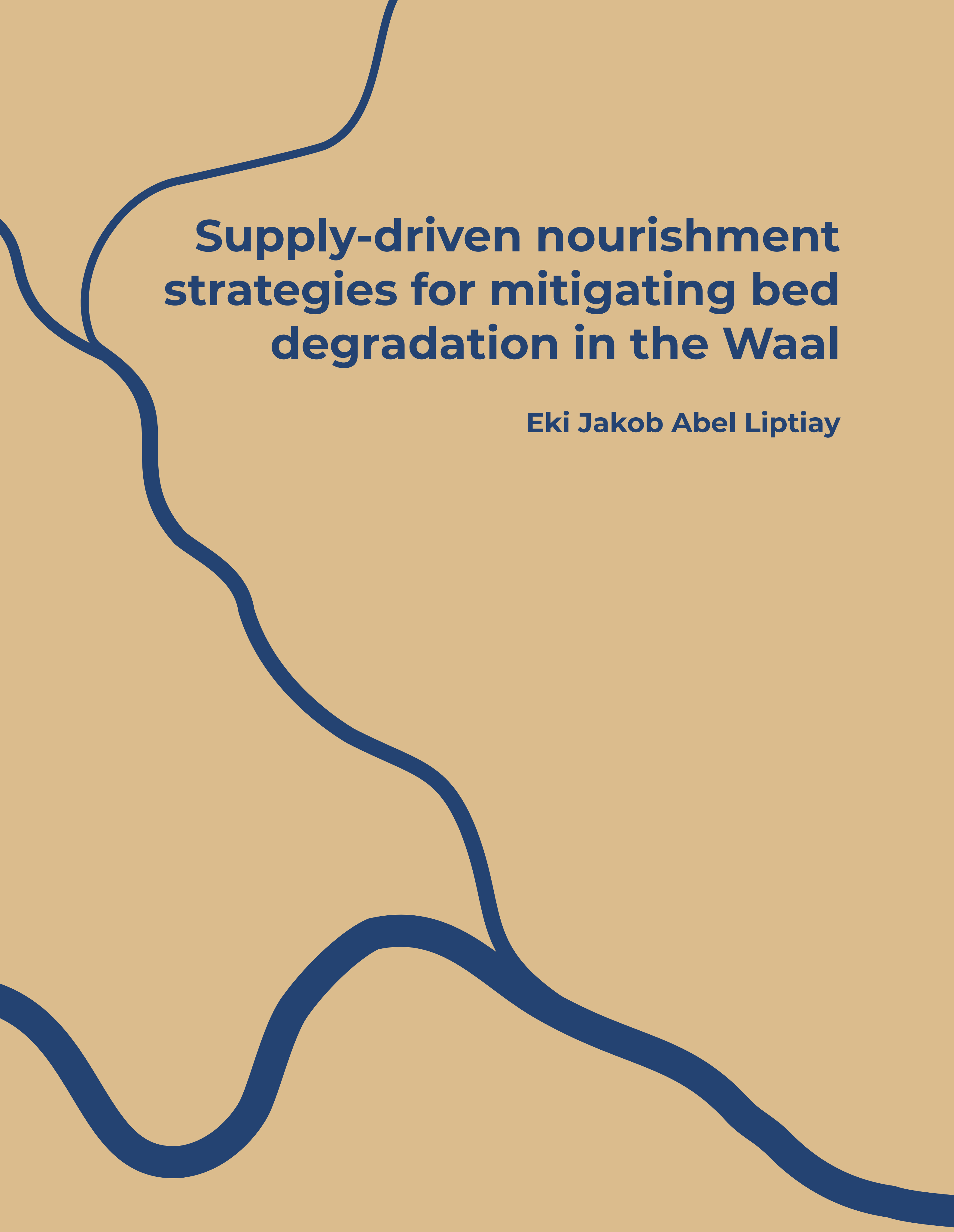
Supply-driven nourishment strategies for mitigating bed degradation in the Waal

Eki Jakob Abel Liptiay



Supply-driven nourishment strategies for mitigating bed degradation in the Waal

by

Eki Jakob Abel Liptiay

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Preface

This thesis marks the end of my time at the University of Twente. My academic journey in Enschede started with a Bachelor's in Applied Physics, which I enjoyed very much. However, after finishing my bachelor's degree I decided that it was time for something else. With a slight detour via Mechanical Engineering, I eventually landed in the Civil Engineering Department. It was not until then that I discovered that rivers fascinate me so much; perhaps growing up next to the IJssel in the beautiful city of Doesburg had secretly rooted this passion in me. What could have been better specialisation than River and Coastal Engineering to embrace this interest? During the last six months, I have been able to dive deep into the subject of river morphology, where I studied the morphological effects of supply-driven sediment nourishments in the Waal and their efficacy in mitigating bed degradation.

This research was conducted at Sweco in cooperation with Rijkswaterstaat. I want to thank Niels Welsch and Marthe Oldenhof, who both fulfilled the task as my daily supervisor. Furthermore, I would like to express my thanks to Roel Velner for allowing me the opportunity to undertake this research at Sweco and for his advice. In addition to my supervisors, I would like to thank their colleagues for their hospitality.

Next, I would like to thank my university supervisors. First, Vasilis Kitsikoudis, who fulfilled the role of daily supervisor. It felt like he was always available for questions, and our meetings always resulted in new, interesting insights. Additionally, I want to thank Denie Augustijn for his close involvement to my research as well and making sure that my graduation process went smoothly.

Moreover, I want to thank Saskia van Vuren from Rijkswaterstaat. Saskia's participation in my research and knowledge of the Dutch river system, as well as her participation in the *Integraal Riviermanagement* programme, greatly increased the practical relevance of my research. Her invitations to several IRM meetings showed me what is actually happening within the Dutch rivers, which made me even more interested in the subject. Perhaps the most fun part of my thesis was our trip to a floating sand classification plant in the Waal, which put all the numbers regarding sediment compositions and nourishment volumes in a real perspective. In addition, I would like to thank her for connecting me with various experts in the field so that I could enhance the quality and relevance of my research. A big thanks goes to her colleagues from Rijkswaterstaat as well, who provided me with valuable data and information regarding the Dutch river system.

Furthermore, I would like to thank Birgit de Lange for helping me to understand the model and answering my questions whenever I got stuck. Lastly, I would like to thank Victor Chavarrías and Willem Ottevanger of Deltares, who developed the model that I used for my research. They provided me with answers to my questions and helped me to understand the fundamental properties of the model. They, together with Kees Sloff, provided me with valuable insights and possible improvements for my research during a visit to Deltares where we discussed my progress.

Finally, I want to thank everyone else who participated in my thesis in some way, as I have been in contact with professionals from various fields who were very eager to help me on my way.

Eki Jakob Abel Liptiay
Rotterdam, October 2023

Summary

In the past several decades, the summer bed of the Waal has eroded between 1-2 metres. Among other things, this causes instability of structures, damage to floodplains due to less frequent inundations, and disturbance to shipping. Furthermore, since the erosion rate of the Waal is not equal to that of the Pannerdensch Kanaal, the discharge distribution in the bifurcation changes. As the Waal erodes faster, more discharge is routed there. This is more severe for lower discharges. Consequently, during low flows, less water is supplied to the IJssel, which limits the fresh water supply. A possible intervention to mitigate this ongoing degradation is the execution of sediment nourishments.

This research aims to identify different sources of sediment near the Waal and their efficacy in mitigating bed degradation. A source is classified as 'nearby' when sediment can be transported over the river itself, such that there is no need for transport over land. The research question answered by this study is:

What is the optimal nourishment strategy to mitigate bed degradation in the Waal based on sediment availability in nearby sources?

In this research, the sediment availability of four different sources is identified over a period of 50 years: Area Vision Midden-Waal (7,500,000 m^3), mooring facility Spijk (750,000 m^3), Maas-Waal Canal maintenance (200,000 m^3), and downstream aggradation (570,000 m^3). The identified sources typically contain sediment that is finer than the nourishment location in the Boven-Waal. However, there is a possibility that these sediment sources contain small amounts of coarser sediment. This is the case for the sediment from Spijk and the Maas-Waal Canal. In total, 11 different nourishment schemes are constructed from these different sources. Using a 1D model of the Dutch Rhine branches, the sediment nourishments are modelled. These nourishments are placed in the Boven-Waal, centred around rkm 879.

The nourishments influence the bed level, discharge distribution at the Pannerdensche Kop and the geometric mean grain size. It is found that large nourishments (Area Vision Midden-Waal) are capable of counteracting river bed erosion in specific reaches of the Waal. These nourishments also mitigate skewing of the discharge distribution. Furthermore, the nourishments cause a fining of the bed, which makes it more erodible. For the other sources, similar observations are made regarding the different parameters. However, as these sources contained less sediment, their effects are much smaller and only have a noticeable influence during the first few years of the simulation.

Comparing the different nourishment schemes is challenging because they differ in several aspects. This makes it difficult to identify a single optimal approach. However, when considering the same nourishment volume, it is found that a single larger nourishment is preferable to multiple smaller ones when feasible. Both strategies result in similar aggradation upstream of the nourishment in year 50. This maximum bed level increase is reached faster for the singular nourishments. Therefore, its mitigating effect is relatively greater. Furthermore, the initial backwater curve effects have a more significant impact on the discharge distribution at low flows for the singular nourishment, causing more water to enter the Pannerdensch Kanaal. In the long-term, placing a single nourishment leads to more sediment reaching the already aggrading part of the Waal, increasing the need for maintenance dredging.

Singular nourishments investigated in this study can only delay bed erosion, as their nourished volumes are insufficient. To fully counteract erosion, repeated nourishments are required. This research included, among others, three scenarios with varying ratios of nourishment frequency to nourishment volume. In these scenarios, the length of the placement area for nourishments

remained the same, resulting in higher nourishment heights for larger volumes. This led to more pronounced initial morphological changes for larger nourishments, causing greater fluctuations in bed levels at the nourishment location. Smaller, more frequent nourishments resulted in less severe fluctuations. From an morphological point of view, it is desired to decrease these fluctuations as the presence of a nourishment forms an obstacle on the river bed, and thus to nourish more frequently. On the other hand, it can be preferable to minimise the nourishment frequency to reduce the disturbance of river ecosystems.

The efficiency of a nourishment scheme is determined by normalising the average bed level increase with the total amount of sediment nourished in that specific scheme. It is found that the most effective source is not the most efficient source. This hypothesises that the amount of sediment required to mitigate bed degradation can be reduced by selecting an appropriate source. In this research, singular nourishments constructed from sediment from the Maas-Waal canal and from downstream aggradation had the highest efficiencies. Therefore, their composition may be more optimal than those of the other sources.

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1 Introduction

The Dutch Rhine branches have been degrading over the past century. Of these branches, the Waal shows the strongest erosion. (Blom, 2016; Klijn et al., 2022; Programma Integraal Riviermanagement, 2021). Fig. 1.1 shows the average bottom depth of the Boven-Rijn and the Waal between 1950 and 2018. For the largest part of this section, the bed has degraded over the time domain shown. On average, the bed level of the Boven-Waal (rkms 868-887) erodes at a rate of 1.9 cm/year (Programma Integraal Riviermanagement, 2021). The Midden-Waal (rkms 887-917.5) erodes at a slightly lower rate, with 1.1 cm/year on average. The Beneden-Waal (rkms 917.5-953) is the transition area between the incising upper river area and the aggrading lower river area. In this section, the river bed shows a varying pattern of slight erosion and aggradation. On average, the river bottom has increased slightly in recent decades at a rate of 0.1 cm/year (Programma Integraal Riviermanagement, 2021). The erosion of the summer bed threatens several functions of the river. This includes, for example, the stability of structures (Slob, 2022; Wang et al., 2017), and damage to floodplains due to less frequent inundations such as soil degradation and disturbance of habitats (Blom, 2016).

The Dutch Rhine has been heavily modified in the past centuries. The primary goals of these adaptations were to increase flood safety and navigability. This was done, for example, by removing islands, constructing dykes, groynes, and cutting off meanders. Fig. 1.2 presents an overview of interventions in the Rhine of the last 400 years. Up to the 21st century, these interventions led to a decrease in the available flow width. Currently, the focus of river management has changed to a more integral management strategy instead of only considering navigability and flood safety (Programma Integraal Riviermanagement, 2021).

