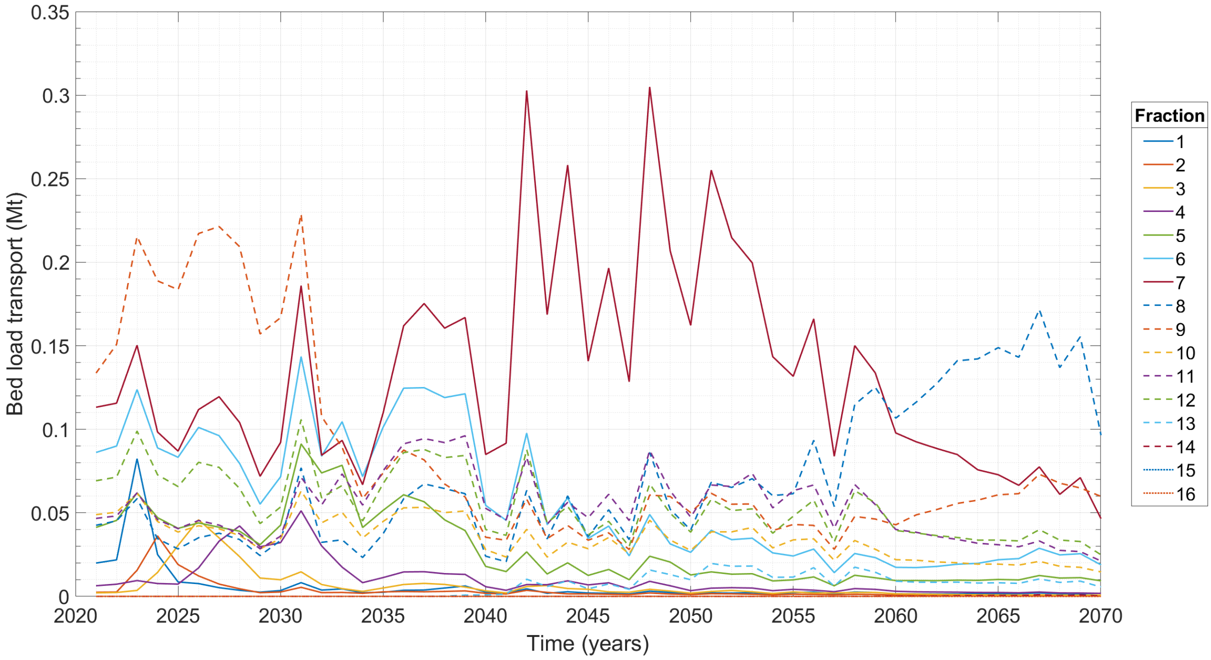


**Figure A.16:** Yearly sediment transport per sediment fraction at the location of the nourishment in the Midden-Waal (rkm 890) in the reference simulation. Fraction 1 is the finest fraction, while fraction 16 is the most coarse fraction.

# B Estimation of the influence length of interventions in the Waal

The influence length of an intervention in a system in equilibrium is determined by Equation 13 (Ribberink, 2011). In this equation, $L$ is the influence length $[m]$; $\alpha$ is a dimensionless factor that is dependent on the percentage of reduction of the influence of the intervention; $h_e$ is the equilibrium water depth $[m]$; and $i_b$ is the bed slope $[m/m]$.

$$L = \alpha \frac{h_e}{i_b} \tag{13}$$

In this case, the equilibrium depth is not known. However, it can be derived by using the Chézy equation as shown in Equation 14, in which $u$ is the flow velocity $[m/s]$; $h$ is the flow depth $[m]$ (in this case $h = h_e$); and $i_b$ is the bed slope $[m/m]$.

$$u = C\sqrt{hi_b} \tag{14}$$

Since the flow velocity in equilibrium conditions is not known, the definition of the flow velocity as shown in Equation 15 is used to rewrite Equation 14. $Q$ is the discharge [m$^3$/s] for which the equilibrium water depth is computed; $B$ is the flow width $[m]$; and h is the flow depth $[m]$.

$$u = Q/(Bh) \tag{15}$$

Combining Equation 14 and 15 gives Equation 16. Rewriting Equation 16 to give the equilibrium water depth gives Equation 17.

$$Q = hBC\sqrt{hi_b} \tag{16}$$

$$h_e = \left(\frac{Q}{BC\sqrt{i_b}}\right)^{2/3} \tag{17}$$

The values for the parameters in Equation 17 can be estimated for the Waal. The discharge for which the influence length is calculated has to be chosen. When the goal is to determine the influence length as exactly as possible, a representative discharge has to be chosen, based on either the flow conditions or the morphological development. Determining which discharge to use is difficult, since there is not one 'right' value to use. Since the primary goal here is not to determine the exact influence length for a certain discharge, but to determine whether it is possible for the bifurcation point to lie within the influence length of the nourishment, the influence length is calculated for both the mean discharge and a flood discharge. The mean discharge is 2,221 m$^3$/s (see Section 3.2.1) and the chosen flood discharge is 5,000 m$^3$/s.

For the flow width, the width of the main channel at the location of the singular nourishment in the Midden-Waal is taken, which is approximately 280 m. It should be noted that in the case the discharge exceeds the bankfull discharge (which is the case for the flood discharge), the flow width is larger in reality, since the flow partially goes over the floodplains. It is chosen not to include this complexity of the flow going over the floodplains, since that would also require an estimation of the average Chézy value over the main channels and floodplains combined and that exceeds the purpose of this calculation. The Chézy value of the main channel of the Waal is estimated at 45 $m^{1/2}/s$ (Chavarrias et al., 2020). The average bed slope of the Midden-Waal is estimated to be $10^{-4}$ m/m from the results of the reference simulation.

Subsequently, the equilibrium water depth can be used to determine the influence length using Equation 13. For a reduction to half of the original influence, factor $\alpha = 0.23$ and for a reduction to 5% of the original influence, factor $\alpha = 1.00$ (Kitsikoudis and Huthoff, 2021). It is assumed that the influence is negligible below 5% of the original influence. This leads to the results as shown in Table B.1.

**Table B.1:** Influence length as estimated for discharges of 2,221 $m^3/s$ and 5,000 $m^3/s$

| Q ($m^3/s$) | $h_e$ ($m$) | $L_{0.5}$ ($km$) | $L_{0.05}$ ($km$) |
|---|---|---|---|
| 2,221 | 6.77 | 15.6 | 67.7 |
| 5,000 | 11.63 | 26.8 | 116.3 |

# C Additional simulation results

## C.1 Nourishments under the reference discharge conditions

### C.1.1 Area-specific nourishment in the Midden-Waal

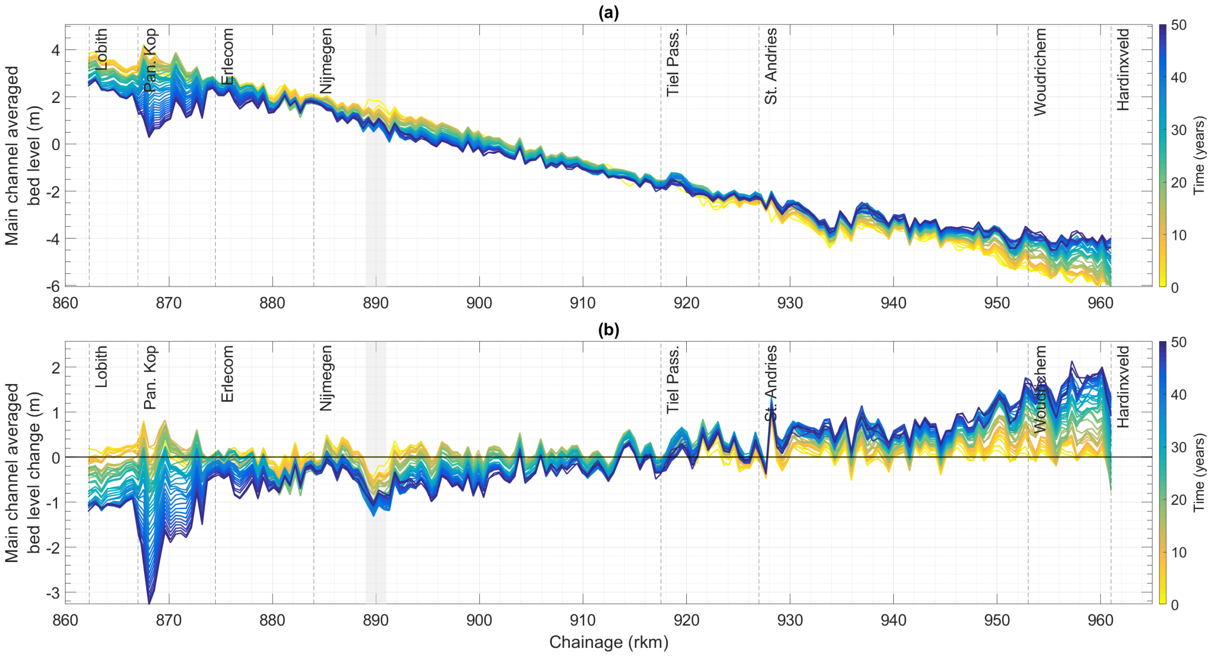


**Figure C.1:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn and Waal for the simulation with an area-specific nourishment in the Midden-Waal. The original location of the nourishment is indicated by the grey area.

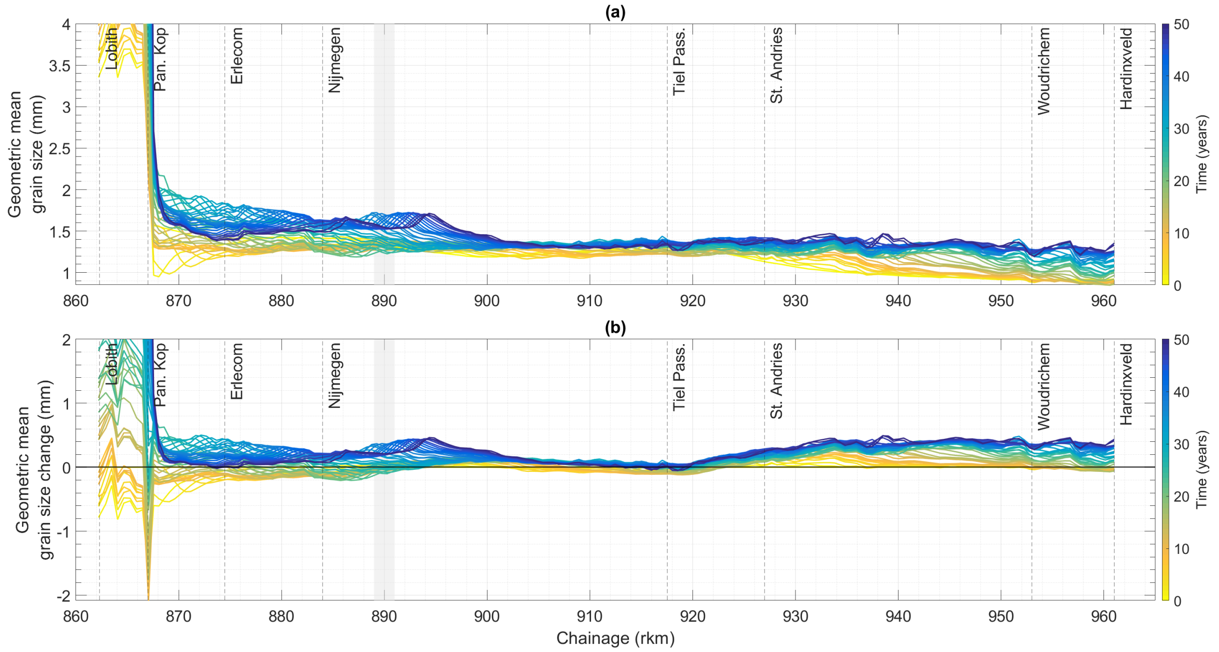


**Figure C.2:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition after nourishing (b) in the Boven-Rijn and Waal for the simulation with an area-specific nourishment in the Midden-Waal. The original location of the nourishment is indicated by the grey area.