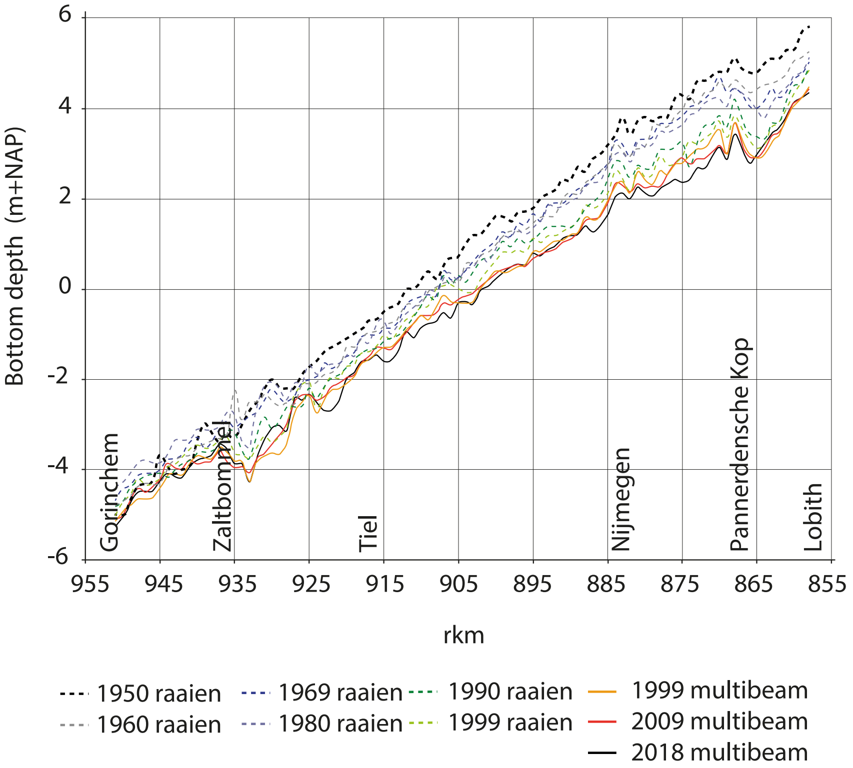
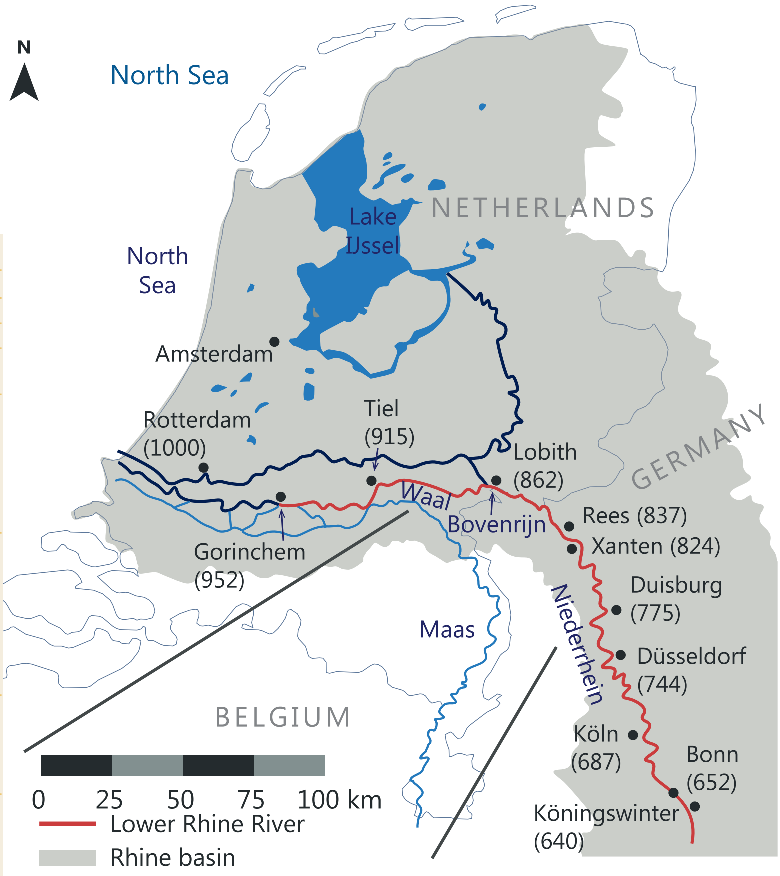


Fig. 1.1 Average bed elevation of the Rhine between rkm 855 and 955 between 1950-2018. Adapted from Barneveld et al. (2020).



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 m^3/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 70'000m^3 of gravel

Period	River km	Intervention
1770-1790	640-858	Training works for flood protection - Channel narrowing, groyne construction - Meander cutoffs - Connection of islands with banks - Installation of bank revetments
1880-1900	640-858	Training works for improvement of navigation: - Channel narrowing (from 475-500 to 325-285 m) - Meander cutoffs (net shortening since 1770 ~10%) - Embankment reinforcement and heightening
1870-	640-858	Dredging for navigation and construction purposes. Since the late 1970s dredged sediment is reallocated.
1900-	640-858	Dam construction in tributaries
1920-	640-858	Several local engineering and flood protection works
1920-	775-824	Coal and salt mining cause river bed subsidence. Since 1976 subsidence pits are filled with mining waste.
1985-	665-860	Sediment nourishments to mitigate bed degradation. 2Mt of fine gravel, and 6.4Mt of coarse gravel and cobbles supplied between 1991-2010 along the entire reach. Largest quantities supplied between river km 815-855.

Fig. 1.2 Human interventions in the Rhine since the 17th century. Adapted from Ylla Arbós et al. (2021).

The narrowing of the river has been achieved using groynes. Additionally, the degradation of the bed and the corresponding decrease in the water level have caused the groynes to be relatively higher, leading to increased water transport through the main channel and more erosion of the river bed. This creates a positive feedback loop, which further increases bed degradation (De Vriend, 2015). A decrease in available flow width results in erosion of the summer bed, as it causes an increase in flow velocity (Blom, 2016). Therefore, the flow can transport more sediment. With equal sediment influx, the amount of sediment entrained from the bed increases, causing a decrease in the bed slope. Consequently, the river shifts towards a new equilibrium. The downstream boundary condition is the level of the sea (or IJsselmeer for the IJssel), which remains relatively constant. Therefore, the bed rotates around its downstream end, leading to bed degradation, with the highest rates occurring upstream and the lowest rates occurring downstream. However, as a result of climate change, the sea level increases. This causes changes in the downstream boundary (Ylla Arbós et al., 2023).

Another factor contributing to bed degradation is coarsening of the sediment supply from the upstream boundary in Germany. Previously, the Rhine had a bed dominated by sand, but now it mainly contains gravel with less than 25% sand (Frings et al., 2019). This is due to sediment sorting, where finer sediments are eroded before coarser sediment. Furthermore, nourishments using coarse sediment in the German Rhine have resulted in downstream erosion. Frings et al. (2019) argue that current upstream nourishments may have an even larger impact on the Dutch Rhine's bed evolution than other training works have had in the past. However, more research is needed to understand the long-term effects of upstream sediment nourishments.

Local bed degradation in the Pannerdensch Kanaal, Nederrijn, and Lek is caused by the construction of weirs, which are partially closed at all times except during high flows. This results in sediment starvation and erosion downstream of the weirs. A similar effect is observed in dams such as those placed along the Oberrhein (Dietrich et al., 1989; Frings et al., 2019; Kondolf et al., 2014; Zheng et al., 2018).

Since bed degradation is not a spatially uniform phenomenon, a local decrease in flow depth can occur (Blom, 2016). At locations where the bed does not degrade, a bump is created, which causes an obstacle in the waterways. One location where this happens is the armoured layer near Nijmegen. In combination with low discharges, this creates a great danger for shipping. Additionally, structures such as bridges are solid and cannot be lowered with the river and therefore can become unstable. Bed degradation has also caused the port fronts of Nijmegen and Arnhem to subside, since the water flows under the quay walls and removes the sand beneath them (Blom, 2016; Ebbers, 2020). The same holds for the strength of pipelines and cables that are on or in the river bed, when the surrounding and underlying bed are eroded. In extreme cases, erosion can cause the collapse of structures (Simão Antunes Do Carmo, 2021).

Lowering the bed level leads to a decrease in the water level, causing the groundwater table to drop. This negatively impacts agriculture, water supply and ecology. Floodplains are also affected, as they flood less often, leading to drying and a reduction in the supply of nutrients from the river (Anderson et al., 2018; Baxter, 1977; Blom, 2016; Velísková et al., 2014; Ward and Stanford, 1995). It also concentrates floodwater more in the summer bed. This accelerates the discharge of flood waves, causing higher downstream discharge peaks.

Wu et al. (2016) describe that an increase in depth due to erosion of the river bed, can lead to an increase in saltwater intrusion. The processes that cause this intrusion are complicated: It is assumed that a deeper depth leads to stronger vertical circulation of the flow, which increases the saltwater transported upstream at the bottom. When discharge decreases, saltwater can travel further inland and increase salinity.

Furthermore, while bed degradation may initially seem beneficial for flood safety, it may also have negative consequences for flood safety. The degradation rate is not equal in all Rhine branches, causing an increased difference in the bed level of different branches at the bifurcation points (Blom, 2016; Klijn et al., 2022). Since flood safety standards are based on a specific discharge distribution, a change in this distribution poses a threat to flood safety.

After the (near) floods of 1993 and 1995, the vision of the interventions changed. The programme *Ruimte voor de Rivier* (RftR) was started, 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). Some measures caused a decrease in the erosion rate, but the bed degradation process was not stopped.

Following the RftR programme, in 2019 the *Integraal Riviermanagement* (IRM) programme was established by local and national governments (Programma Integraal Riviermanagement, 2021). Their aim is to enhance the different functions of the Rhine and Meuse by looking at integral solutions which treat the whole system as one to address multiple problems at a time. Currently, this has led to a *Systeembeschouwing* (Klijn et al., 2022), which concludes that climate change and bed degradation have serious consequences for the functioning of river systems (De Lange, 2022). Currently and in the future, possible interventions and policy options will be further researched and implemented.

Furthermore, the World Wildlife Fund, together with other nature organisations, set up the plan and vision 'Room for Living Rivers', which included a pilot in the Midden-Waal. The issues they address include creating more room and nature along rivers, improving flood safety, and stopping the continuous degradation of the bed. Welsch (2021) calculated the effect of a combination of side channels, large-scale lowering of floodplains, and removal of obstructions in the floodplains. He concluded that, while interventions may help counteract bed degradation, the effects are only seen locally, close to the interventions. He concludes that interventions should be imposed over a longer distance to be effective. Barneveld et al. (2020) also studied these interventions and concluded that giving the river more room to flow will not be enough to meet the goal of stopping bed degradation. They conclude that sediment nourishments are needed to reach this goal. Then, other interventions could be used to reduce the amount of sediment needed. This is also mentioned by Sloff et al. (2023).

The latest step in the IRM programme involves creating a *Programma onder de Omgevingswet* (POW), aiming to be implemented at the end of 2023 (Sloff et al., 2023). The POW contains an integrated vision of the river area, including the levels of ambition to be achieved for the discharge capacity, the bed level and the type of measures to be taken with the corresponding locations. Three policy options are identified: currently, it is advised to stabilise the current bed level (Option 1) and to restore the low-water discharge distribution of 1980 at the Pannerdensche Kop (Option 2). Restoring the low-water discharge distribution will not happen immediately. In POW IRM 1.0 the goal is to prevent the discharge distribution from becoming even more skewed (Van Vuren, 2023). At the next recalibration of the POW IRM, a final choice must be made about the degree of restoration of the discharge distribution (Van Vuren, 2023). When these measures are eventually designed, it is expected that it takes 10-20 years to implement them (Sloff et al., 2023; Van Vuren et al., 2015). That time is also needed to understand how the river responds to the measures. Restoring the bed level to an earlier level (Option 3) will not be applicable until the measures for the other policy options have laid the foundation for it, and when sufficient lessons have been learnt from experience in implementing those measures (Sloff et al., 2023).

Several possible measures have been identified by Sloff et al. (2023). They state that a first measure is to stop sediment extraction from the summer bed of the Waal. Furthermore, the construction of side channels provides a suitable structural solution for stabilising the Waal summer bed (Rorink, 2022; Welsch, 2021). The double flow channels on the Waal affect the distribution of all discharges over the Rhine branches. Realisation of the desired discharge distributions provides a design task for the bifurcation at the Pannerdensche Kop. Other possible additional measures are groyne lowering on the Boven-Waal, summer quay lowering on the Boven-IJssel, restoration of cutoff bends on the IJssel, such as Het Zwarte Schaar near Doesburg, and combination with floodplain measures for nature (e.g. side channels). Inevitably, adaptive sediment management will also remain necessary in the form of dredging and nourishing.

1.1 Problem Statement

While the process of bed degradation in the Waal is slowing down due to the decrease in equilibrium slope, it will not be fully stopped soon (Klijn et al., 2022). This degradation can be mitigated in two ways: either by decreasing the erosivity of the flow or by increasing the sediment supply. The latter can be realised by implementing sediment nourishments. Furthermore, to elevate the bed level of the river to compensate for past degradation, sediment nourishments are needed.

In the Netherlands, sediment nourishments have traditionally been used along the coast to nourish beaches. The most famous example is the Zandmotor in Monster. However, recent pilot studies in 2016 and 2019 have explored the use of sediment nourishments in the Dutch Rhine (Rijkswaterstaat, 2023). Sediment nourishments have already been implemented in the German part of the Rhine, as shown in Fig. 1.2. This is done because the section of the Rhine upstream of Iffezheim is blocked by several dams, causing bed erosion downstream. To get a better understanding of sediment nourishments before implementing them, they can be modelled.

In a 1D numerical modelling study, the effects of coarse and fine sediment nourishments were modelled (Czapiga et al., 2022). They found that to mitigate erosion, the sediment flux must be altered to increase the equilibrium channel slope. This can be done by coarsening the sediment flux. Alternatively, a large volume of relatively fine sediment can be added to increase the equilibrium channel slope. De Lange (2022) investigated the 1D effect of both riverine and coarse nourishments in a numerical modelling study. She focused on the erosion problem in the Waal. In this study, it was 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. The coarse nourishments performed better than the riverine nourishments. However, the modelled nourishments were not able to completely prevent erosion.

Although the nourishments modelled by De Lange (2022) reduced erosion in the Waal, they may not be achievable. The sediment compositions that were used are very expensive to obtain. In this research, nourishments composed of sediment that is available from nearby sources are investigated. *Nearby* indicates all the sediment that can be reached by ship from the Waal. Therefore, no transport over land is needed. This could be, for example, the much finer sediment that is aggradating in the lower parts of the Waal. Other sources could be floodplains, material that becomes available during maintenance works in the Rhine system, or imported sediment from neighbouring countries. The nearby sources of this research consist mainly of sediment that is finer than the Waal itself.

1.2 Research Aim and Questions

This research aims to determine what nourishment strategies can be designed in the Waal to mitigate bed degradation, based on sediment available in nearby sources. To structure this, a main research question and subquestions are defined. The main research question is:

What is the optimal nourishment strategy to mitigate bed degradation in the Waal based on sediment availability in nearby sources?