### C.1.2 Coarse nourishment in the Midden-Waal

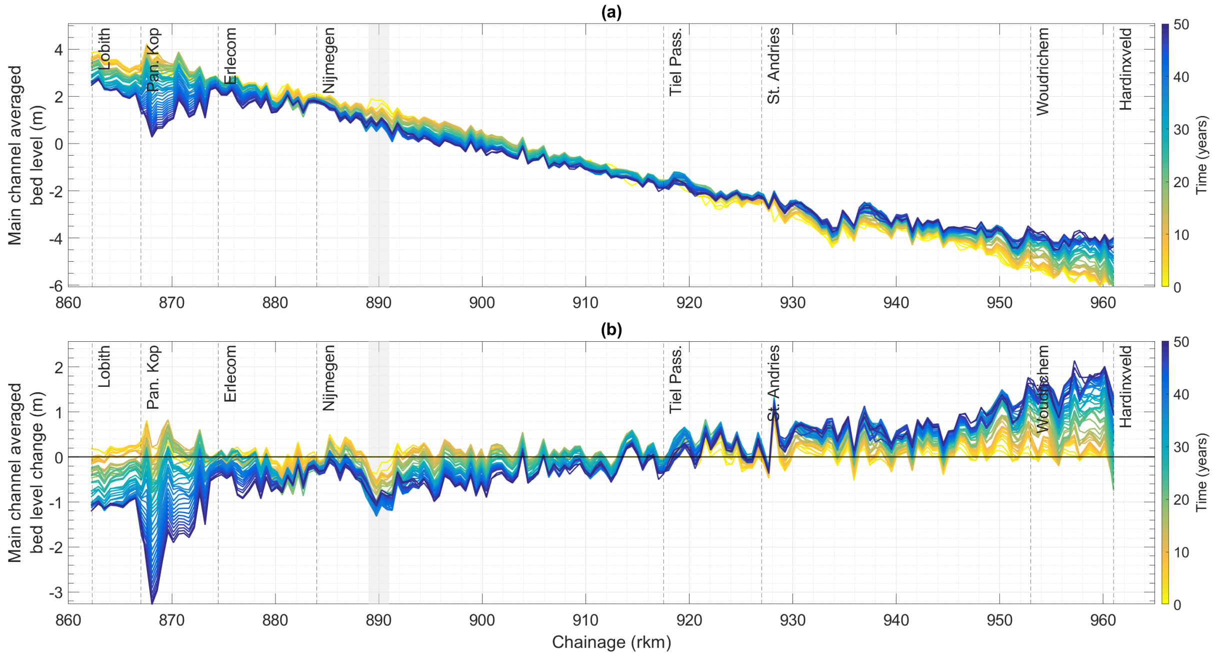


**Figure C.3:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Midden-Waal. The original location of the nourishment is indicated by the grey area.

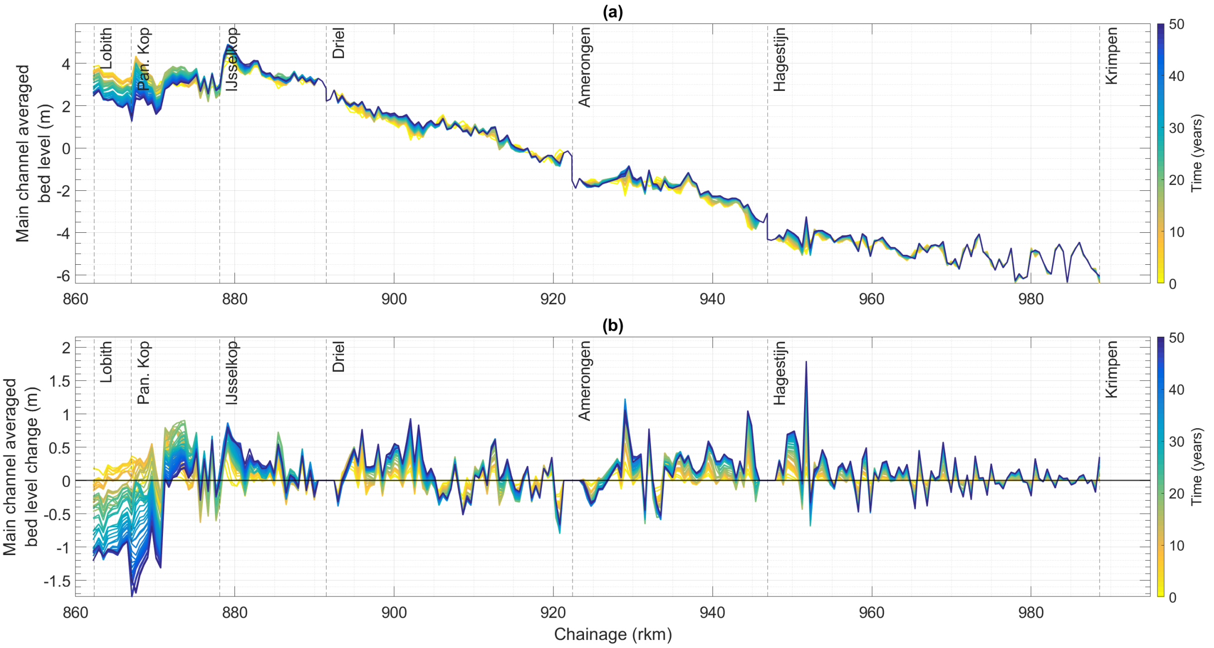


**Figure C.4:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn, Pannerdensch Kanaal, Neder-Rijn and Lek for the simulation with a coarse nourishment in the Midden-Waal.

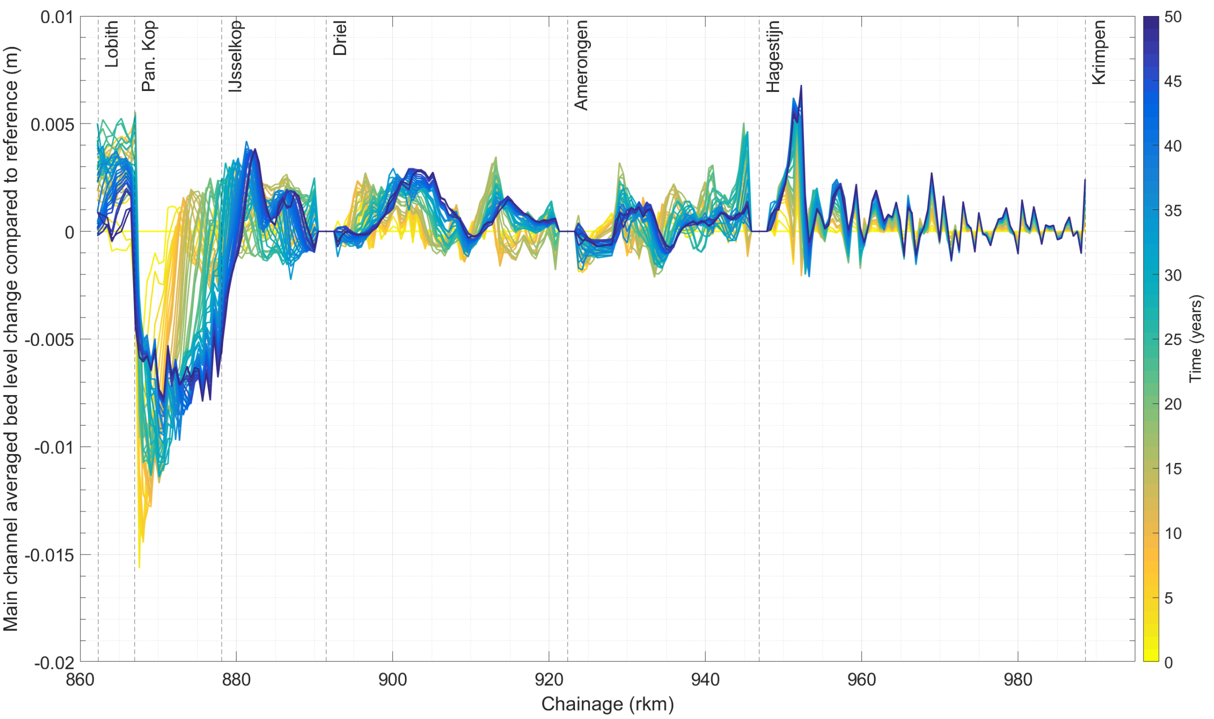


**Figure C.5:** Difference in bed level in the Boven-Rijn, Pannerdensch Kanaal, Neder-Rijn and Lek between the simulation with a coarse nourishment in the Midden-Waal and the reference simulation.

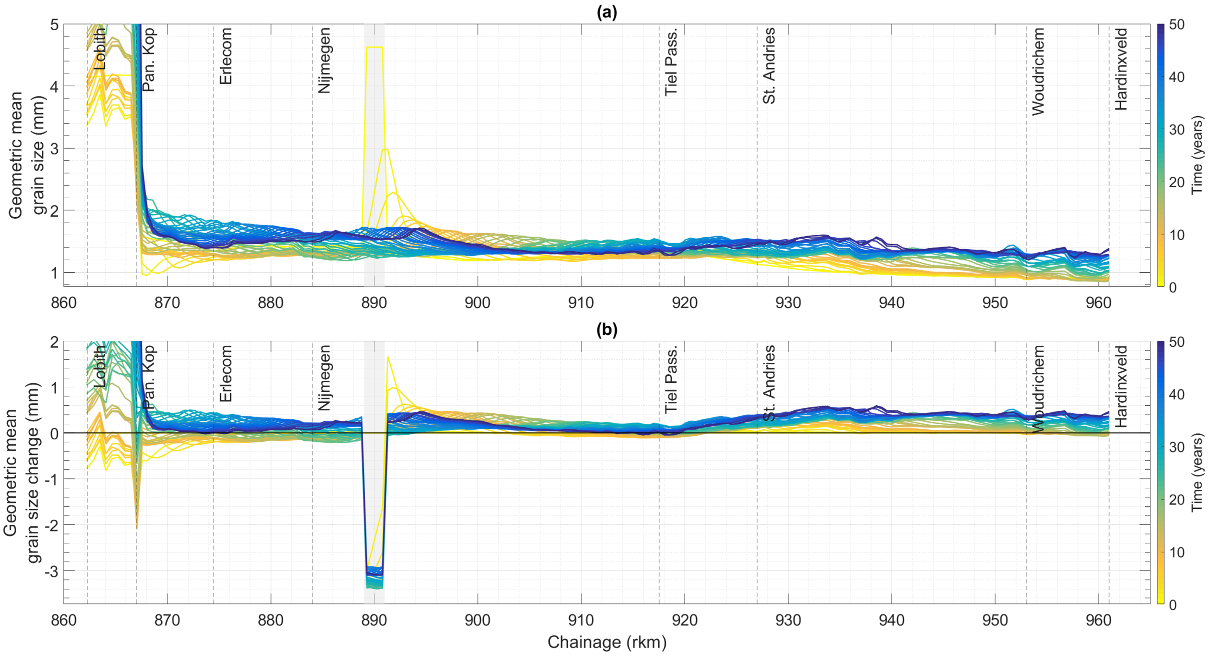


**Figure C.6:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Midden-Waal. The original location of the nourishment is indicated by the grey area.

### C.1.3 Coarse nourishment in the Boven-Waal

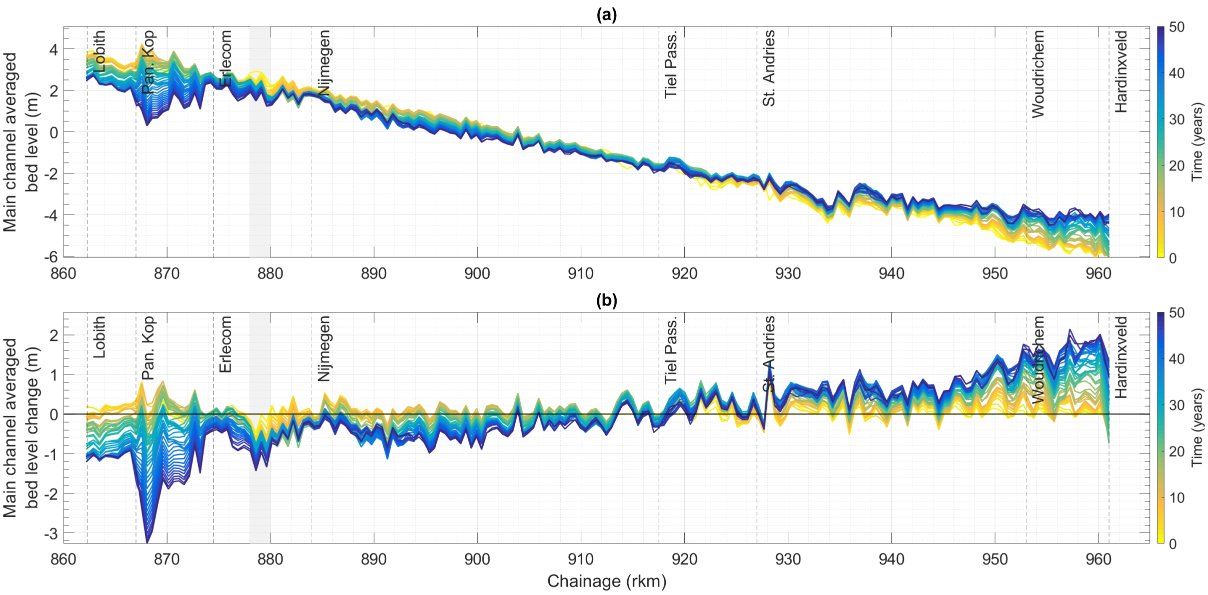


**Figure C.7:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Boven-Waal. The original location of the nourishment is indicated by the grey area.