Which is split up in the following subquestions:

1) What sediment is or will become available in the nearby system?
2) What nourishment strategies can be developed based on the available sediment?
3) What are the morphological effects of the different nourishment strategies?

1.3 Study Area

Fig. 1.3 shows the Dutch Rhine branches. The Waal is specifically chosen as the study area since it has the highest erosion rates of all the Dutch Rhine branches (Programma Integraal Riviermanagement, 2021). It is the southernmost and largest of the Dutch Rhine branches, with a total length of approximately 85 km. It can be divided into three morphodynamically similar reaches: the Boven-Waal, Midden-Waal, and Beneden-Waal.

The Boven-Waal runs from the Pannerdensche Kop (rkm 868) near Millingen to just downstream of Nijmegen (rkm 887) at the Maas-Waal Canal, with a length of almost 20 km. It is characterised by four successive sharp river bends. The summer bed is bordered by groynes and the floodplains vary considerably in width. At Erlecom (rkms 873-876) bottom groynes were constructed in the outer section of the river bend. Near Nijmegen, the Waal has been considerably constricted. Between rkms 883-885, a fixed layer was applied in the outer bend. In this research, the Boven-Waal is split up in two reaches: Boven-Waal I (rkms 868-874), Boven-Waal II (rkms 874-887). The reason for this is explained in Section 4.3.1.

The Midden-Waal section runs from downstream of Nijmegen (rkm 887) at the Maas-Waal Canal to Tiel Passewaaij (rkm 917.5). The stretch is more than 30 km long. The summer bed is bordered by groynes and the floodplains vary considerably in width. Except for the bend in the river near Tiel, this part of the Waal is characterised by a straight river with wide banks and narrow floodplains. Near Tiel, the Amsterdam-Rijn Canal joins the Waal. The Amsterdam-Rijn Canal forms the shipping connection to Amsterdam. The groynes have been lowered on the entire stretch as part of the RftR programme. In the Wamel-Ophemert section (rkms 911-922) the groynes in two inner bends of the Waal have even been completely removed and replaced by longitudinal dams. The longitudinal dams lie parallel to the direction of flow of the river and divide the river into a wide main channel and a riparian channel.

The Beneden-Waal runs from Tiel Passewaaij (rkm 917.5) to Woudrichem (rkm 953) at the junction of the Afgedamde Maas. The stretch is more than 35 km long. The summer bed is bordered by groynes and longitudinal dams, and the floodplains vary in width. Except for the river bend at St. Andries, the course of the river section is fairly straight with very gentle river bends. From St. Andries, the influence of the North Sea becomes noticeable through tidal action. In the bend at St. Andries, a fixed layer is applied in the outer bend.

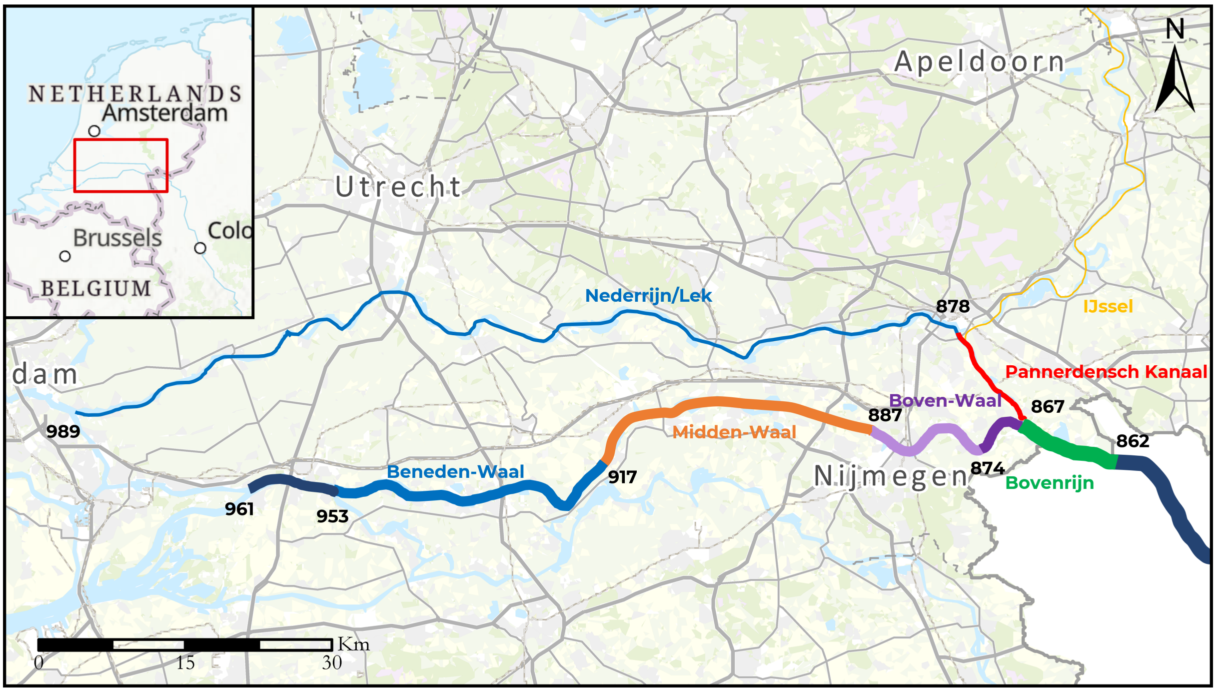


Fig. 1.3 Study area showing the Dutch Rhine branches. The Waal is split up in four reaches: Boven-Waal I (rkms 868-874), Boven-Waal II (rkms 874-887), Midden-Waal (rkms 887-917.5), and Beneden-Waal (rkms 917.5-953).

1.4 Report Outline

The theoretical background for this research is provided in Chapter 2. Chapter 3 provides a description of the model used, including its input and boundary conditions. Chapter 4 outlines the research methodology for the different research subquestions. Chapters 5-7 contain the answers to the different formulated subquestions. Chapter 8 provides a discussion of the methodology employed and the results achieved. In Chapter 9, the primary research question is answered, and suggestions for additional research are provided.

2 Theoretical Background

2.1 The Morphodynamic Feedback Loop

In general, morphological processes take place on a long time scale, i.e., years, decades, to centuries. A river system can change its shape over tens of years to adapt to interventions carried out on the river. To adequately manage rivers, it is important to be able to predict hydraulical-morphological effects.

To describe a morphodynamic system, individual process descriptions for hydrodynamics, sediment transport, and bed level changes are combined. This is presented in Fig. 2.1 as the morphodynamic feedback loop. Since morphological changes generally occur very slowly, the equations for water flow, sediment transport, and bed changes can be solved consecutively for a certain morphological time step.

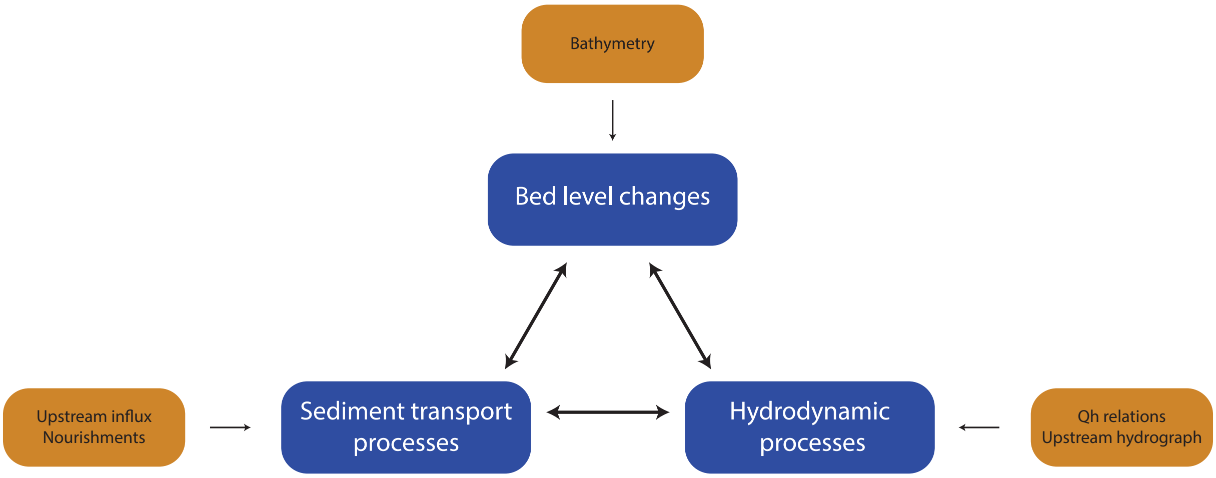


Fig. 2.1 The morphodynamic feedback loop.

Each of the three elements is affected by external factors. The way the river channel is shaped is partly guided by the landscape of the valley through which it passes. The discharge is mainly shaped by the patterns of flooding upstream. Sediment transport is influenced by the amount of sediment brought into the system from upstream sources.

Furthermore, these three elements have a significant mutual influence. The attributes of the bed level, such as the slope of the river bed, its roughness, and the width available for flow, determine how water is discharged. This, in turn, affects the hydrodynamics, such as velocity. As the water moves downstream, it applies force to the river bed. If this force is strong enough, it picks up sediment particles from the bed and carries them along. Changes in sediment, whether eroded from or deposited on the river bed, lead to changes in the pattern of the channel.

In contrast, the three components also impact each other in reverse. The characteristics of the channel determine the movement of the sediment because the characteristics of the bed dictate the force necessary to mobilise the sediment. Consequently, sediment transport affects water flow because energy is needed to move sediment, leading to energy loss and a decrease in flow speed. Ultimately, the behaviour of the water flow affects the pattern of the river bed.

2.2 Sediment Transport

The material carried by rivers originates within their river basins. Characteristics such as size, shape, density, fall velocity, chemical composition, and pore content play a crucial role in the way sediment is transported, eroded, and deposited. Sediments are categorised by their diameters, although their actual grain size is not solely determined by diameter. For the grain sizes discussed in this research, a classification is performed using a sieve diameter. This diameter represents the size of the opening in the sieve that a grain can pass through.

When a fluid flows over a loose granular bed, it exerts forces on the grains. If these forces exceed a critical threshold, the grains will begin moving. As the water velocity increases, more grains are set into motion, resulting in sediment transport. This transport is differentiated into bed load and suspended load, as presented in Fig. 2.2. The bed load refers to the material that is moved through rolling and sliding, while the suspended load refers to sediment suspended in the fluid for a period.

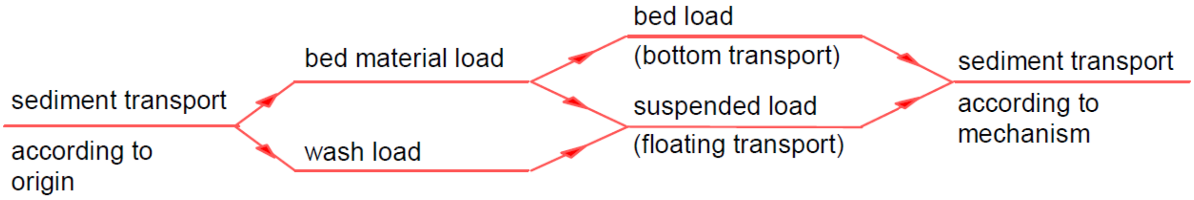


Fig. 2.2 Classification of sediment transport (Jansen, 1979).

Furthermore, a distinction can be made between the wash load and the bed material load. The wash load involves fine sediments suspended far upstream, which do not settle on the river bed. Consequently, this sediment fraction is rarely found on the river bed. The wash load does not interact with the river bed, and its quantity is determined solely by the flow supply, not by its capacity. The sediment that interacts with the river bed, known as the bed material load, encompasses both the bed load and a portion of the suspended load.

When addressing morphological issues, the wash load, which does not engage with the bed, should be disregarded. However, in specific scenarios such as sediment settling behind a dam, the wash load settles on the bed and must be considered.

2.3 Sediment Nourishments

Sediment nourishments have an effect not only on the bed at the location of the nourishment, but also upstream and downstream of this location (Mosselman et al., 2007). This can be seen schematically in Fig. 2.3. Upstream of the nourishment, an M1 backwater curve is induced. Downstream of the nourishment, an M2 drawdown curve is induced over the nourishment. This flow pattern results in sedimentation upstream of the nourishment and erosion of the downstream part of the nourishment (Czapiga et al., 2022). However, the exact behaviour of a nourishment is influenced by its design. Czapiga et al. (2022) identified grain size distribution, applied volume and frequency, and location of the nourishment as key variables in the design of a nourishment.

Finer sediment is more easily entrained and transported downstream by the flow, resulting in faster downstream movement than coarser sediment. Mosselman et al. (2007) suggest that nourishing with coarser sediment allows it to remain in place for a longer period, thus requiring longer before a new nourishment is required at that location. Additionally, the relative grain size of the sediment used in the nourishment and that present in the system determine the system's

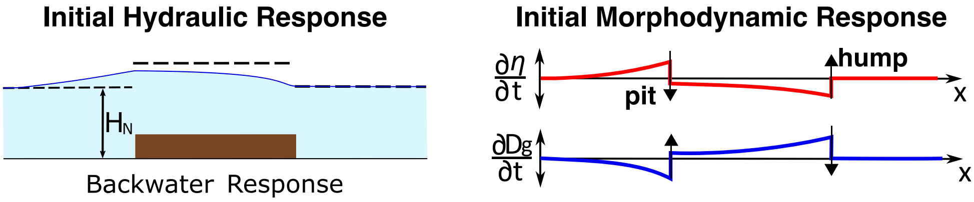


Fig. 2.3 Short-term channel response regarding hydraulic change showing local increase in bed elevation resulting in M1 backwater and M2 drawdown effects (Czapiga et al., 2022).

response to the nourishment. Previous studies suggest that nourishing with the same grain size as the present sediment is not the most efficient solution in terms of reducing erosion (Czapiga et al., 2022; Mosselman et al., 2007).