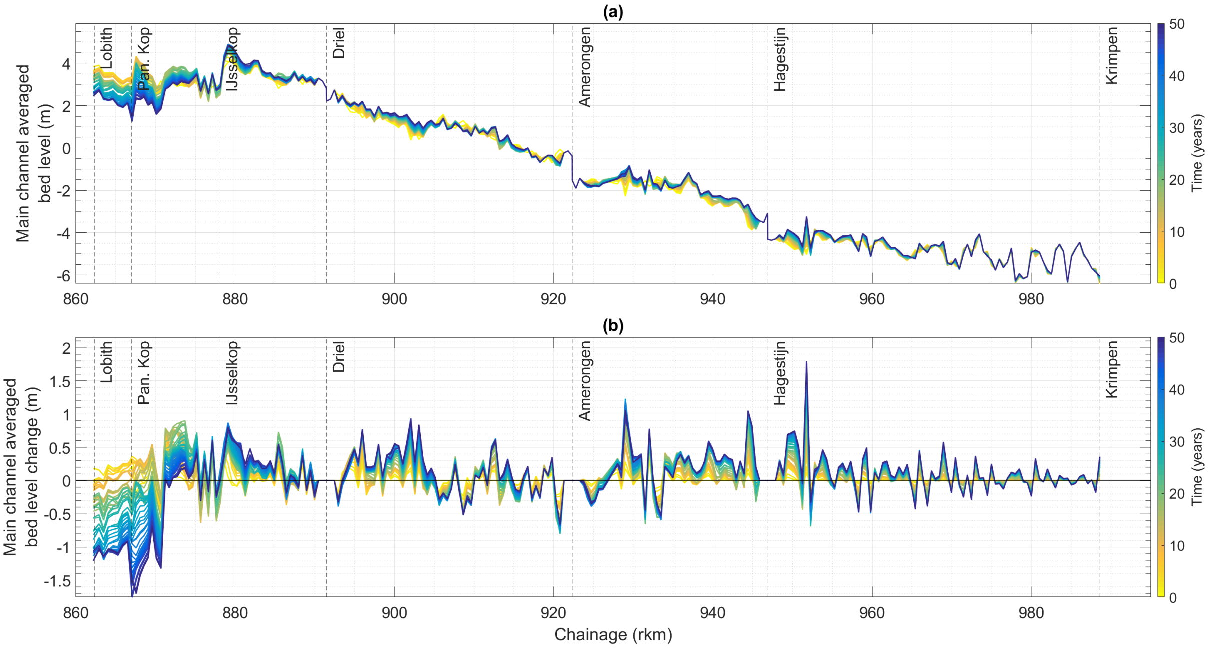


**Figure C.8:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn, Pannerdensch Kanaal, Neder-Rijn and Lek for the simulation with a coarse nourishment in the Boven-Waal.

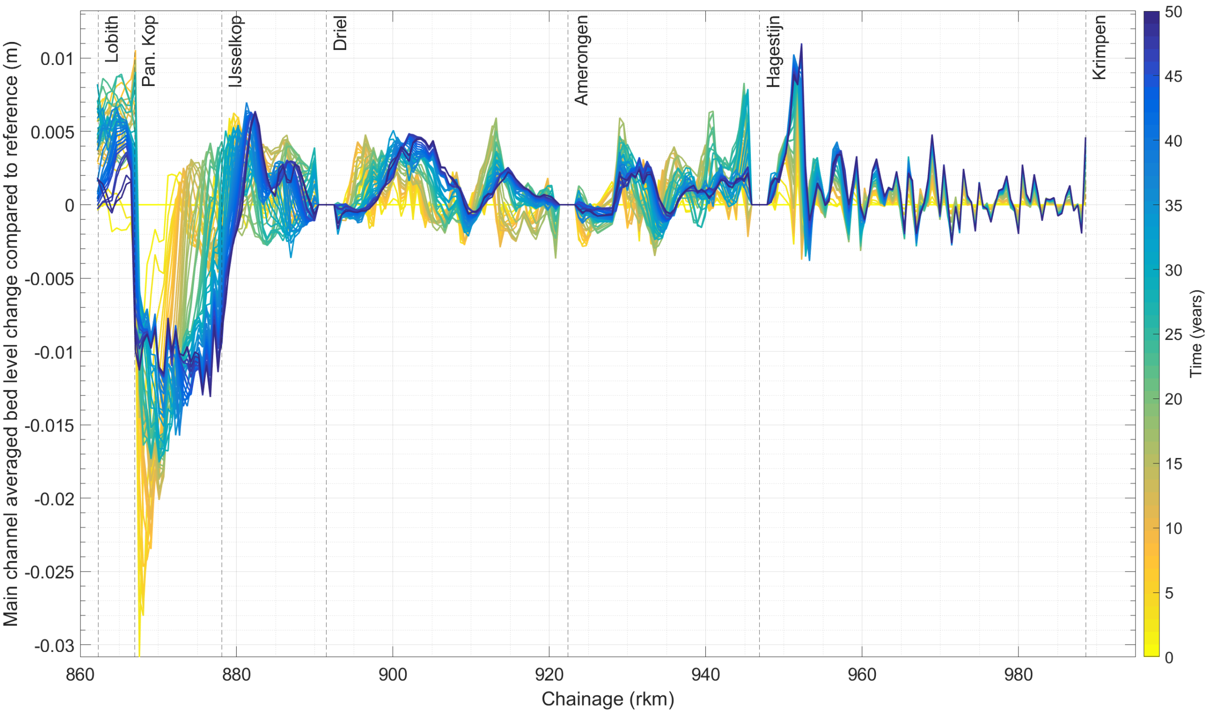


**Figure C.9:** Difference in bed level in the Boven-Rijn, Pannerdensch Kanaal, Neder-Rijn and Lek between the simulation with a coarse nourishment in the Boven-Waal and the reference simulation.

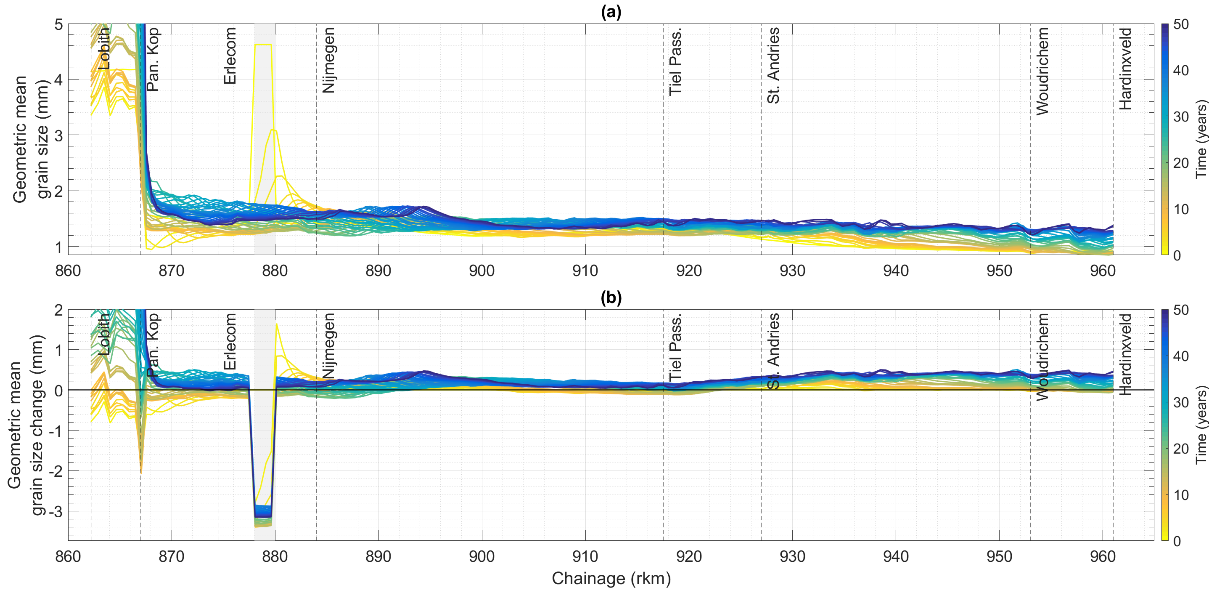


**Figure C.10:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Boven-Waal. The original location of the nourishment is indicated by the grey area.

### C.1.4 Coarse nourishment in the Midden-Waal distributed in two parts

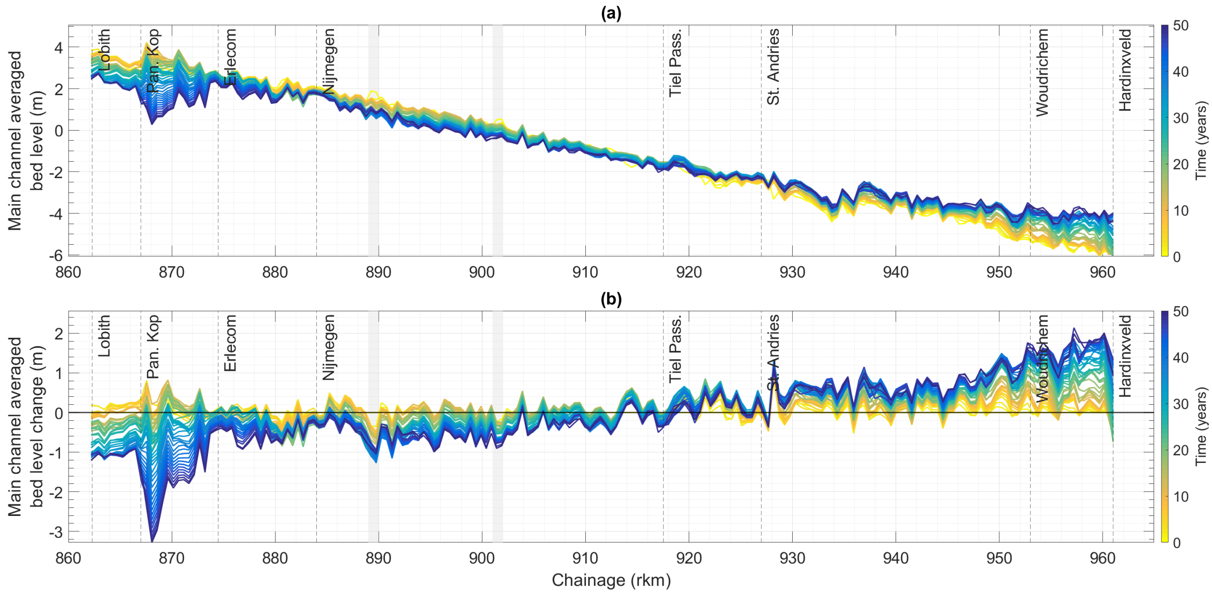


**Figure C.11:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Midden-Waal distributed in two parts. The original location of the nourishment is indicated by the grey area.

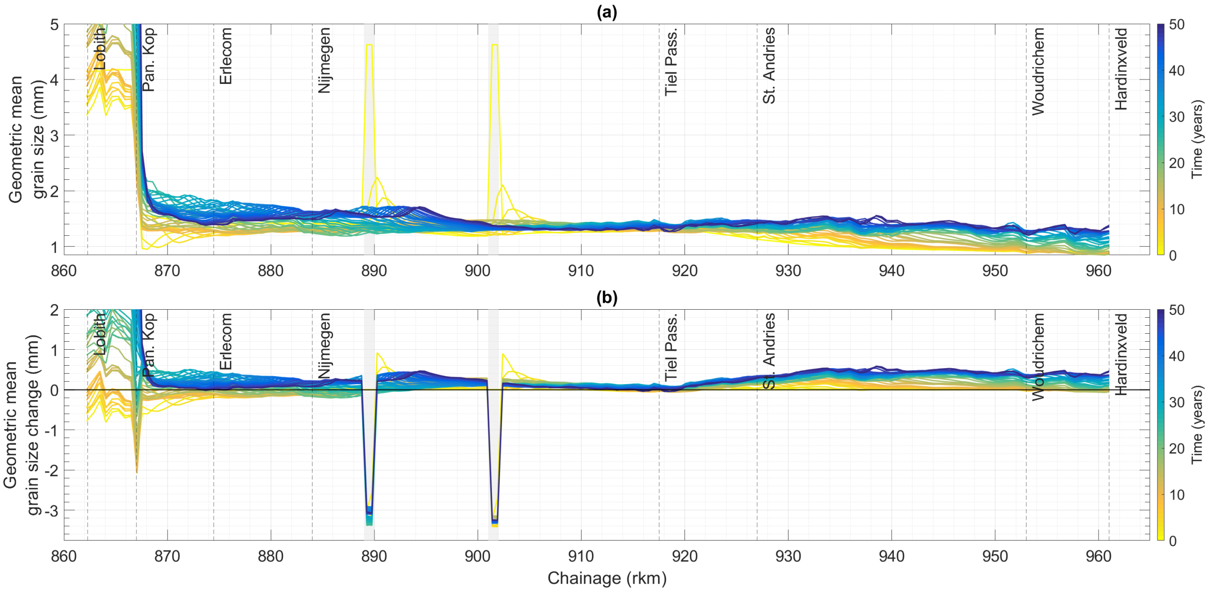


**Figure C.12:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Midden-Waal distributed in two parts. The original location of the nourishment is indicated by the grey area.

### C.1.5 Coarse nourishment in the Midden-Waal distributed in four parts

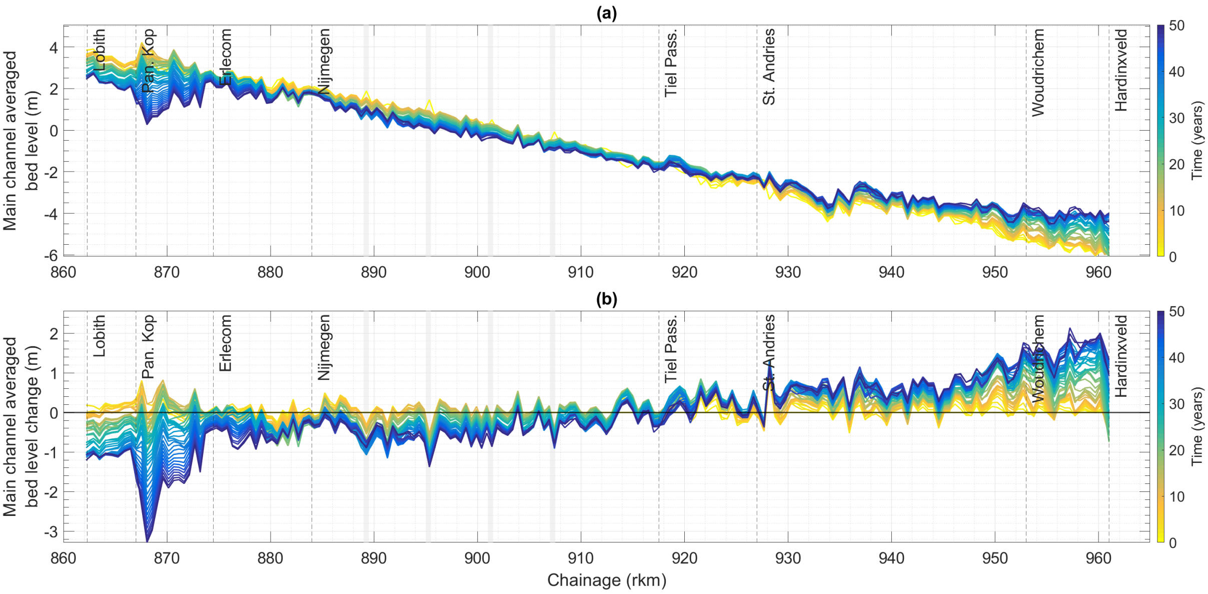


**Figure C.13:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Midden-Waal distributed in four parts. The original location of the nourishment is indicated by the grey area.

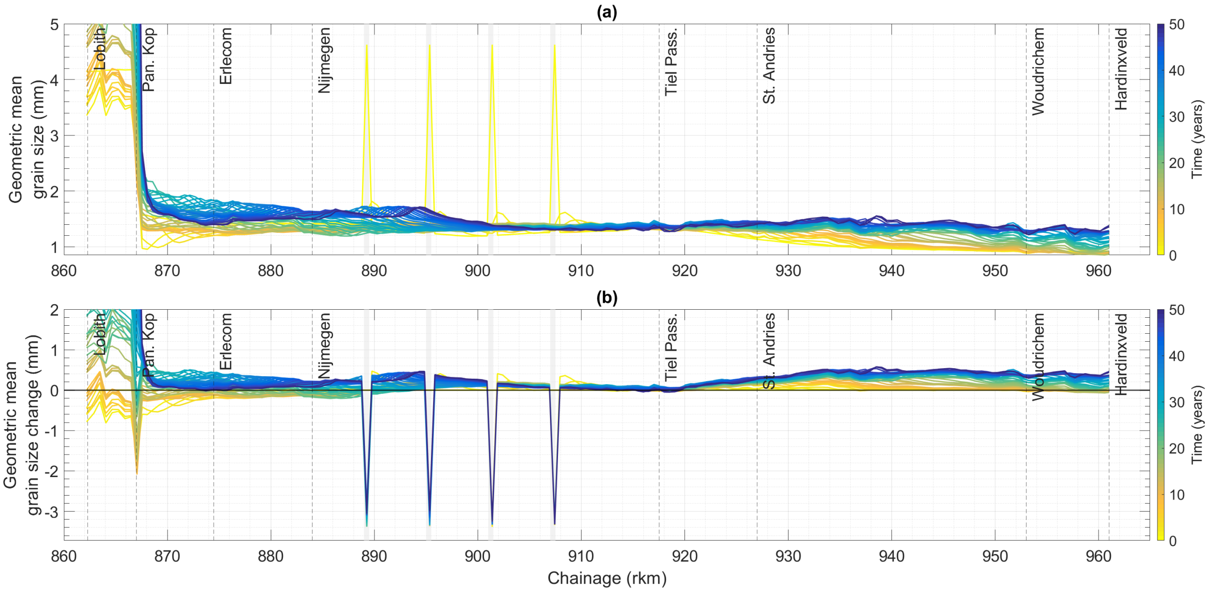


**Figure C.14:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Midden-Waal distributed in four parts. The original location of the nourishment is indicated by the grey area.

### C.1.6 Coarse non-distributed nourishment of a large volume in the Midden-Waal

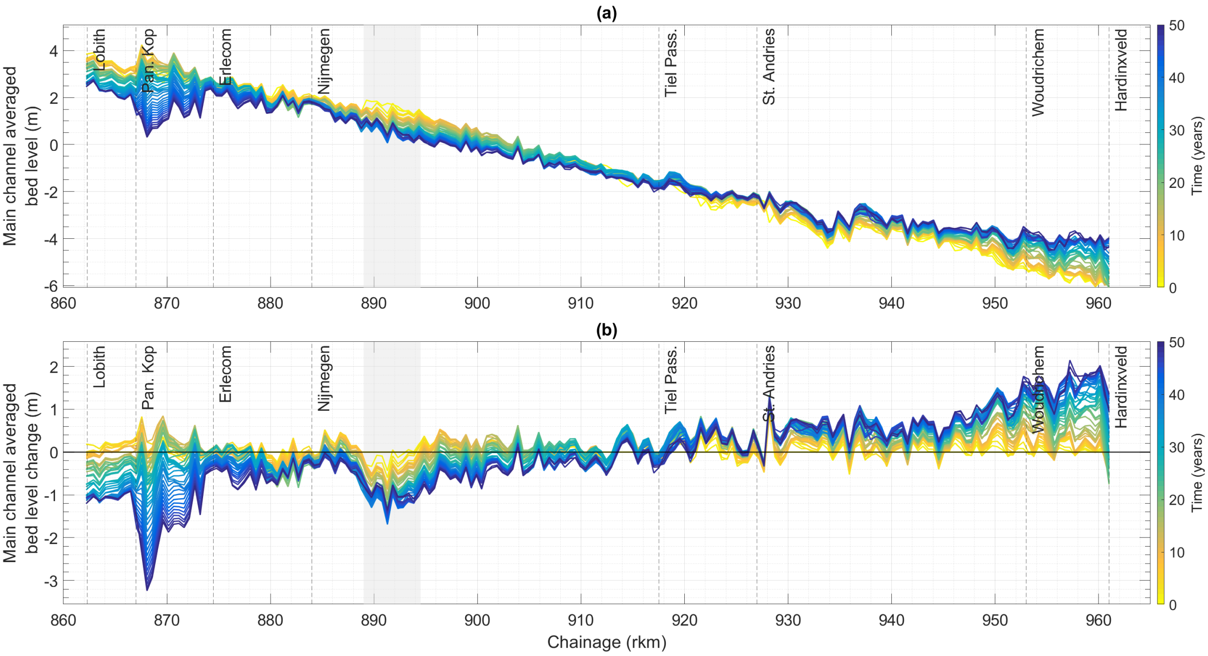


**Figure C.15:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse non-distributed nourishment of a large volume in the Midden-Waal. The original location of the nourishment is indicated by the grey area.

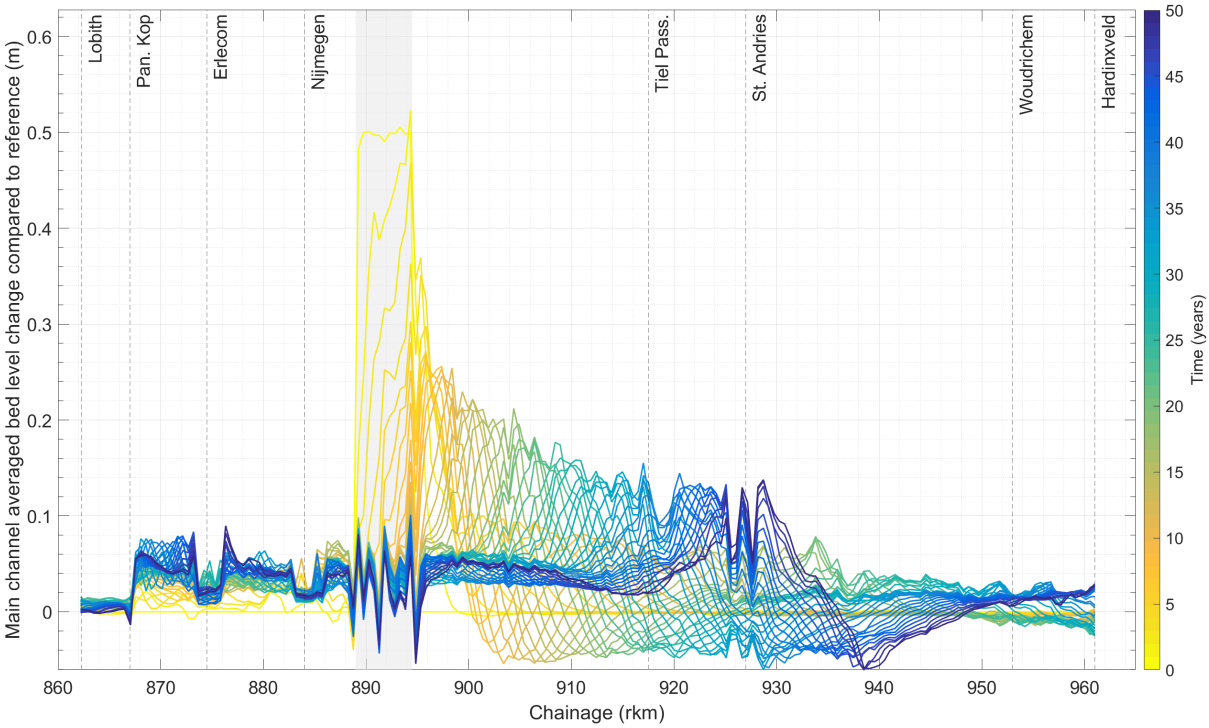


**Figure C.16:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a coarse non-distributed nourishment of a large volume in the Midden-Waal and the reference simulation. The original location of the nourishment is indicated by the grey area.