Nourishing with finer sediment than the sediment present in the bed causes rapid downstream transport of the nourishment by the flow, which causes the sediment to not fill erosion holes and instead be transported to shallower areas, which may increase the need for dredging. Large volume nourishments at once are recommended to mitigate these negative consequences of nourishing with finer sediment (Czapiga et al., 2022). On the other hand, nourishing with coarser sediment than the present sediment may also have negative consequences, such as forming an armoured layer on the bed, reducing the sediment transport load, and causing erosion downstream of the nourishment (Becker, 2021; Blom, 2016). Sloff et al. (2023) discusses that large-scale coarsening (a layer of 1 m thick over the entire summer bed) of the river bed can counteract both bottom erosion and shallows for navigation. A bed of coarser sediment leads on the one hand to a steeper bottom length profile that cuts less deeply, and on the other hand to flatter bottom cross profiles with less pronounced banks (Mosselman et al., 2004). However, this is not considered a promising solution direction. When nourishing on a smaller scale with coarser sediment, one should account for the enhanced degradation downstream of the nourishment before aggradation occurs. Multiple smaller nourishments are preferred to one large nourishment in the case of nourishing with coarser sediment (Czapiga et al., 2022; De Lange, 2022).

Czapiga et al. (2022) found that mixed sediment behaves differently from uniform sediment when used for nourishments. For mixed sediments, there is a grain size threshold above which aggradation increases as volume increases. When nourishments are executed below this threshold, an increase in volume leads to enhanced degradation. This happens because the addition of fine sediment in a relatively small volume makes the coarse sediment more mobile. These findings indicate that nourishing with mixed sediments of a wide range of fractions is recommended to mitigate unwanted effects such as reduced erosion.

In conclusion, the preferential grain size for sediment nourishment to counteract bed degradation is not yet known (Barneveld et al., 2020; Czapiga et al., 2022). Studies suggest that it is preferred to use a mixture of grain sizes that are generally coarser than the present bed material (Czapiga et al., 2022; De Lange, 2022). The grain size distribution of the river bed material is not constant and is coarsening over time, making it difficult to choose the correct grain sizes for a nourishment.

3 Model Description

3.1 Model Properties

This research utilises a 1D model to calculate changes in bed elevation and composition due to sediment nourishments. The model used in this study is the 1D Rhine branches model developed by Chavarrías et al. (2020). This model has been developed for the planning phase of the IRM programme to investigate the effect of different morphological interventions. Paarlberg and Van Lente (2021) and Rorink (2022) used this model to investigate the effect of side channels, while De Lange (2022) used this model to investigate the effect of sediment nourishments.

The model is specifically designed for morphodynamic simulations, which means that it captures sedimentation and erosion processes more accurately than a model calibrated for hydraulic calculations. To do this, the model is calibrated to capture the flow velocities as accurately as possible. As a trade-off, this causes the model to be less accurate regarding its water levels. An error of 1 to 10 cm can occur in the calculation of the water levels (Chavarrías et al., 2020). The model covers all branches of the Dutch Rhine: this includes the Boven-Rijn, the Waal, the Pannerdensch Kanaal, the Neder-Rijn, the Lek, and the IJssel. The upstream boundary is 48 km upstream of Lobith at the confluence of the Lippe and the Rhine, and the downstream boundaries are located in Hardinxveld, Krimpen, Keteldiep and Kattendiep. For this research, only adaptations are made in the Waal. However, since this is a connected system, interventions at the Waal will also result in changes at the other branches. This model allows for a more comprehensive understanding of the impact of nourishments.

The 1D shallow-water equations are used to calculate the hydrodynamics in the model, using the D-Flow FM 1D computational core, which are described in Appendix A. Bathymetry is based on SOBEK-3 schematization of the 2019 bathymetry of the Netherlands and the 2012 bathymetry of Germany. The sediment composition is based on measurements made in 1995, as already implemented in an earlier version of the model Sloff (2006). Sediment transport is modelled using different formulas for the sand and gravel fractions. These fractions are presented in Table 3.1. 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). Sedimentation and erosion in floodplains are not captured and sediment transport is modelled as bed load. However, sediment can be deposited and subsequently eroded from the floodplains.

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

#	Grain size (mm)	Type	#	Grain size (mm)	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

Hiding-exposure is only implemented for the gravel fractions using the relation of Ashida and Michiue (1972). This relation adjusts the critical bed shear stress, such that the mobility of gravel is affected by the presence of sand particles, whereas gravel particles have no effect on the mobility of sand (Chavarrías et al., 2020).

The active layer model by Hirano (1971) is used to model sediment in the river bed. The model consists of a single active layer with a constant thickness of 1 m and nine substrate layers with a maximum thickness of 0.4 m. The active layer represents the part of the bed that interacts with the flow. The sediment is perfectly mixed in this layer and forms the only place where the sediment can be transported. When sedimentation occurs, the sediment in the active layer is mixed and its height is reduced to 1 m as presented in Fig. 3.1. The excess sediment is pushed back into the first available substrate layer, which is then perfectly mixed again. This layer is then reduced to 0.4 m again, upon which the excess sediment is pushed back into the next substrate layer. This process is repeated until the substrate layer height is no longer exceeded. When the maximum of nine substrate layers is reached, a base layer is created which is not limited in thickness. Vice versa, when erosion occurs in the active layer, it is replenished by sediment from the first substrate layer such that its height becomes 1 m again, which is also mixed. The uppermost substrate layer is then replenished by the next substrate layer to a thickness of 0.4 m, and so on. In the model, it is assumed that the substrate has the same grain size distribution as the bed surface due to lack of knowledge about the actual substrate layers (Chavarrías et al., 2020).

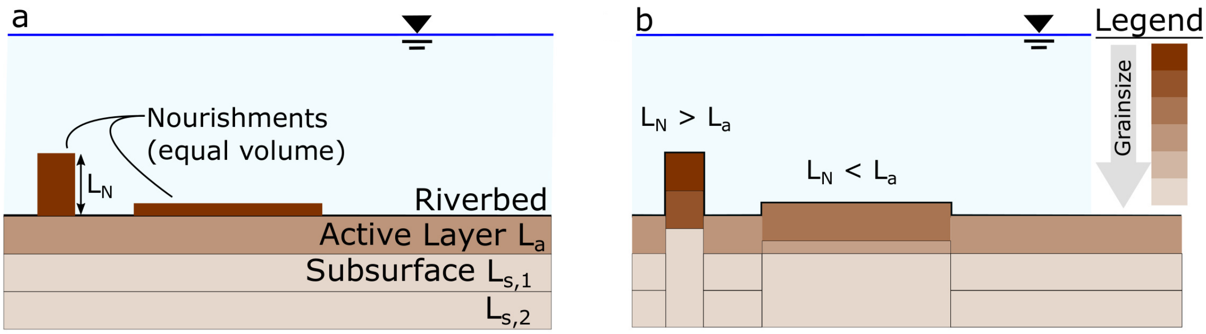


Fig. 3.1 Schematisation of the river bed using the active layer concept when implementing nourishments with a height larger and smaller than the active layer height (Czapiga et al., 2022).

The sediment transport distribution at the bifurcation points of the Pannerdensche Kop and the IJsselkop is determined using a nodal-point relation introduced by Sloff (2006), which can be found in Appendix A.1. This relation calculates the sediment load distribution based directly on the discharge distribution at the bifurcation point. To apply this relation, a calibration parameter specific to each sediment type and bifurcation point is implemented, as defined by Chavarrías et al. (2020), who based their calibration on measurements by Frings et al. (2019). Such a nodal-point relation is also implemented in another study (Ylla Arbós et al., 2023).

In the model, three weirs are included 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 Lobith. To handle unrealistic morphological behaviour observed around the weirs, adjustments were made by fixing the modelled bed level in these areas (Chavarrías et al., 2020). In reality, this would mean that continuous dredging and nourishing is performed to counter sedimentation or erosion. This assumption is expected to not have a significant impact on the Waal.

The model also considers fixed layers in the Waal at Erlecom (rkms 873-876), Nijmegen (rkms 883-885), and St. Andries (rkms 925-928). In reality these fixed layers are located across only part of the width of the river, for example, in an outer bend. The model considers them over the entire width due to its 1D nature. To maintain sediment transport over these fixed layers, the layers are modelled as lacking sediment by removing the substrate layers (Chavarrías et al., 2020). This approach allows erosion of up to 1 m at the location of the fixed layers, but the active layer is not replenished. As the thickness of the active layer decreases, the transport of sediment over it is reduced (Paarlberg and Van Lente, 2021). At the fixed layers, the bed level does not necessarily match what would occur in reality. However, the model captures sediment transport over these layers correctly.

The simulation period for this study is set at 50 years, starting on October 1, 2019. The temporal resolution at which the data is exported is five days. It should be noted that predictions on future bed levels are typically made up to 2050 (Programma Integraal Riviermanagement, 2021; Sloff et al., 2023), so that a comparison after 2050 is made mainly with other modelling studies, such as De Lange (2022) and Ylla Arbós et al. (2021).

3.2 Boundary Conditions

The model needs both upstream and downstream boundary conditions. To be able to make a quantitative comparison with the results of De Lange (2022), the same boundary conditions are applied, which are described in this section.

At the upstream boundary, located at Wesel (rkm 815), a discharge series generated by De Lange (2022) is applied with a duration of 50 years. This series is based on the historical discharge at Lobith (rkm 865) and was generated using bootstrap resampling. It is acknowledged that the upstream boundary of the model does not coincide with the location at which the historical discharge was measured. Both Chavarrías et al. (2020) and Paarlberg and Van Lente (2021) explain that this difference does not have influence on the results, since long-term morphological development is investigated and not the effect of a single flood wave. The complete discharge series is shown in Fig. 3.2a, and the maximum yearly discharges are presented in Fig. 3.2b. The presented maximum values are calculated per calendar year, and thus not the hydrological year.

At the downstream boundaries, Qh relations are applied. This relation couples a water *level* to a specific discharge. These relations are taken from Paarlberg and Van Lente (2021) and presented in Fig. 3.3. Finally, lateral inflows to the Rhine branches are removed. This is common in large-scale morphological simulations, as their effect is negligible (Paarlberg and Van Lente, 2021).

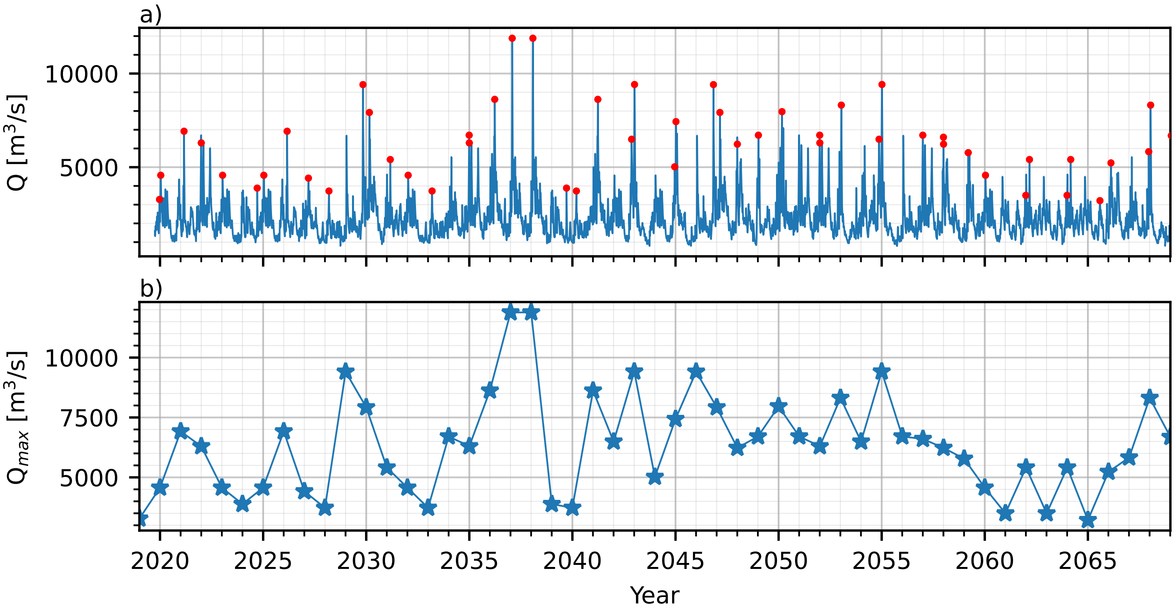


Fig. 3.2 a) Discharge and b) yearly maximum discharge at the upstream boundary. The red dots indicate the maximum discharges per calendar year.