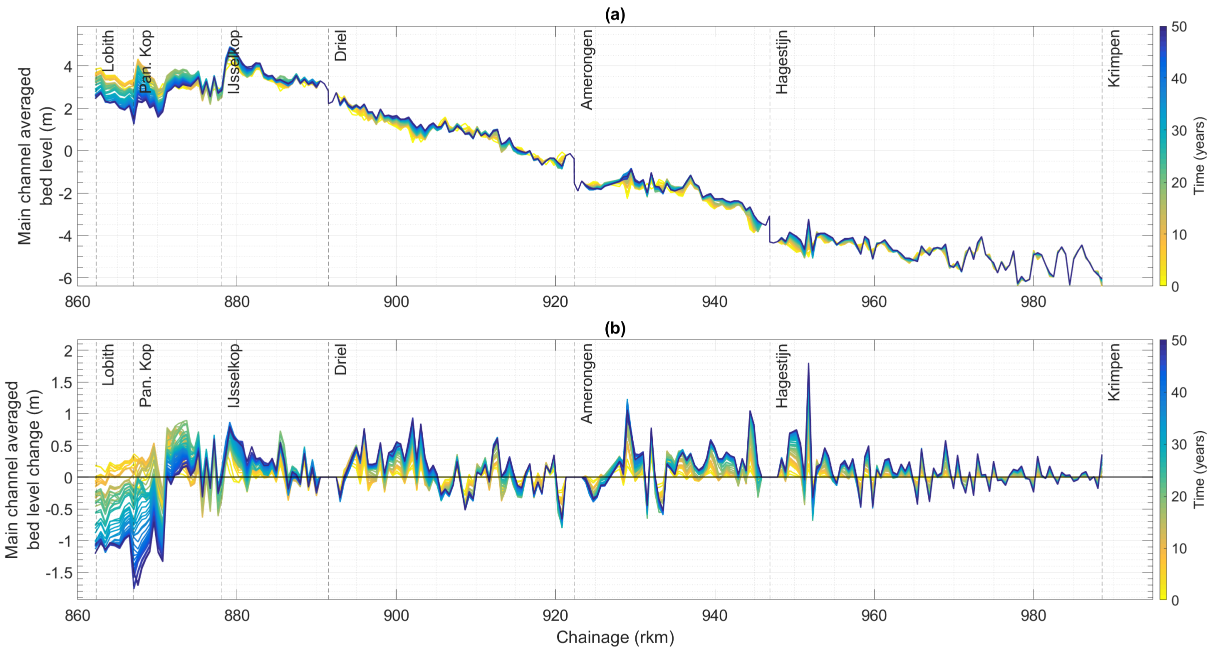


**Figure C.17:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn, Pannerdensch Kanaal, Neder-Rijn and Lek for the simulation with a coarse non-distributed nourishment of a large volume in the Midden-Waal.

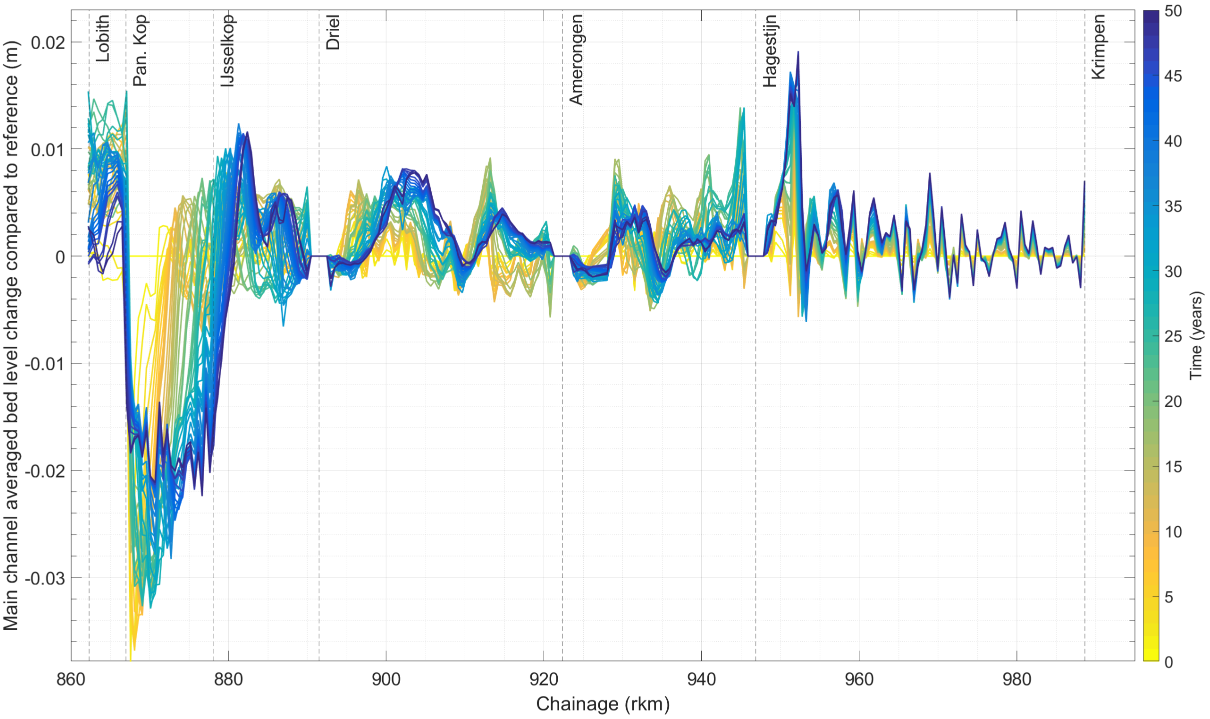


**Figure C.18:** Difference in bed level in the Boven-Rijn, Pannerdensch Kanaal, Neder-Rijn and Lek between the simulation with a coarse non-distributed nourishment of a large volume in the Midden-Waal and the reference simulation.

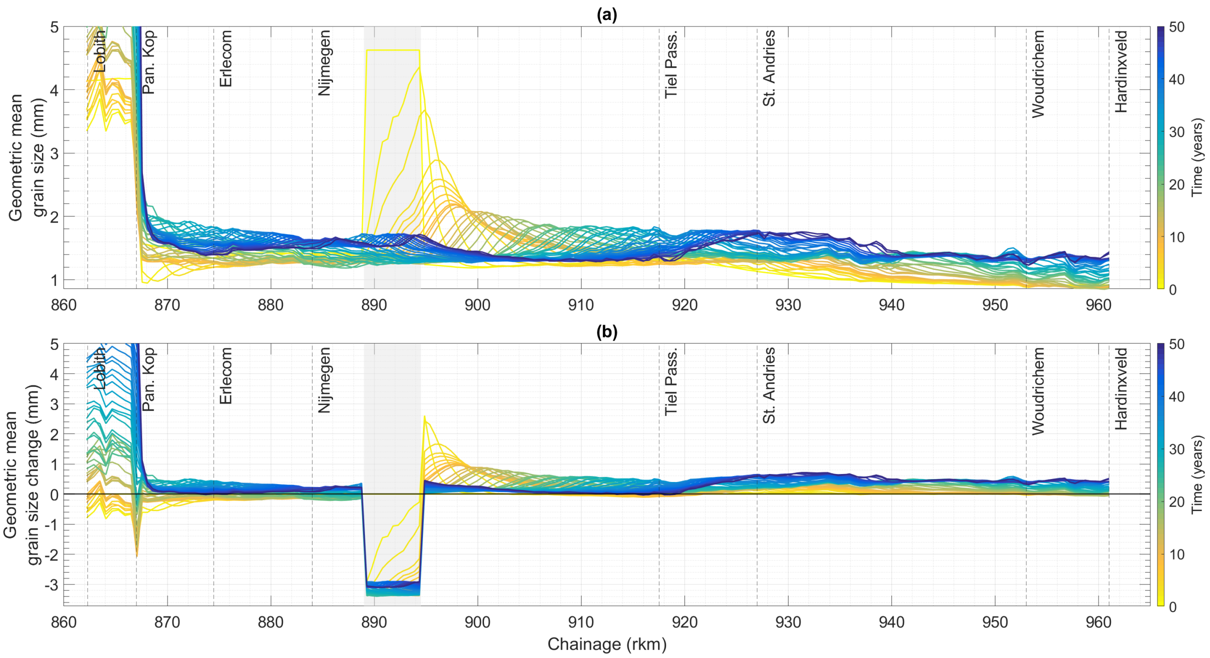


**Figure C.19:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse non-distributed nourishment of a large volume in the Midden-Waal. The original location of the nourishment is indicated by the grey area.

### C.1.7 Coarse distributed nourishment of a large volume in the Boven-Waal & Midden-Waal

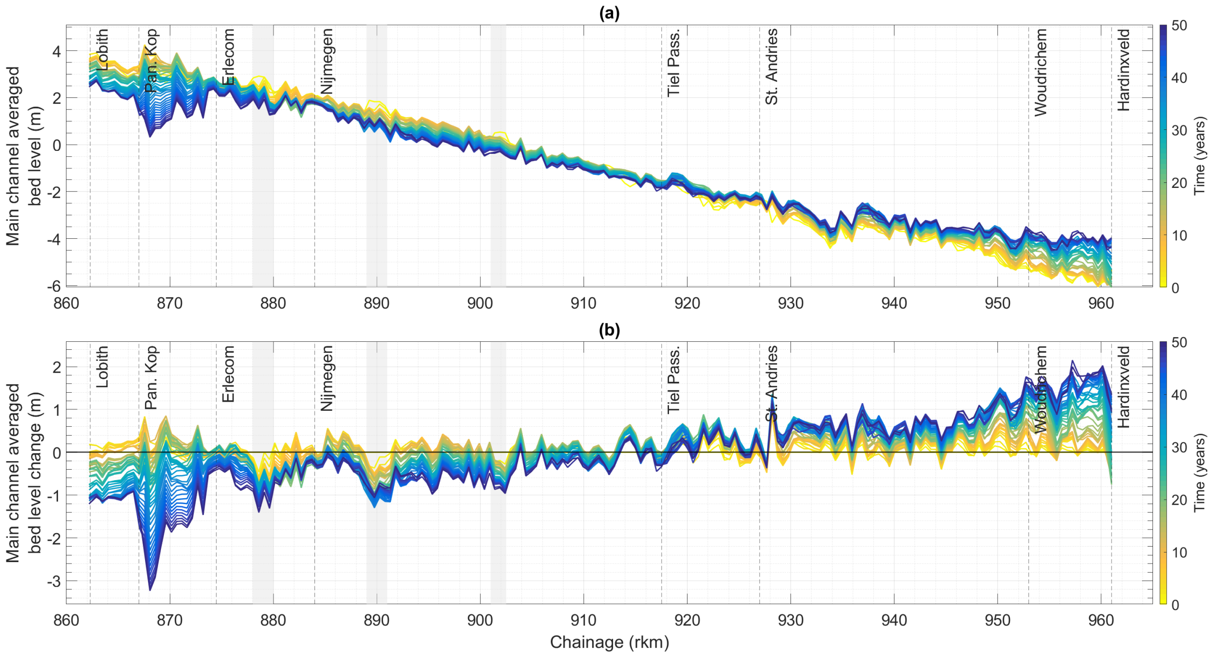


**Figure C.20:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse distributed nourishment of a large volume in the Boven-Waal & Midden-Waal. The original location of the nourishment is indicated by the grey area.