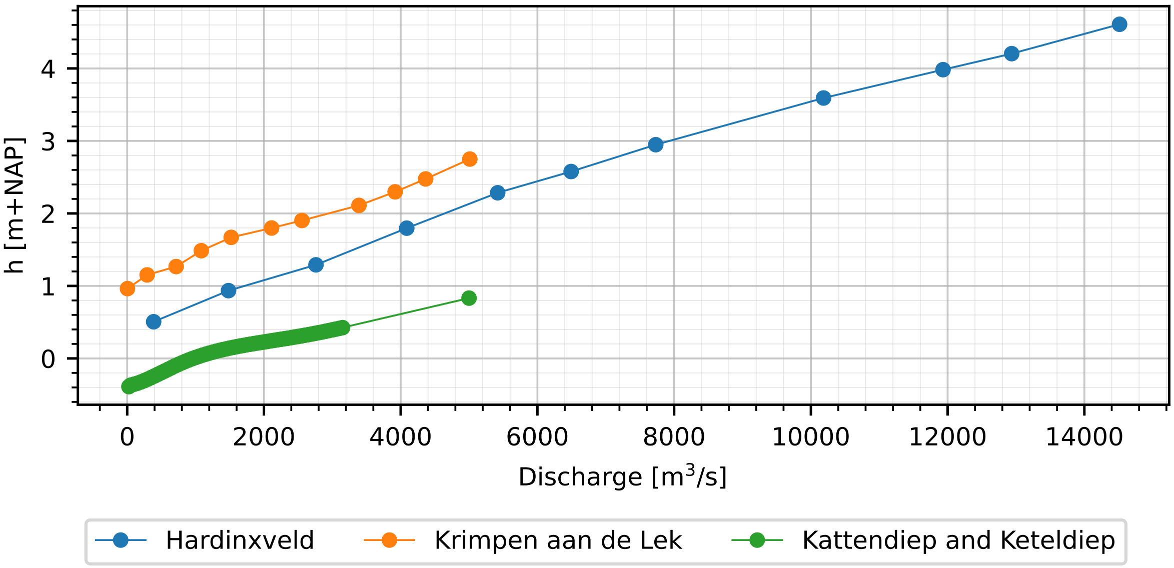


Fig. 3.3 Qh relations of the different downstream boundaries. Data obtained from Paarlberg and Van Lente (2021).

4 Methodology

4.1 Identification of Different Sources

To answer the first research question, different sources of sediment are identified. This is based on three categories defined in preliminary research:

- Commercial sediment mining;
- River management and maintenance;
- Downstream aggradation.

Information concerning these different sources is retrieved via the corresponding authorities. For information regarding commercial sediment mining, contact is established with Dekker Groep. This company is active for more than 100 years in the extraction of sand, gravel, and clay for construction, landscape development, logistics, soil for redevelopment, and concrete. Rijkswaterstaat provides information regarding governmental projects and has data available regarding the composition of the Waal and the other Dutch Rhine branches. Additionally, the IRM programme made predictions for the downstream aggradation rates (Programma Integraal Riviermanagement, 2021).

For the different sources, the sediment composition must be determined. Additionally, the temporal properties of the sediment availability are important. This includes the expected volume, as well as how often this volume becomes available. In this research, it is not possible to identify all possible sediment sources and their properties. Therefore, this research aims to have a limited number of sources that represent a variety in available volumes and grain size distributions.

4.2 Design of Modelling Scenarios

Nourishments are implemented using the dredge and dump module in D-Hydro. They are characterised by their placement in space, placement in time, volume, and grain size distribution. To control these characteristics, several properties of the nourishment should be defined (Deltares, 2023).

The placement in space is controlled by defining one or more polygons where the nourishments are placed. These polygons cover the riverkilometres on which the nourishments are applied. Nourishments are then placed with an equal thickness over the entire summer bed of the cells that fall within the defined polygons. Nourishments are not modelled as rectangles but rather as trapezoids: this is because the bed level is linearly interpolated. This should be considered when designing polygons. While there is no strictly defined minimum length for the implementation of nourishments in the model, there are some considerations. A length of five cells (approximately 2,500 m in the Boven-Waal) is considered low for the numerical scheme implemented in this model. This results in the dominance of numerical diffusion over the physical dampening of the actual feature (Chavarrías, 2023). This length is expected to introduce an error of at least 10% in the morphological calculations (Chavarrías, 2023).

Placement in time is controlled by defining active periods in which the nourishments are executed. The volume supplied in these active periods is controlled by a nourishment rate, which is defined in m^3/year. In this research, each separate nourishment is executed in exactly one day. For nourishments of either large or small volumes, this can result in artificially high or low nourishment rates. The consequences of this are discussed in Section 8.4.4. The initial nourishment of each time series is carried out between days 9 and 10. This specific time window is chosen because the first week of the simulation serves as a morphological spin-up period. Additionally, since data is recorded every five days, it is desired to implement nourishments right before the data is captured.

Finally, the grain size distributions of the nourishments are defined. The model uses 16 grain sizes, as presented in Table 3.1. These grain sizes do not necessarily match the sieve sizes used in the sieve analysis of the identified sources. Therefore, it may be necessary to apply linear interpolation at the defined grain sizes of the model so that the distributions can be implemented in the model. Another consideration is the fact that the smallest grain size implemented in the model (75 μm) is not equal to the smallest grain size used in conventional sieve analysis (63 μm). Directly applying linear interpolation at 75 μm would lead to an incomplete distribution, as the sediment between 63-75 μm would be discarded. This would result in an incomplete distribution. To prevent this, it is assumed that the amount of sediment retained on top of the 63 μm sieve also remained on top of the 75 μm sieve.

The design of the scenarios is shaped by the properties of the different sources. The grain size distribution is chosen to be uniform over time, by taking the average distribution of each source. All of the nourishments are placed in between the two fixed layers at the Boven-Waal. Two widths are defined: The first is the standard (rkms 876.3-882.7) width, and the second is the narrow (rkms 877.4-880.1) width. Klijn et al. (2022) recommends to increase the bed level of the Boven-Waal between 35 and 50 cm. These heights are based on the elevation needed in the Boven-Waal to restore the desired discharge distribution at the Pannerdensche Kop. Currently, the desired discharge distribution is met at 1.590 m^3/s, whereas an increase of 35 cm in the Boven-Waal reduces this to 1.400 m^3/s (Klijn et al., 2022). Fifty centimetres is mentioned as an upper limit. For small volumes, the height of the nourishment may not reach the recommended minimum threshold of 35 cm for the chosen placement lengths. To reach this minimum value, the nourishment would have to reduce in length. As stated above, nourishments should have an appropriate length to minimise numerical diffusion. The implications of this trade-off are discussed in Section 8.4.4.

4.3 Analysis of Morphological Development

The development of the river bed is highly variable in both time and space. In this research, the analysis is performed in two ways: by analysing data with a high spatial resolution and by analysing data with a high temporal resolution. The data with high spatial resolution are presented every 10 years. The data with a high temporal resolution are presented every 5 days, with their values being spatially averaged as described in the next section. The parameters considered regarding the effect of nourishments are the bed level and geometric mean grain size changes. For the reference scenario, the sediment transport is also investigated. The geometric mean grain size is defined as follows:

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

where x_i is the fraction of the grain size D_i present in the active layer. This summation is performed over all the 16 fractions present in the model. For readability, ‘geometric’ is ommited throughout this report.

First, the reference scenario is investigated. Here, no nourishments or other human interventions are included. This allows for a quantitative comparison with scenarios in which nourishments are applied.

4.3.1 Spatial Averaging

Spatial averaging is applied by averaging the parameters over their specific reaches. In this research, the reaches included are the Rhein (rkms 815-862), Boven-Rijn (rkms 862-868), Boven-Waal I (rkms 868-874), Boven-Waal II (rkms 874-887) Midden-Waal (rkms 887-917.5) and Beneden-Waal (rkms 917.5-953). The Boven-Waal is split into two parts because the erosion in the Boven-Waal I is larger than that in Boven-Waal II. If no separation is applied, averaging over the entire Boven-Waal would present a distorted picture of the erosion, as well as the mitigating effect of nourishments. Furthermore, the nourishments are placed in the Boven-Waal II. Due to this separation, the morphological effects due to the backwater curves are isolated. When analysing the reach averaged results, it is kept in mind that these reaches have different lengths. Therefore, nourishments will have a smaller averaged influence on longer branches.

4.3.2 Absolute and Relative Changes

The development of parameters is analysed in two different ways: absolute and relative. The change in absolute bed level ($\Delta z_{b,a}$) defines the changes with respect to their initial values. In this case, the value 0 represents the difference between net erosion (smaller than 0) or net aggradation (larger than 0).

Relative changes are discussed in two ways. The first way is to analyse changes relative to the reference scenario. When analysing the relative bed level change ($\Delta z_{b,r}$), the mitigating effect of a nourishment can be isolated. The bed levels considered here indicate how a nourishment strategy can increase (larger than 0) or decrease (smaller than 0) the bed level with respect to the reference scenario. Analogous, analysing the relative geometric mean grain size change ($\Delta D_{g,r}$) indicates whether a nourishment fines (smaller than 0) or coarsens (larger than 0) the river bed compared to the reference scenario. The second way of relative analysis includes the comparison of two different scenarios with each other. The relative differences between two scenarios indicate how different nourishment strategies generate differences in bed level and geometric mean grain size changes. Using this type of relative analysis, it is identified how large the differences are between different strategies.

4.3.3 Influence on Discharge Distribution

It is acknowledged that this model is calibrated for the purpose of morphological analysis and, therefore, contains errors in the hydrodynamic calculations. In the model, the water level is not captured with the accuracy (in the order of mm) required to assess the impact of interventions for the sake of evaluating permits (Chavarrías, 2023). Instead, the results of the hydrodynamic calibration show that there are errors in the water level of the order of one cm and up to one dm (Chavarrías et al., 2020). Although these results may not meet the desired level of precision for permit evaluation, they do offer insights into the discharge distribution and its correlation with sediment nourishments.

The discharge distribution at the Pannerdensche Kop is determined by calculating the ratio between the discharge in the Waal and the discharge at Lobith. In this study, the distributions are calculated every year. Since the hydrograph that is applied upstream is not cycled, hydrological years vary. Therefore, the discharge distribution of each individual year is composed of different discharges. Furthermore, the water levels throughout the system do not stabilise, since the upstream discharges vary faster than the time it takes for the system to reach a stable water level. This results in the fact that the same discharge can result in a different discharge distribution (hysteresis). Lastly, the distributions are calculated every year. Throughout the year, the system undergoes morphological changes. Therefore, the same discharge has a different effect on January 1 than on December 31. These effects introduce uncertainty in the calculated discharge distributions.

The influence of a nourishment on the discharge distribution is calculated relative to the reference scenario. In this study, negative values indicate that *less* discharge enters the Waal. Although it is also of interest to determine the absolute changes in the discharge distribution, this is not possible with the boundary conditions implemented. Since the hydrograph varies from year to year, no absolute differences can be calculated.

To compare the discharge distribution at the same discharge at Lobith, a linear least square fit (LLSF) is applied. The error is classified by a standard error with a 95% confidence interval. In the model, the weir at Driel opens when Lobith reaches a water level of 8.65 m+NAP. As a result of hysteris, different discharges can result in this water level. For the modelled discharges, the weir opens from a discharge of 1,800 m^3/s. This opening causes a knick (Fig. 7.13). The discharges higher than 1,500 m^3/s are discarded in the LLSF, so only the discharges with low flow conditions are considered. In this discharge regime, the distribution is approximately linear. It is of interest to investigate the effect of a nourishment on the *Overeengekomen Lage Afvoer* (OLA) of 1,020 m^3/s, as the water level associated to this discharg is used as a guideline in various practices. However, at OLA too few data points are available. Therefore, it is chosen to quantify the effect of a nourishment strategy at a Lobith discharge of 1,400 m^3/s as this discharge is located in the centre of the available discharge regime. This quantification is done by comparing the changes in discharge fractions that go to the Waal when a nourishment is placed. Again, negative values indicate that less discharge enters the Waal.

5 Sediment Sources

This chapter gives an overview of the different identified sediment sources, which answers the first research sub-question: “*What sediment is or will become available in the nearby system?*” It should be noted that the sources presented in this section do not form a complete overview of all the sources, but rather a sample that shows variety in volume and availability in time. In this research, a distinction is made between three different types of sources:

1) Commercial sediment mining;
2) River management and maintenance;
3) Downstream aggradation.

First, the different sources are described in Sections 5.1-5.3. Second, some grain size distributions are introduced for reference in Section 5.4. Finally, an overview of the volumes, availability in time and grain size distributions is presented in Section 5.5.

5.1 Commercial Sediment Mining

Gravel and sand are extracted in large quantities. In the Netherlands, more than 20 companies are active in this industry. In 2020, approximately 35 Mm^3 of sediment was extracted (Van Hardeveld, 2022). Each company extracts sediment at multiple sites, most of which are located in the floodplains of the Rhine and Meuse. While the deposited sediment is primarily used for the production of concrete and asphalt, it can also be used for nourishments due to its riverine nature.

Although there are numerous extraction areas, this research focuses on one particular project as an example: Area Vision Midden-Waal (Dekker Groep, 2023). This project is located in the northern bank of the Waal, between Dodewaard and Tiel. It consists of four smaller projects, with a total length of approximately 12 km. For 30 years, 700,000 m^3 of sediment will be extracted every year. In May 2023, the second smaller project has started: *Willemspolder fase 1*. In an exploratory consultation with Dekker Groep, it has been established that it is possible to supply a volume of 150,000 m^3 yearly. This volume is based on the findings of Van der Deijl (2021), which represents the yearly volume needed to fixate the Waal. For this research, this volume is assumed to be available annually for 50 years. In reality, this would mean that during the first 30 years 3 Mm^3 of additional sediment is bought and stored or that a similar extraction site is opened after 30 years. The average sediment composition of this project was estimated by Dekker Groep, based on a project they executed in the vicinity of Area Vision Midden-Waal. The grain size distribution is presented in Fig. 5.4.

5.2 River Management and Maintenance

The Dutch river system has been heavily modified in the past several centuries to maintain the different functions of the rivers. This includes factors such as ecology, water quality and safety, navigability, and the presence and maintenance of the necessary infrastructure. A recent example is the RftR programme, which aimed to increase flood safety (Rijkswaterstaat, n.d.). Currently, the Water Framework Directive (WFD) is being implemented with the aim of increasing the biological, hydromorphological, and chemical quality of ground and surface waters in the Netherlands (Helpdesk Water, 2023a). In the near future, the implementation phase of the Programmatic Approach to Great Waters (PAGW) will start (Helpdesk Water, 2023b). This programme aims to improve the ecological functioning of the large waters of the Dutch delta. RftR, WFD, and PAGW all contain projects where resources can become available.