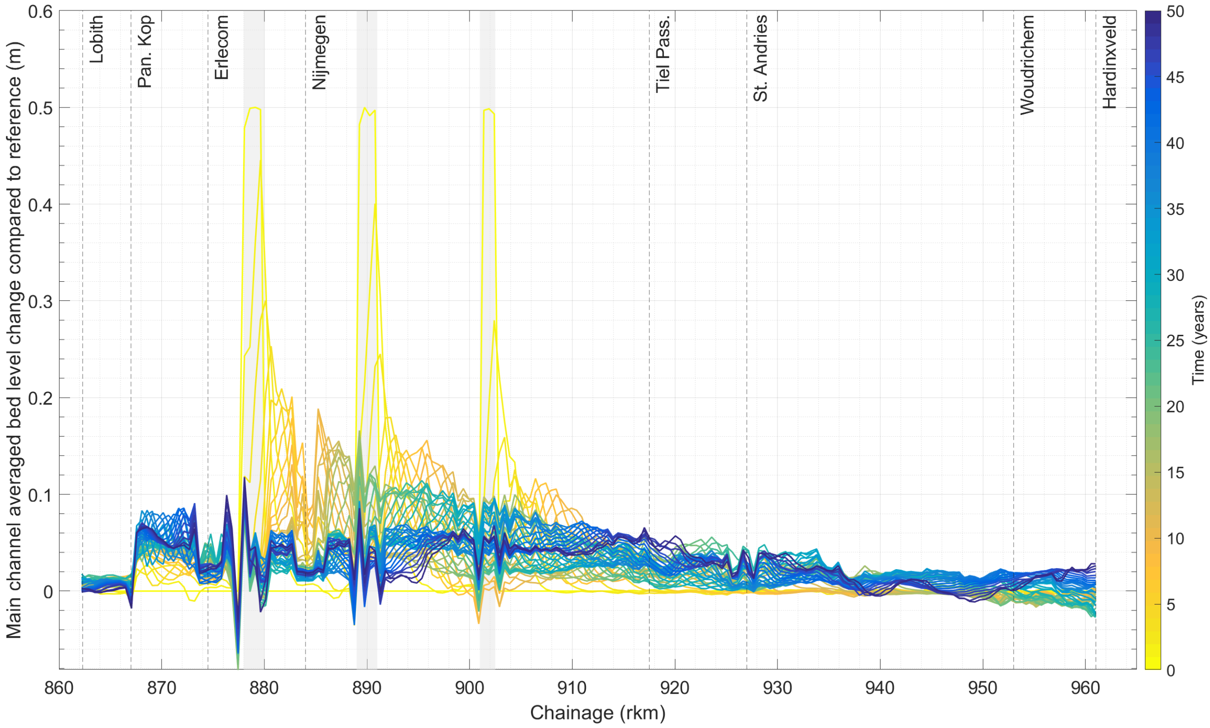


**Figure C.21:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a coarse distributed nourishment of a large volume in the Boven-Waal & Midden-Waal and the reference simulation. The original location of the nourishment is indicated by the grey area.

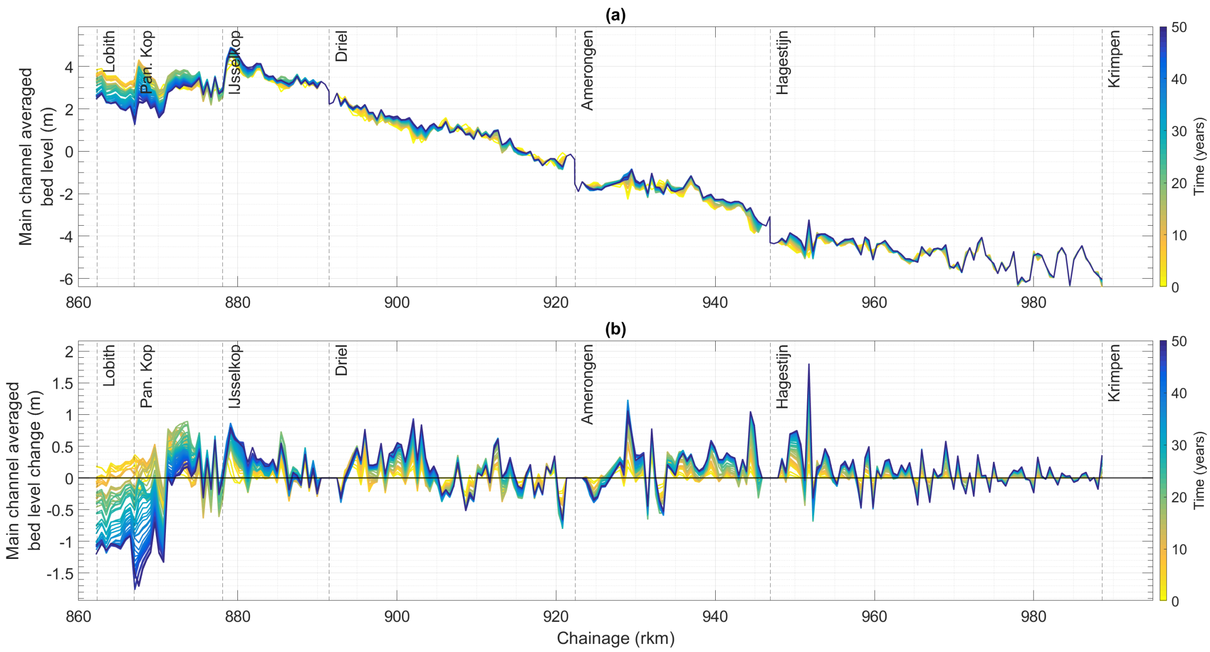


**Figure C.22:** Main channel averaged bed level (a) and bed level change compared to the initial bed level after nourishing (b) in the Boven-Rijn, Pannerdensch Kanaal, Neder-Rijn and Lek for the simulation with a coarse distributed nourishment of a large volume in the Boven-Waal & Midden-Waal.

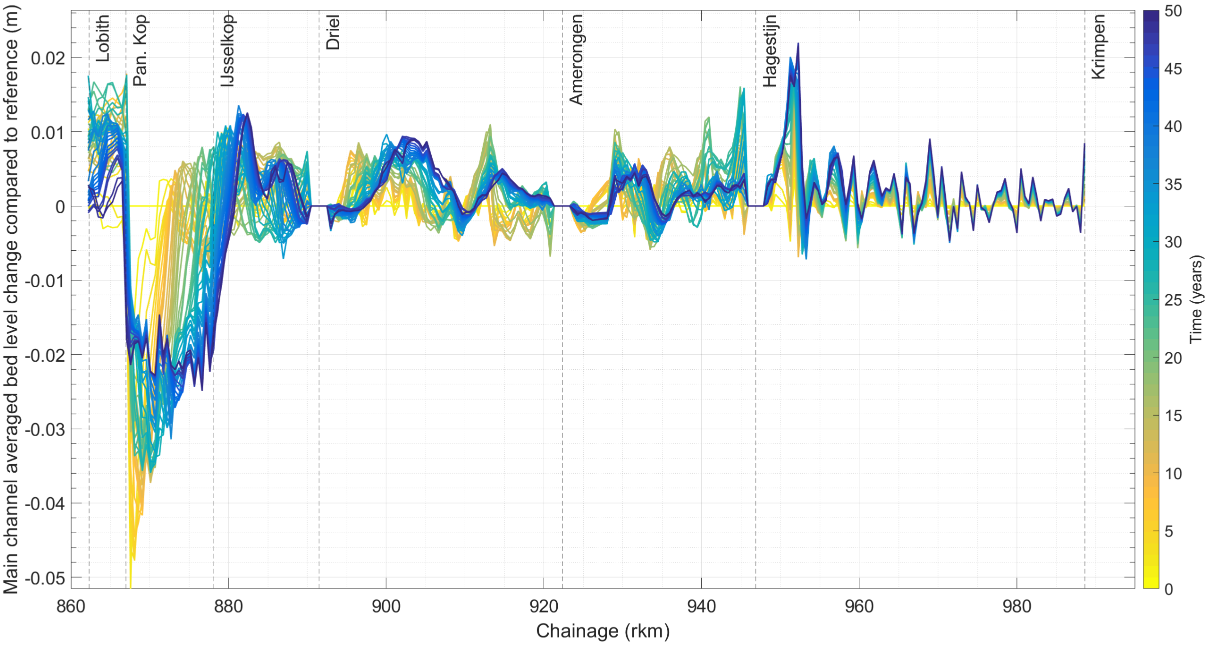


**Figure C.23:** Difference in bed level in the Boven-Rijn, Pannerdensch Kanaal, Neder-Rijn and Lek between the simulation with a coarse distributed nourishment of a large volume in the Boven-Waal & Midden-Waal and the reference simulation.

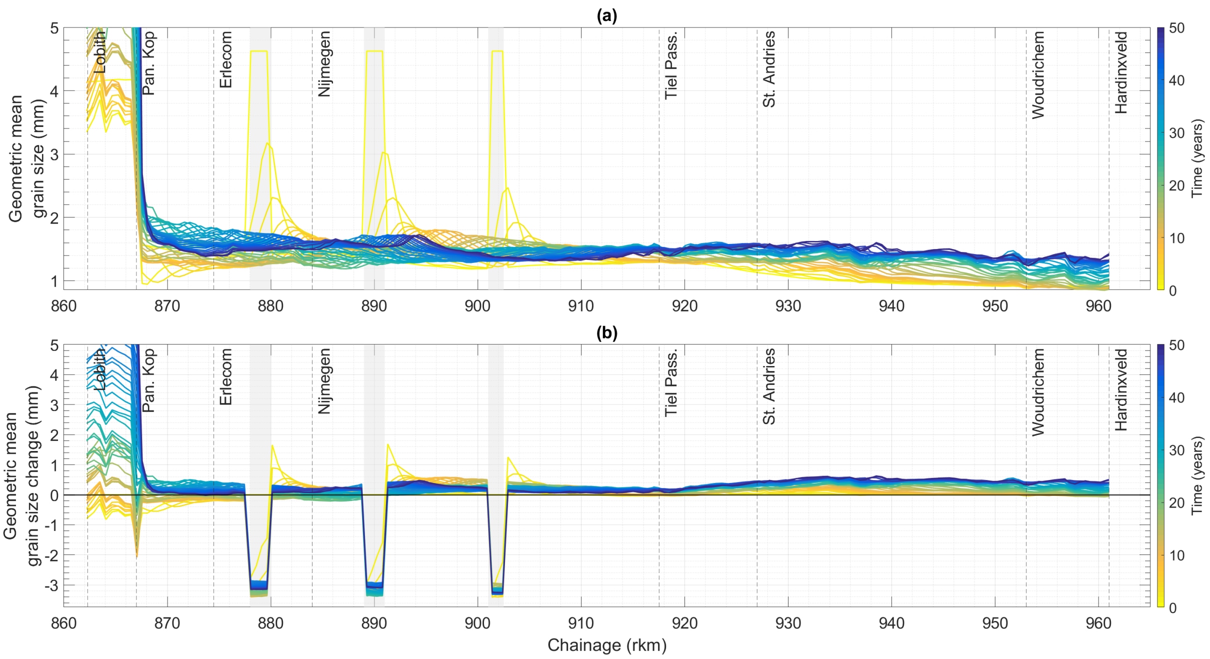


**Figure C.24:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition after nourishing (b) in the Boven-Rijn and Waal for the simulation with a coarse distributed nourishment of a large volume in the Boven-Waal & Midden-Waal. The original location of the nourishment is indicated by the grey area.

## C.2 Development of the bed without future human intervention under various discharge conditions

### C.2.1 Development of the bed under discharge condition SMHM

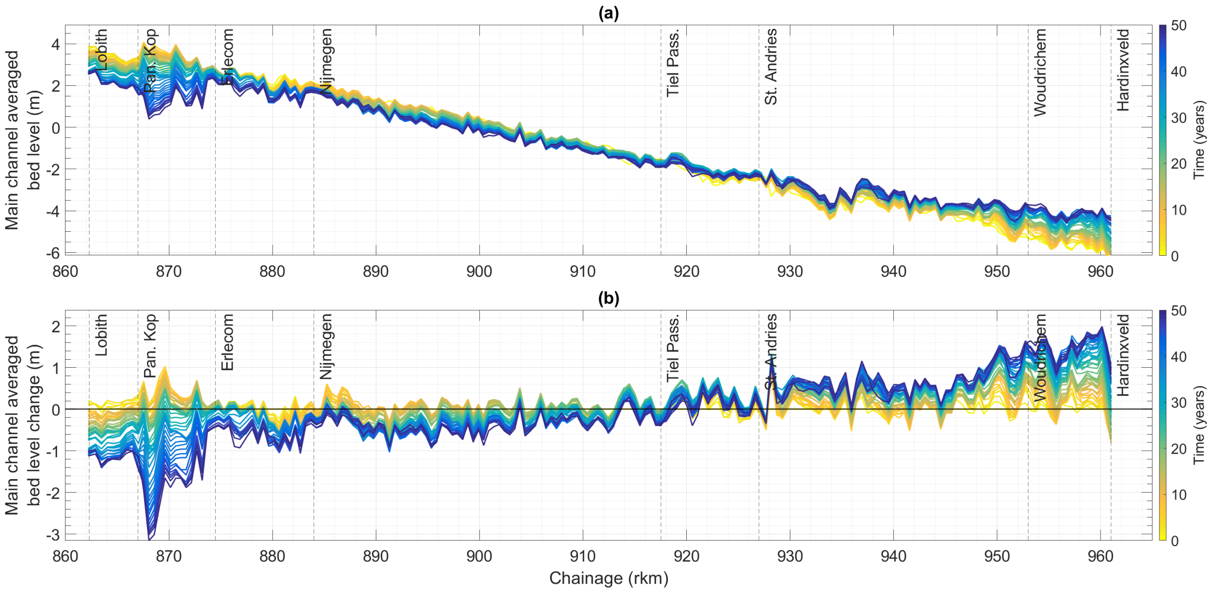


**Figure C.25:** Main channel averaged bed level (a) and bed level change compared to the initial bed level (b) in the Boven-Rijn and Waal in case of development of the bed without future human intervention under discharge condition SMHM.