These resources can be used to 'make work with work'. Rijkswaterstaat is implementing a soil flow model (*grondstromenmodel*), which focusses on monitoring resources that become available during government projects so that they can be used in nearby projects (Wieggers, 2023). When resources are used close to their origin, this reduces the need for transport and thus decreases the environmental impact. In addition to gravel and sand, many more resources are included, such as clay and humus. Furthermore, commercial sectors such as agriculture and ceramics are also being considered for receiving sediment, next to applications in government projects. This could be, for example, the application of humus in orchards or farmlands or clay in the construction of bricks.

For this research, two sources are investigated regarding river management and maintenance. The first source is the construction of mooring facility Spijk. During its construction, about 2,300,000 m^3 of sediment was extracted. Data is available for 750,000 m^3 sediment. This sediment was divided into seven products with different grain size distributions. For this research, an average grain size distribution is used. This is calculated by using the volumes and grain size distributions of the separate products. The average grain size distribution can be seen in Fig. 5.4. Data of the separate products are presented in Appendix B.1. In reality, the sediment at Spijk is not perfectly mixed and its composition differs highly at different extraction points, as measured by Dabek and Van Geloven (2018).

The second source is the maintenance of the Maas-Waal Canal, which is part of the Eastern Netherlands Waterways Maintenance. During this project, approximately 20,000 m^3 of sediment was extracted. This sediment has been used to fill the erosion pit near St. Andries. Its composition was determined by taking 25 samples from the total volume and performing a sieve analysis. The average of these distributions is taken as its composition in this research. It is assumed that this maintenance will be performed every five years. The grain size distribution is presented in Fig. 5.4.

5.3 Downstream Aggradation

Downstream of rkm 917.5, the Waal aggrades. This aggrading part can be used as a source of sediment for nourishments by dredging it. Different dredging procedures can be applied here:

1) Adjusting the bed to an earlier level;
2) Removing sediment from the shallowest parts first;
3) Removing the same thickness everywhere.

The first method bases its procedure on historic bed levels. Aggrading parts can be dredged up to a bed level corresponding to a previous point in time. However, basing the bed level on past levels may not be desired. In the past, major works have been performed in the river. Therefore, it is currently not known what the optimal bed level is (Klijn et al., 2022). The second procedure aims at first removing sediment from the shallowest parts: that is, the places where the depth of the water is the smallest. The third procedure involves removing the same thickness of sediment everywhere in the aggrading section. Depending on which dredging procedure is applied, different volumes of sediment become available. For this research, the last is used, since it results in an equal amount of sediment each year. Based on the aggradation rate of Programma Integraal Riviermanagement (2021) of 0.1 cm/year, the length of the Beneden-Waal (35.5 km) and its average width (320 m), approximately 11,400 m^3 sediment can be extracted per year. The average grain size distribution of the sediment is approximated to be the average grain size distribution in the aggrading part of the Waal. This is a simplification that excludes the variety in the summer bed width along the Beneden-Waal. Furthermore, to prevent additional effects as a cause of downstream dredging, no downstream dredging is applied. This allows to isolate the effect of the nourishments. The consequences of these simplifications are discussed in Section 8.2.

The sediment composition of the summer bed of the Dutch Rhine branches was last measured in 2020. (Reneerkens, 2020). Fig. 5.1 shows the sampling methodology that was applied. Using a Hamon gripper, approximately 25 cm of the top of the summer bed was extracted at different points. Three sampling points were taken at each riverkilometre cross section, one in the centre and two halfway between the centre and each bank. Halfway between each riverkilometre, a sample is taken in the centre (Reneerkens, 2020). Fig. 5.2 shows the grain size distribution along the Waal. For each riverkilometre, the average value is calculated. Additionally, a moving average of 10 km is applied. It can be seen that when moving upstream, the grain size distribution coarsens. The average grain size distribution in the aggrading part of the Waal (Fig. 5.2) will be used as the grain size distribution for the nourishments from this source, as shown in Fig. 5.4.

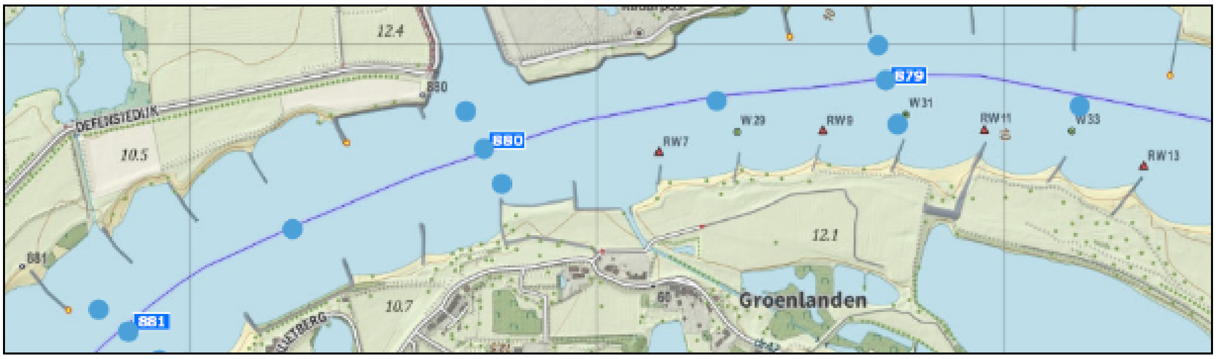


Fig. 5.1 Spatial diagram of the sampling method. The blue dots indicate the sampling points (Reneerkens, 2020).

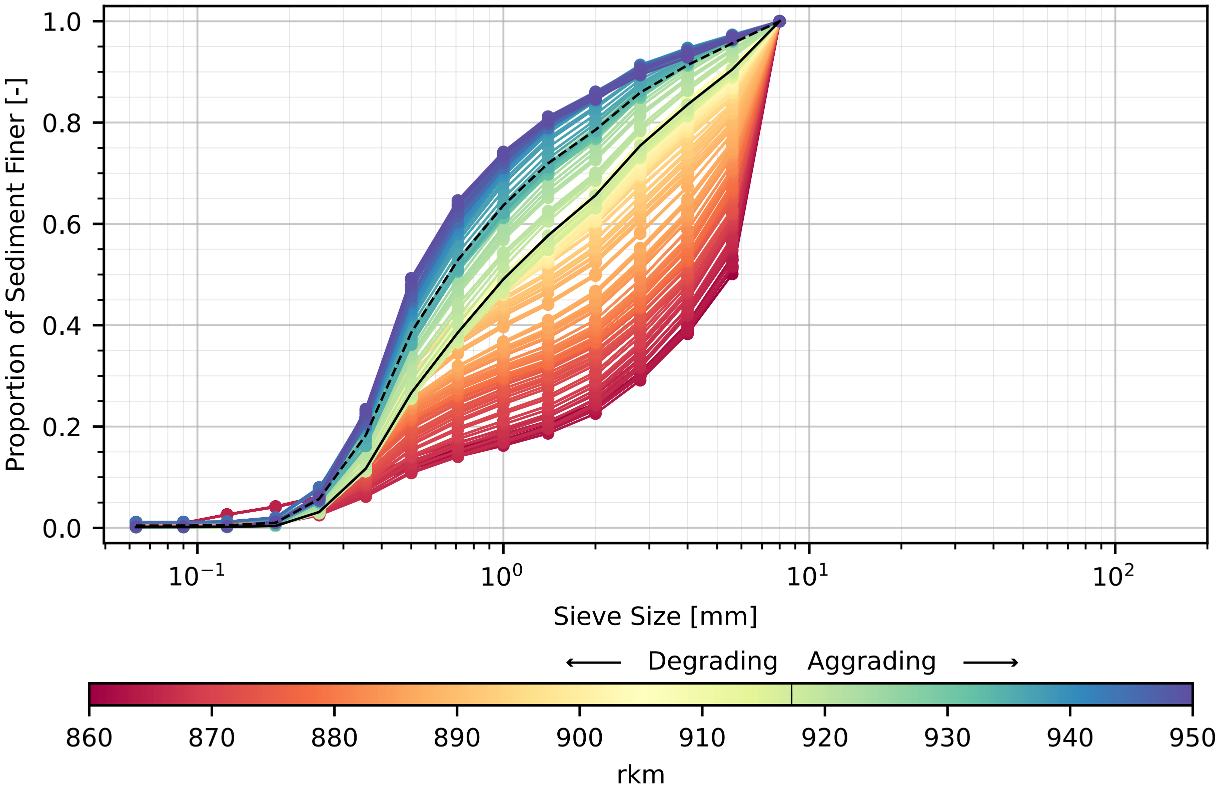


Fig. 5.2 Grain size distributions of the Waal river bed. Moving average with window of 10 km applied. The solid lines (in-plot and colorbar) indicate the border between the aggrading and degrading sections at rkm 917.5. The dashed line indicates the average grain size distribution of the aggrading section. Data obtained from Reneerkens (2020).

5.4 Additional Distributions

The nourishments are executed centred around rkm 879. The grain size distribution of the Waal that is included in the model, originates from 1995. As mentioned above, the Waal was sampled again in 2020. The distribution of rkm 879 is presented for both years in Fig. 5.4. It can be seen that coarsening has occurred between these distributions.

De Lange (2022) executed nourishments with both area specific nourishments and coarse nourishments. The area specific nourishments were implemented by increasing the bed level of a specific cross-section, such that the composition along a specific reach stayed the same. For the coarse nourishments, the grain size distribution was determined such that the D_{10}, D_{50} and D_{90} were larger than those of the bed at the nourishment location after 0 and 50 years of development of the bed without future human intervention. This distribution is also presented in Fig. 5.4.

For the different sources, it can be seen that the grain size distributions of the nourishments are finer than the nourishment location. Furthermore, the distributions found in this study are finer than the coarse nourishments investigated by De Lange (2022).

5.5 Overview of Identified Sources

The research question that is answered by this chapter is “*What sediment is or will become available in the nearby system?*”

Sediment can become available from different locations near the Waal. In this research, four sources are identified, which can be divided in three categories: downstream aggradation, river management and maintenance (two sources), and commercial sediment mining. These sources are presented in Fig. 5.3. This list is not a complete overview: These sources serve as mere examples. Additional sources are available and could be extracted specifically for implementing nourishments. The identified sources encompass various volumes and grain size distributions that could be used for nourishments.

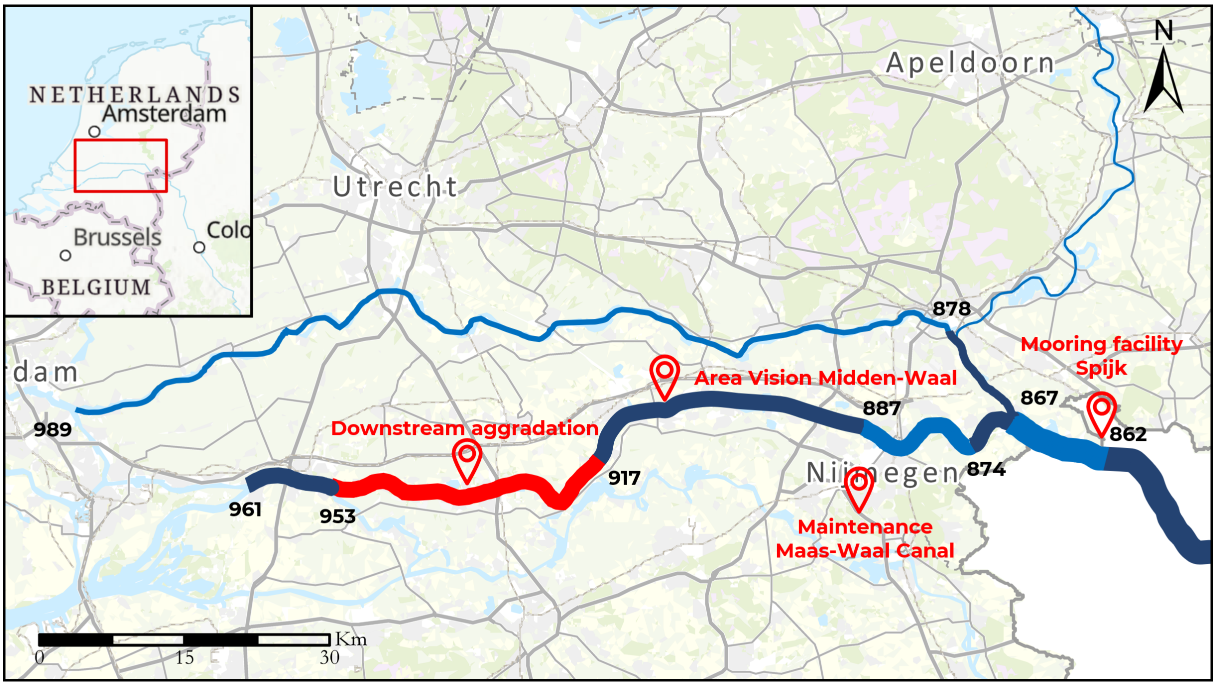


Fig. 5.3 Locations of the different identified sources.