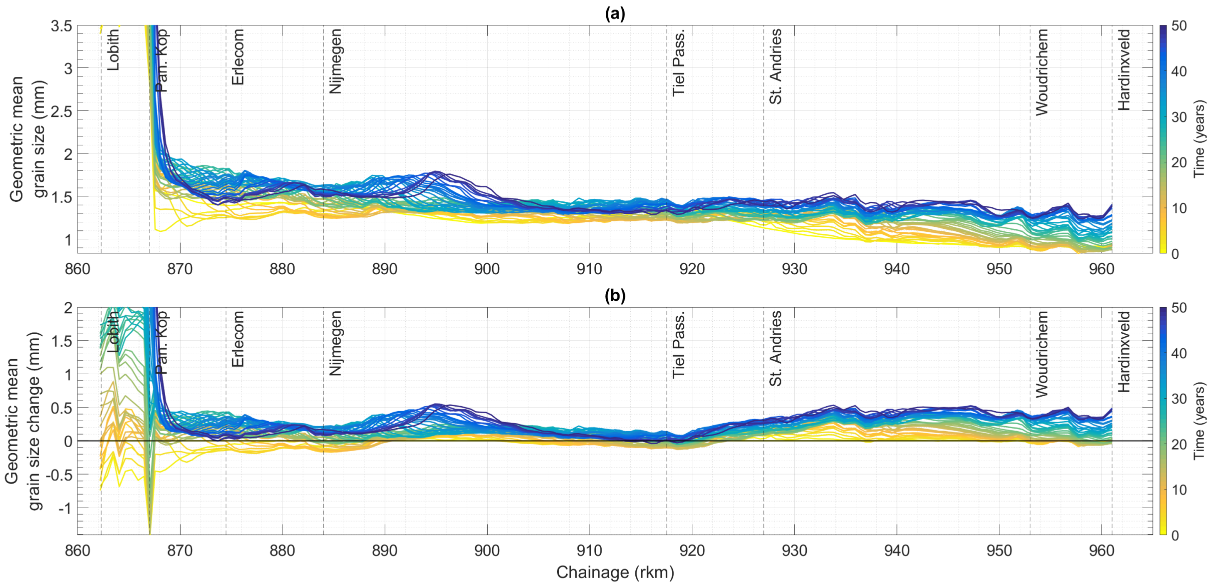


**Figure C.26:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition (b) in case of development of the bed without future human intervention under discharge condition SMHM.

### C.2.2 Development of the bed under discharge condition HMHM

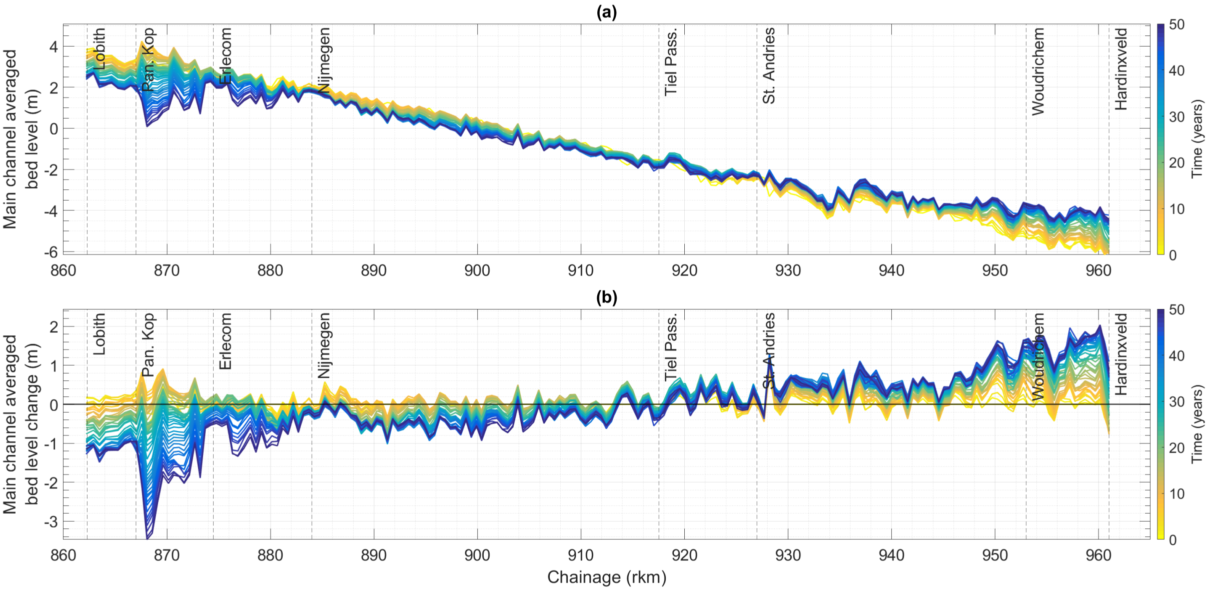


**Figure C.27:** Main channel averaged bed level (a) and bed level change compared to the initial bed level (b) in the Boven-Rijn and Waal in case of development of the bed without future human intervention under discharge condition HMHM.

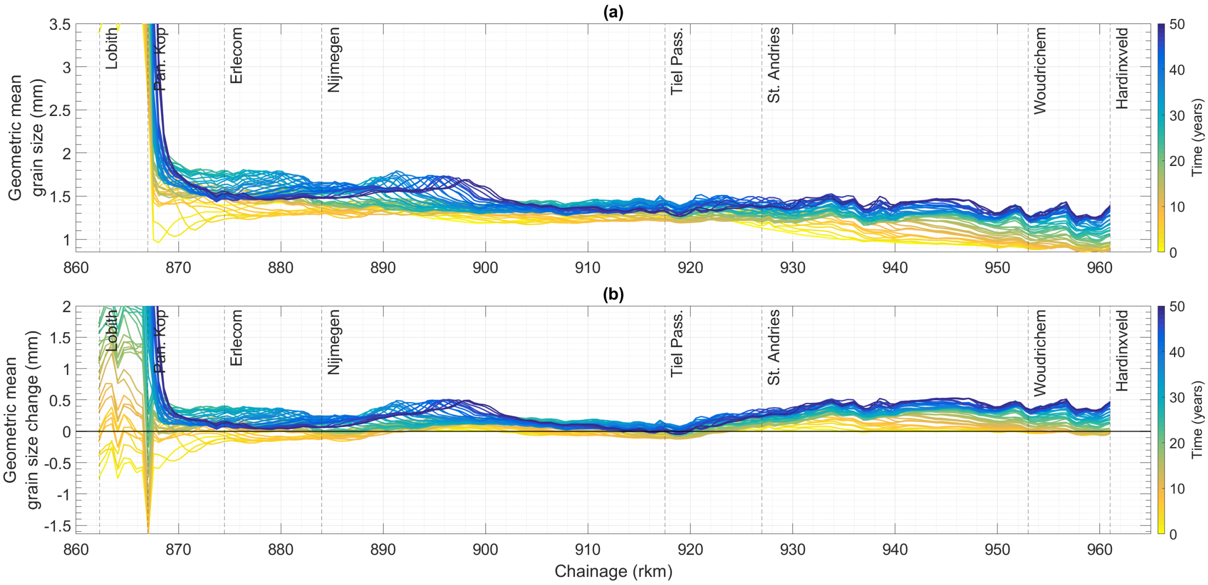


**Figure C.28:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition (b) in case of development of the bed without future human intervention under discharge condition HMHM.

## C.3 Nourishments under various discharge conditions

### C.3.1 Coarse nourishment in the Midden-Waal distributed in two parts under discharge condition SMHM

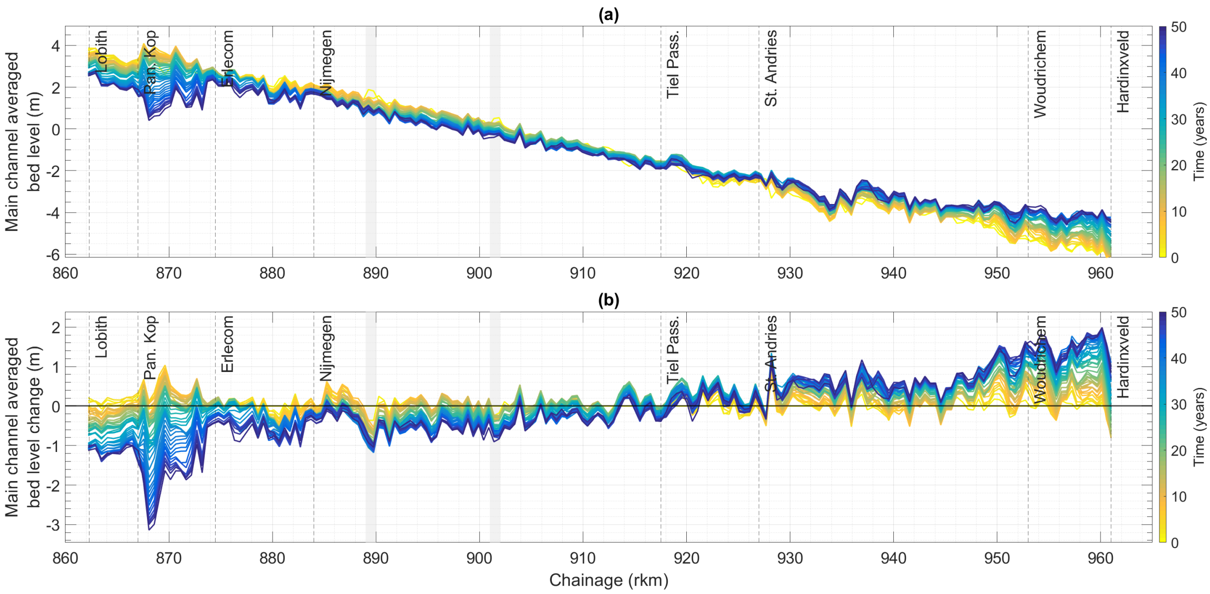


**Figure C.29:** Main channel averaged bed level (a) and bed level change compared to the initial bed level (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Midden-Waal distributed in two parts under discharge condition SMHM. The original location of the nourishment is indicated by the grey area.

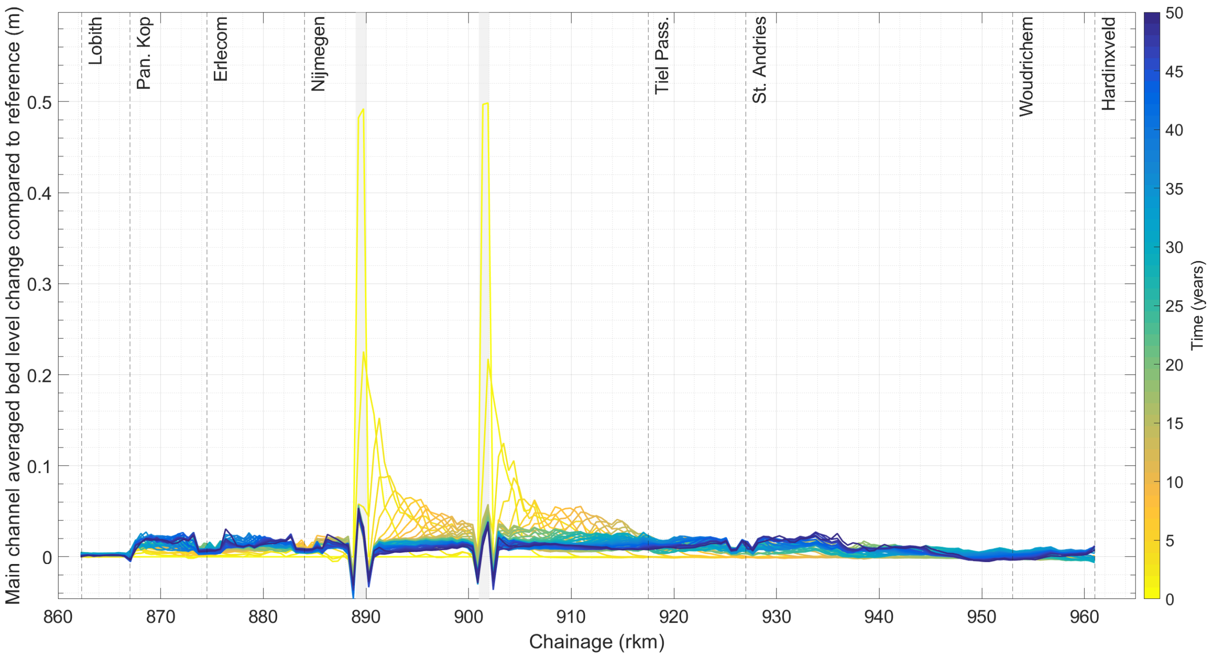


**Figure C.30:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a coarse nourishment in the Midden-Waal distributed in two parts and the simulation without future interventions under discharge condition SMHM. The original location of the nourishment is indicated by the grey area.

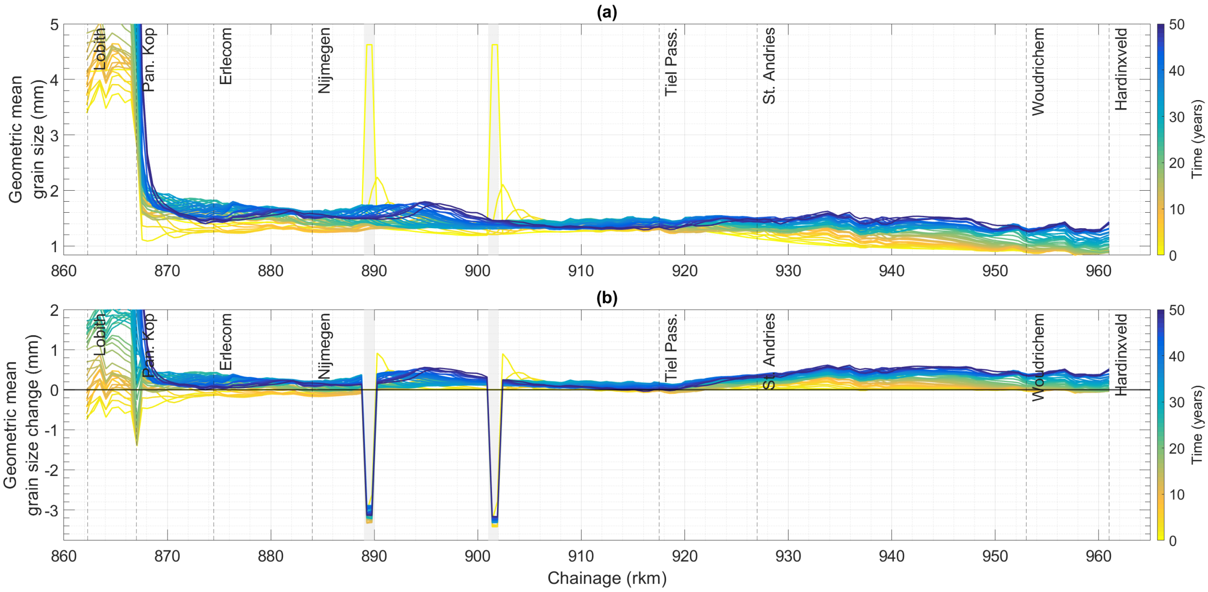


**Figure C.31:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition (b) for the simulation with a coarse nourishment in the Midden-Waal distributed in two parts under discharge condition SMHM. The original location of the nourishment is indicated by the grey area.

### C.3.2 Coarse nourishment in the Midden-Waal distributed in two parts under discharge condition HMHM

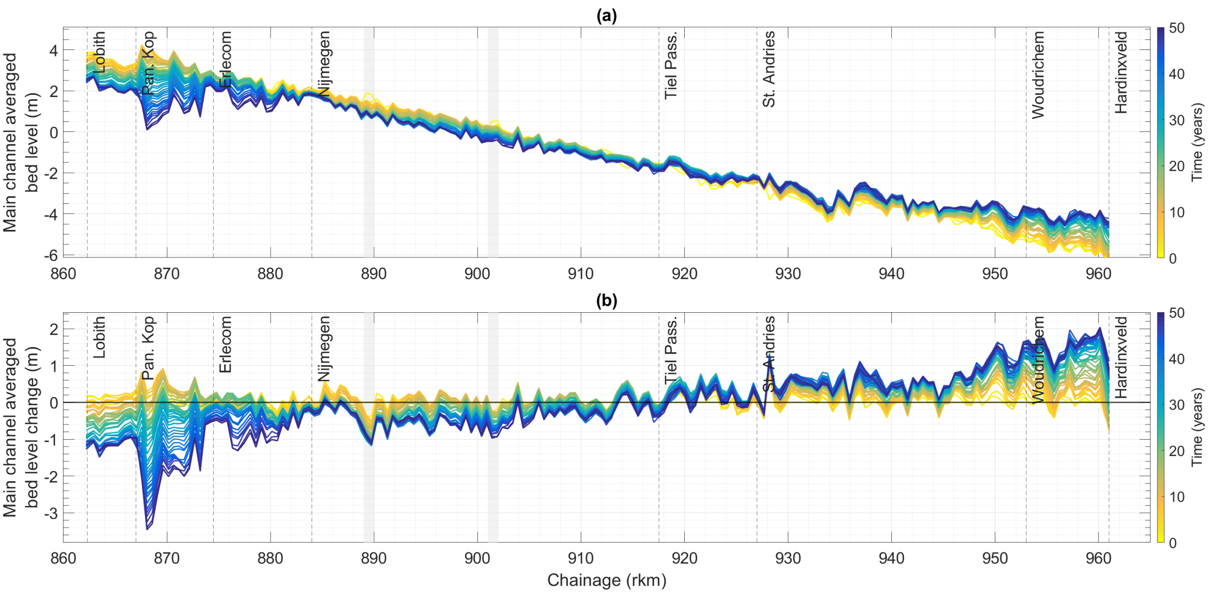


**Figure C.32:** Main channel averaged bed level (a) and bed level change compared to the initial bed level (b) in the Boven-Rijn and Waal for the simulation with a coarse nourishment in the Midden-Waal distributed in two parts under discharge condition HMHM. The original location of the nourishment is indicated by the grey area.

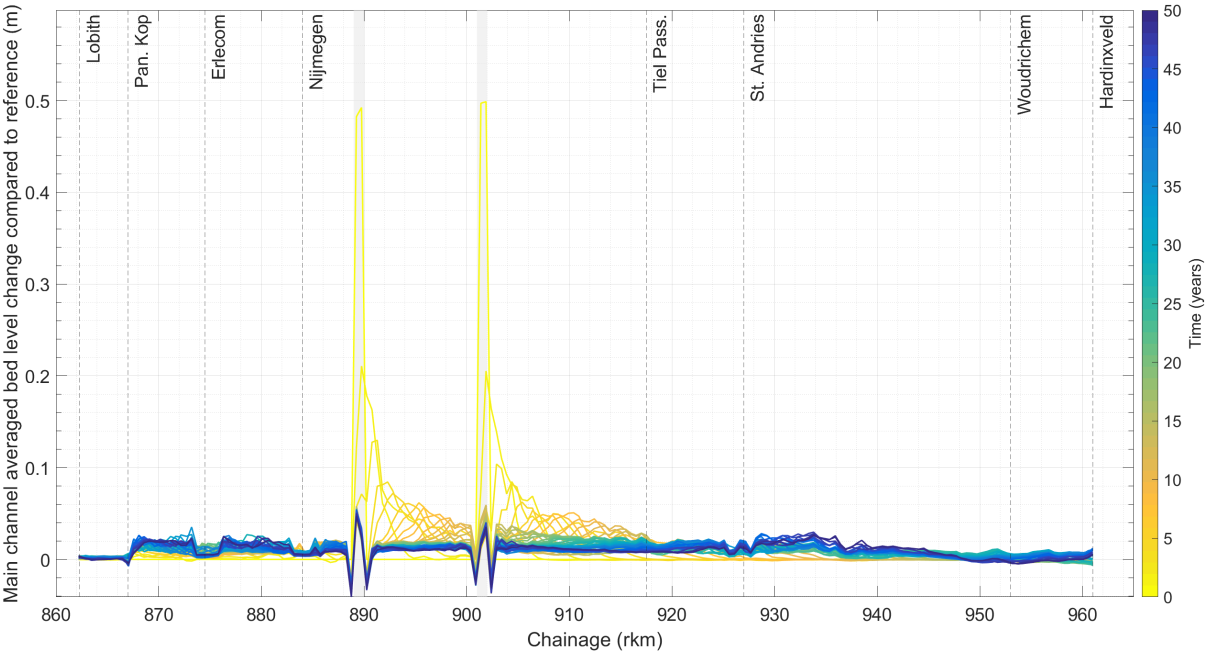


**Figure C.33:** Difference in bed level in the Boven-Rijn and Waal between the simulation with a coarse nourishment in the Midden-Waal distributed in two parts and the simulation without future interventions under discharge condition HMHM. The original location of the nourishment is indicated by the grey area.

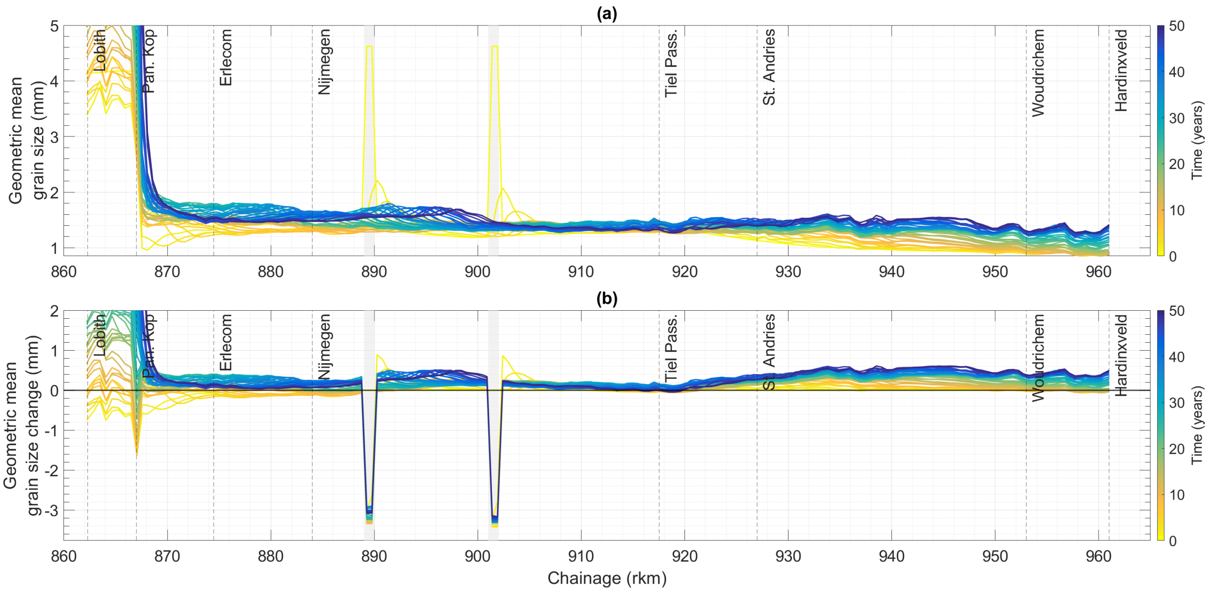


**Figure C.34:** Geometric mean grain size (a) and change in geometric mean grain size compared to the initial sediment composition (b) for the simulation with a coarse nourishment in the Midden-Waal distributed in two parts under discharge condition HMHM. The original location of the nourishment is indicated by the grey area.