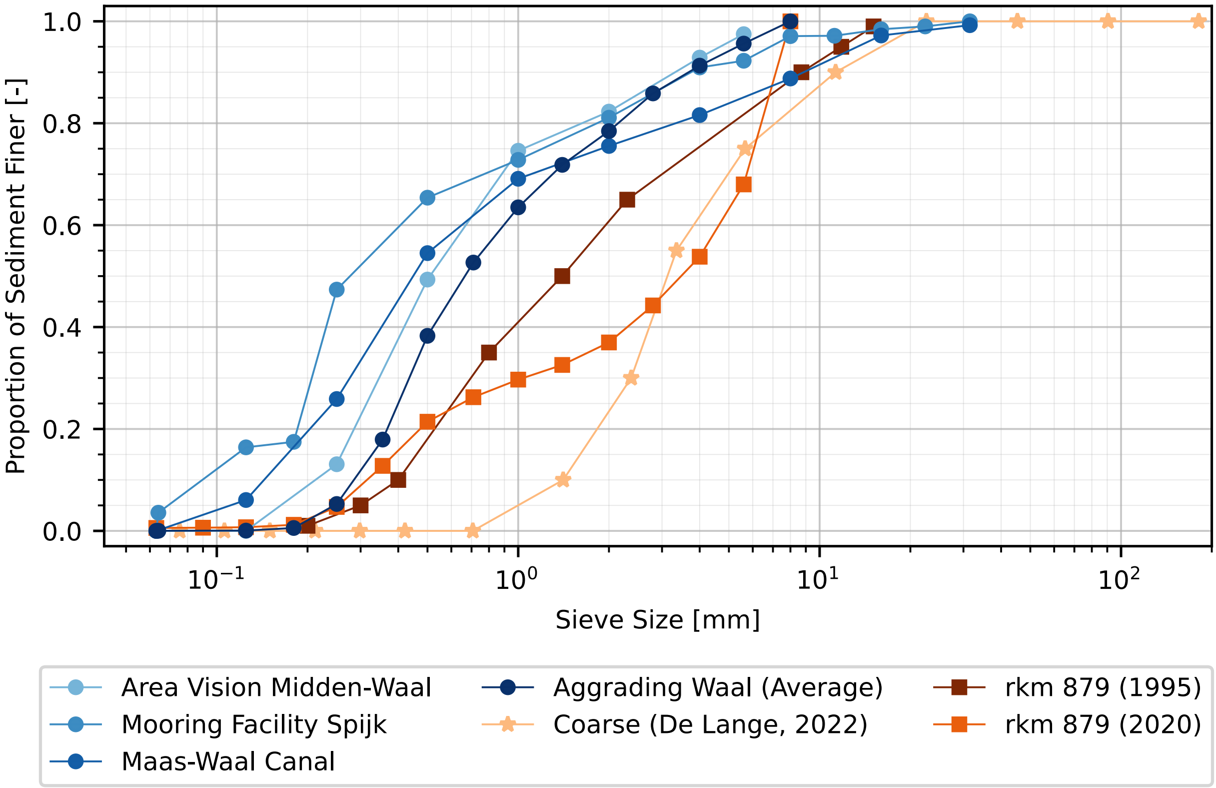


Fig. 5.4 Grain size distributions of the different nourishment sources and the nourishment location centre.

Table 5.1 Properties of the different sources.

Source	**Availability**	**D_1 (mm)**	**D_{10} (mm)**	**D_{50} (mm)**	**D_{90} (mm)**	**D_{99} (mm)**
Area Vision Midden-Waal	150,000 m^3, yearly	0.08	0.21	0.51	3.46	6.13
Mooring Facility Spijk	750,000 m^3, once	0.06	0.09	0.29	3.81	22.41
Maas-Waal Canal	20,000 m^3, five yearly	0.07	0.15	0.46	9.16	29.66
Downstream Aggradation	11,400 m^3, yearly	0.19	0.29	0.67	3.71	7.45

For the identified sources, the average grain size distributions are found to be finer compared to the nourishment location and the nourishments by De Lange (2022), as presented in Fig. 5.4. In reality, the distribution within a source is not uniform and, therefore, can introduce local coarse or fine areas within a nourishment. To prevent this, sediment can be preprocessed. Between the different sources, a large difference in the available volume is identified, as presented in Table 5.1. An uncertainty persists in the available volumes due to assumptions made.

6 Modelling Scenarios

In this chapter, the different scenarios that are designed to answer the research sub-question "*What nourishment strategies can be developed based on the available sediment?*" are presented. The scenarios include various nourishment strategies, based on the characteristics of the different sources: volumes, availability in time, and their grain size distribution. First, Section 6.1 presents the primary scenario properties. Second, Section 6.2 contains the motivations for the different strategies for the different sources. Last, an overview of all the scenarios and their properties is presented in Section 6.3.

6.1 Primary Scenario Properties

The grain size distributions were processed as described in Section 4.2, so that they could be used in the model. The results of this schematisation are presented in Fig. 6.1. The percentages for the individual fractions are presented in Appendix B.3.

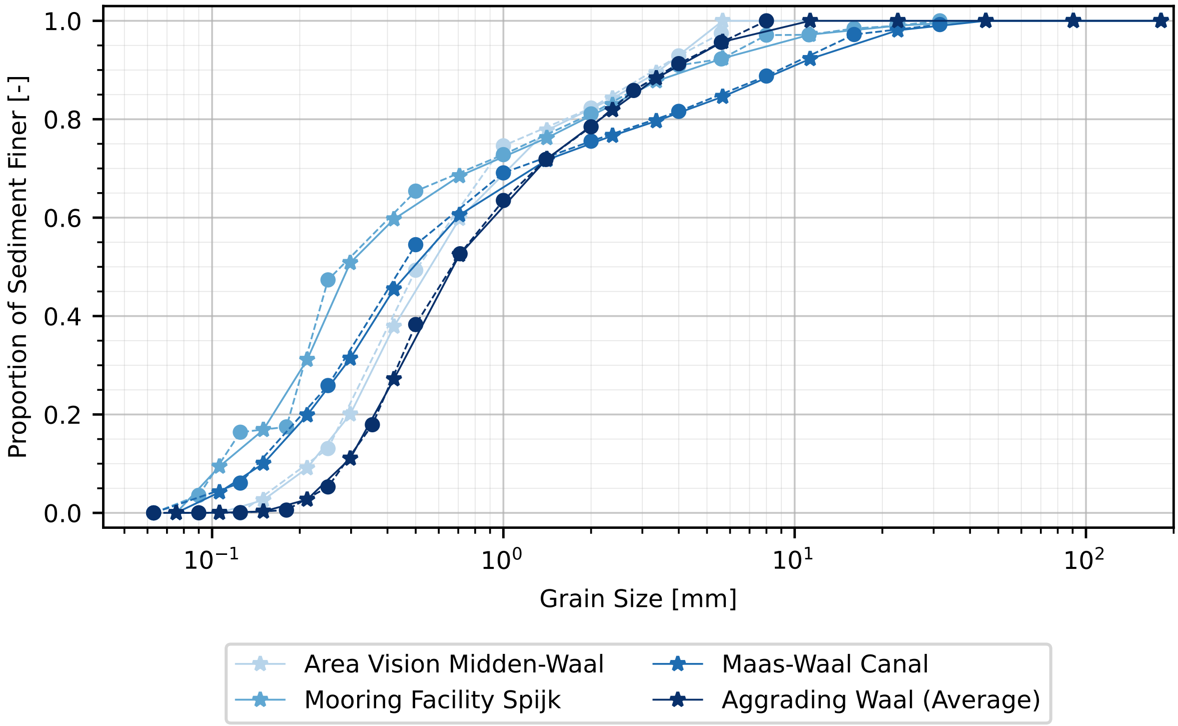


Fig. 6.1 Schematisation of grain size distributions. The dots are the points at which the distributions are measured, and the stars are the grain sizes implemented in the model at which the distributions are interpolated.

Individual nourishments are modelled as a singular parts, i.e., a singular nourishment consists of one long strip of sediment and not of spatially separated humps. The latter is done in other modelling studies to account for erosion downstream of a coarse nourishment (Czapiga et al., 2022; De Lange, 2022). As the sources in this research consist of sediment that is finer than the river, this is not necessary.

6.2 Scenario Descriptions

6.2.1 Reference

A reference scenario is needed to be able to quantify the effects of the different nourishments. This is a scenario in which no nourishments or other interventions are implemented. From this scenario, the development of the Waal can be investigated when nothing is done.

6.2.2 Area Vision Midden-Waal

From Area Vision Midden-Waal it has been established that 150,000 m^3 of sediment can be used on a yearly basis. By varying the ratio of the nourishment frequency and the supplied volume per nourishment, the effect of placement in time can be investigated. In total, three different scenarios are introduced for this sediment source: placing a volume of 37,500 m^3 every quarter, placing a volume of 150,000 m^3 every year, or placing a larger volume of 750,000 m^3 every five years.

6.2.3 Spijk

During the construction of the mooring facility Spijk, approximately 750,000 m^3 of sediment was extracted. This sediment was not extracted all at once, but took approximately two years. When this sediment was extracted, there were two possibilities: either the sediment was nourished immediately, or stored such that it can be nourished later. This allows for two modelling strategies: when the sediment is nourished immediately, the nourishment scheme consists of temporally spaced smaller nourishments. In this research, this is done by executing ten nourishments of 75,000 m^3 every 75 days. This strategy is executed on two different placement lengths to see how the ratio between nourishment length and height affects the development. When the sediment is stored intermediately, it can be nourished all at once. This scenario is investigated by placing a singular nourishment of 750,000 m^3 at the start of the simulation.

6.2.4 Maas-Waal Canal

It is assumed that every five years, 20,000 m^3 of sediment becomes available from maintenance at the Maas-Waal Canal. Similar as the strategy from Spijk, this is modelled as a periodic nourishment every five years. On the other hand, it can be decided to store this sediment intermediately for a total period of 50 years. This is modelled as a singular nourishment of 200,000 m^3 at the beginning of the simulation.

6.2.5 Downstream Aggradation

The last source consists of the sediment that has aggradated downstream, which is modelled in three ways. First, a volume corresponding to 5 cm of aggradation (which corresponds to 50 years) is nourished. This equals 570,000 m^3 and is placed as a singular nourishment at the beginning of the simulation. Second, every year 11,400 m^3 are dumped upstream, corresponding to a yearly excavation of 1 mm. This smaller volume is modelled when placed at both the wide and narrow dumping location. It is chosen to model only the nourishment itself and not the dredging, so that the effect of the nourishment can be isolated. The consequences of this are discussed in Section 8.4.4.

6.3 Scenario Overview

The research question that is answered by this chapter is “*What nourishment strategies can be developed based on the available sediment?*”

Sediment from sources cannot be extracted all at once. Therefore, each source inherently has a variability in time. For the different investigated sources, this variability in time is used to develop the scenarios presented in Table 6.1.

Table 6.1 Overview of the different modelling scenarios. The different sources are Area Vision Midden-Waal (AVMW), mooring facility Spijk, Maas-Waal Canal (MWC) and downstream aggradation (DA). N_{nour} represents the total amount of nourishments, l_{nour} the nourishment placement length and h_{nour} the nourishment placement height.

ID	**Description**	**m^3/Dump**	**Total Volume (m^3)**	**Temporal Spacing**	N_{nour}	$l_{nour} \times h_{nour}$ **(km × cm)**	**Location (rkm)**
0-I	Reference	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1-I	AVMW: five-yearly nourishment	7.50E+05	7.50E+06	5 years	10	6.4 × 47.8	876.3-882.7
1-II	AVMW: yearly nourishment	1.50E+05	7.50E+06	1 year	50	6.4 × 9.56	876.3-882.7
1-III	AVMW: quarterly nourishment	3.75E+04	7.50E+06	1/4 year	200	6.4 × 2.39	876.3-882.7
2-I	Spijk: Once	7.50E+05	7.50E+05	n.a.	1	6.4 × 47.9	876.3-882.7
2-II	Spijk: Frequent	7.50E+04	7.50E+05	75 days (for 2 years)	10	6.4 × 4.79	876.3-882.7
2-III	Spijk: Frequent, narrow	7.50E+04	7.50E+05	75 days (for 2 years)	10	2.7 × 13.3	877.4-880.1
3-I	MWC: Once	2.00E+05	2.00E+05	n.a.	1	2.7 × 35.36	877.4-880.1
3-II	MWC: Periodic	2.00E+04	2.00E+05	5 years	10	2.7 × 3.54	877.4-880.1
4-I	DA: Once	5.70E+05	5.70E+05	n.a.	1	6.4 × 36.3	876.3-882.7
4-II	DA: Periodic	1.14E+04	5.70E+05	1 year	50	6.4 × 0.73	876.3-882.7
4-III	DA: Periodic, narrow	1.14E+04	5.70E+05	1 year	50	2.7 × 2.01	877.4-880.1

7 Morphological Development

This chapter answers the third research sub-question "*What are the morphological effects of the different nourishment strategies?*". Herefore, the morphological analysis of the reference scenario and designed nourishments as described in the previous chapter are presented. First, the development of the bed without human interventions is described in Section 7.1. Then, the impact of the different nourishment strategies are discussed per identified source in Sections 7.2-7.5. An overview of the long-term morphological effects is presented in Section 7.6.

7.1 Reference Scenario

7.1.1 Bed Level Development of the Rhein and Boven-Rijn

Fig. 7.1a shows the development of the bed level between the upstream boundary of the model (Wesel) and the Pannerdensche Kop. This part of the Rhine consists of two reaches: the Rhein (rkms 815-862) and Boven-Rijn (rkms 862-868). The development of the bed with respect to the start of the simulation is presented in 7.1b. In general, an eroding trend can be observed.

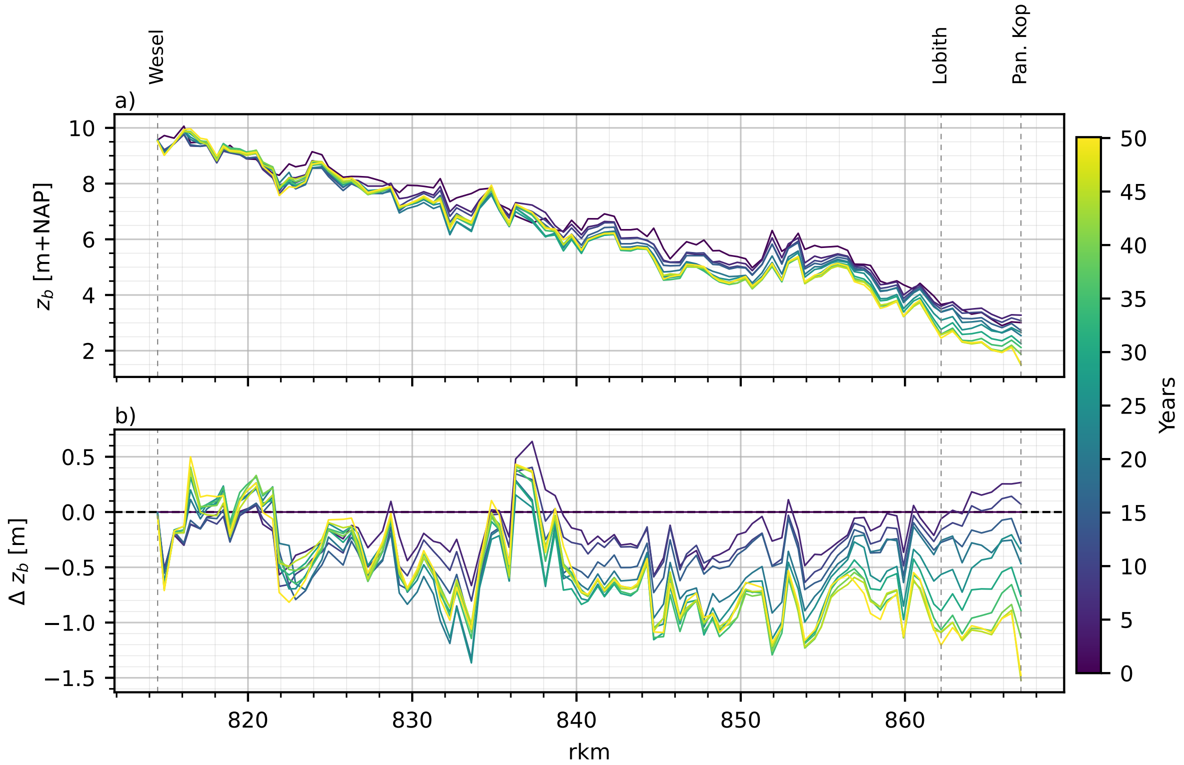


Fig. 7.1 a) Development of the main channel bed level and the b) absolute main channel bed level change in the Rhein and Boven-Rijn.

The bed level development averaged over each reach is shown in Fig. 7.2a. The bed level development with respect to the initial bed level is shown in Fig. 7.2b. The bed level of the Rhein erodes 53 cm up until year 30. At this point, the erosion stabilises as the mean grain size has increased. After 30 years, the bed has coarsened sufficiently so that it cannot be eroded as much (Fig. 7.4a). From year 30, aggradation of 2 cm occurs up until year 50. Given this small change, the Rhein has reached a quasi-equilibrium somewhere between 20-30 years. While the IRM programme has not made a prediction for bed development in the Rhein, it is predicted that between 2020 and 2050 the Boven-Rijn can erode 1 cm/year (Programma Integraal

Riviermanagement, 2021). The erosion of 53 cm in the first 30 years corresponds to a rate of 1.7 cm/year. This is significantly higher than the prediction for the Boven-Rijn, but in the same order of magnitude. In the last 20 years, aggradation of 0.1 cm/year occurs.

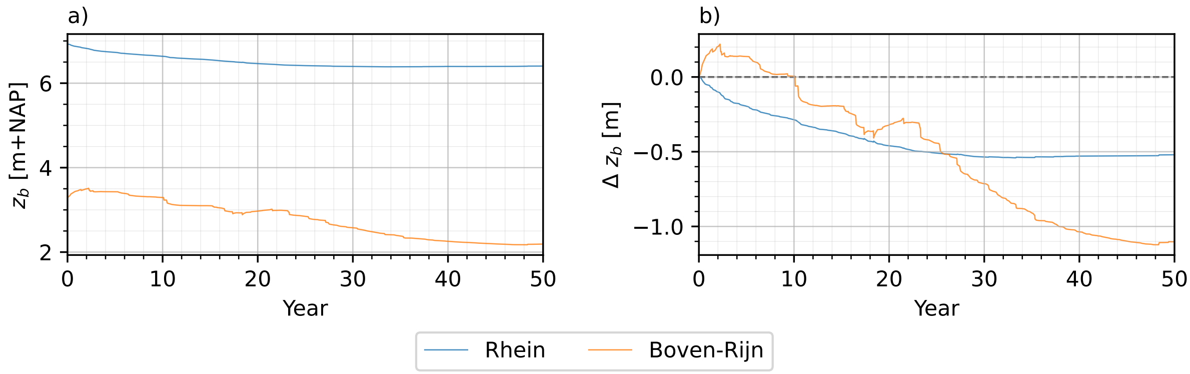


Fig. 7.2 a) Reach averaged development of the main channel bed level and the b) reach averaged absolute main channel bed level change in the Rhein and Boven-Rijn.

Initially, the bed level of the Boven-Rijn aggradates 20 cm in the first two years, after which it erodes. This initial increase is due to the influx of fine sediment eroded from the Rhein. After ten years, the bed level is equal to the initial level again and continues to erode until the end of the simulation. During this erosion, a stable period between years 10-16 is present. Between years 18-22, a period of sedimentation occurs. These phenomena are directly related to the imposed hydrograph (Fig. 3.2): The stable period follows after a high discharge year, whereas the sedimentation period follows after two subsequent high discharge years. After 30 years the bed has eroded 70 cm, which corresponds to an average erosion of 2.3 cm/year. In the last 20 years, the Boven-Rijn erodes 40 cm, or 2 cm/year. Historical measurements show that, while the Boven-Rijn has degraded in the past, the bed level has been stable for the last ten years (Programma Integraal Riviermanagement, 2021; Ylla Arbós et al., 2019). Experts do not fully agree on the expected behaviour of the Boven-Rijn in the future (Programma Integraal Riviermanagement, 2021). It is not clear whether the Boven-Rijn has reached an equilibrium or whether the bed will further erode (Programma Integraal Riviermanagement, 2021). Additionally, the behaviour of the Boven-Rijn is largely dependent on the sediment influx from upstream, specifically from the Rhein. This means that the way the river is managed in Germany has a major influence: German river practices, such as nourishments, will influence the behaviour of the Boven-Rijn. The IRM programme considers two scenarios: next to the erosional trend of 1 cm/year, the possibility is that the bed level will remain stable (Programma Integraal Riviermanagement, 2021). Compared to these predictions, the simulation overestimates the erosion rates.

7.1.2 Mean Grain Size Development of the Rhein and Boven-Rijn

Fig. 7.3a shows the development of the mean grain size in the Rhein and Boven-Rijn. The change with respect to the initial mean grain size is presented in Fig. 7.3b. This increase occurs uniformly over the reaches over time, indicating that it is not caused by an inflow of coarse sediment. Instead, the coarsening of the bed occurs as a result of the erosion of the bed in this area. The finer fractions are transported more easily than the coarser fractions, causing the surface of the bed to coarsen. The same is observed by Paarlberg and Van Lente (2021) and De Lange (2022).

The development of the mean grain size per reach is shown in Fig. 7.4a. The change with respect to the initial mean grain size is presented in Fig. 7.4b. For the Rhein, the mean grain size increases 6 mm during the first 30 years of the simulation. In the last 20 years, the mean grain size stabilises. This increase coincides with the decrease in bed level from Fig. 7.2b.

In the first 10 years, the bed of the Boven-Rijn is finer than the initial situation due to the influx of the fine sediment that eroded from the Rhein. After 10 years, the bed coarsens. In the mean grain size, a stable period is present at the same time (years 10-16) as the stable period in the bed level (Fig. 7.2b). During years 18-22, fining occurs. This coincides with the sedimentation period in the bed level. Therefore, fine sediment is deposited during this sedimentation period. For the Boven-Rijn, the mean grain size has also increased with 6 mm after 50 years.

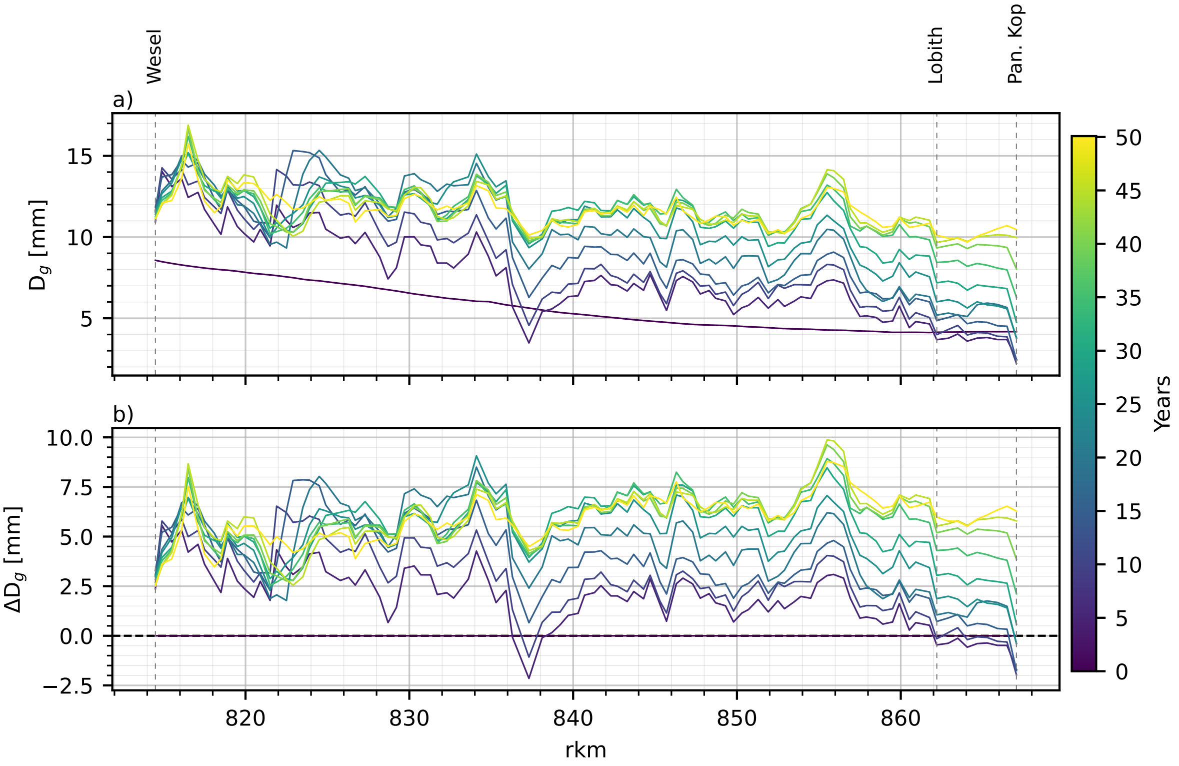


Fig. 7.3 a) Development of the mean grain size and the b) absolute mean grain size change in the Rhein and Boven-Rijn.

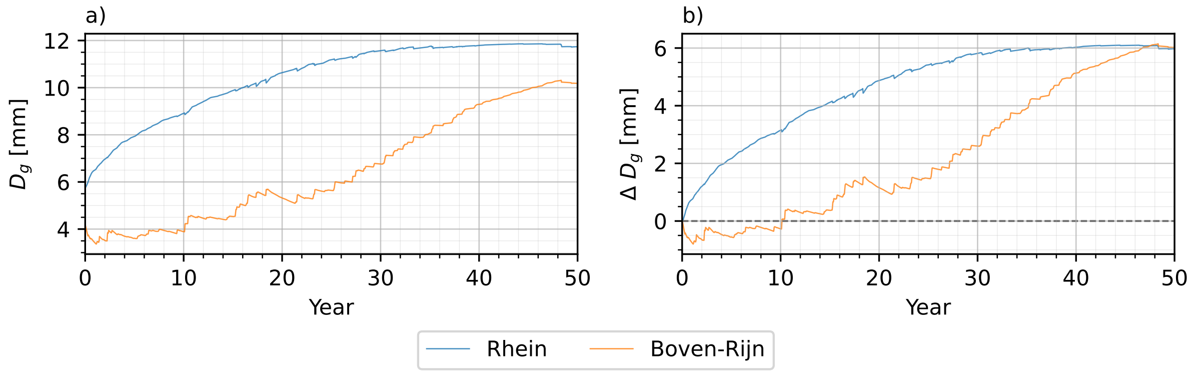


Fig. 7.4 a) Reach averaged development of the mean grain size and the b) reach averaged absolute mean grain size change in the Rhein and Boven-Rijn.

7.1.3 Sediment Transport Development of the Rhein and Boven-Rijn

Fig. 7.5a shows the development of the sediment transport rate in the Rhein and Boven-Rijn. With time, the sediment transport rate decreases. This is also visible in Fig. 7.5b, where the cumulative sediment transport converges. Fig. 7.6 shows the decrease in the sediment transport rate over time for both reaches. The sediment transport rate is larger in the Boven-Rijn than in the Rhein. This is explained by the mean grain size, which is always smaller in the Boven-Rijn (Fig. 7.4). Therefore, the sediment is more easily entrained in the Boven-Rijn. The transport rate decreases over time due to the coarsening of both reaches. In year 2, the sediment transport is the highest during the entire simulation. However, the maximum discharge in this year (7,000 m^3/s), is not the highest discharge that occurs in the hydrograph (Fig. 3.2). The highest maximum discharge (12,000 m^3/s) occurs in years 18 and 19. At these years, the sediment transport rates do not show distinct peaks. This happens because at this point in time, the bed has become much coarser. Therefore, in year 2 (when the bed is finer) a smaller discharge is capable of transporting more sediment. In year 10, a maximum discharge of 9,000 m^3/s is applied, causing the peak at this point.

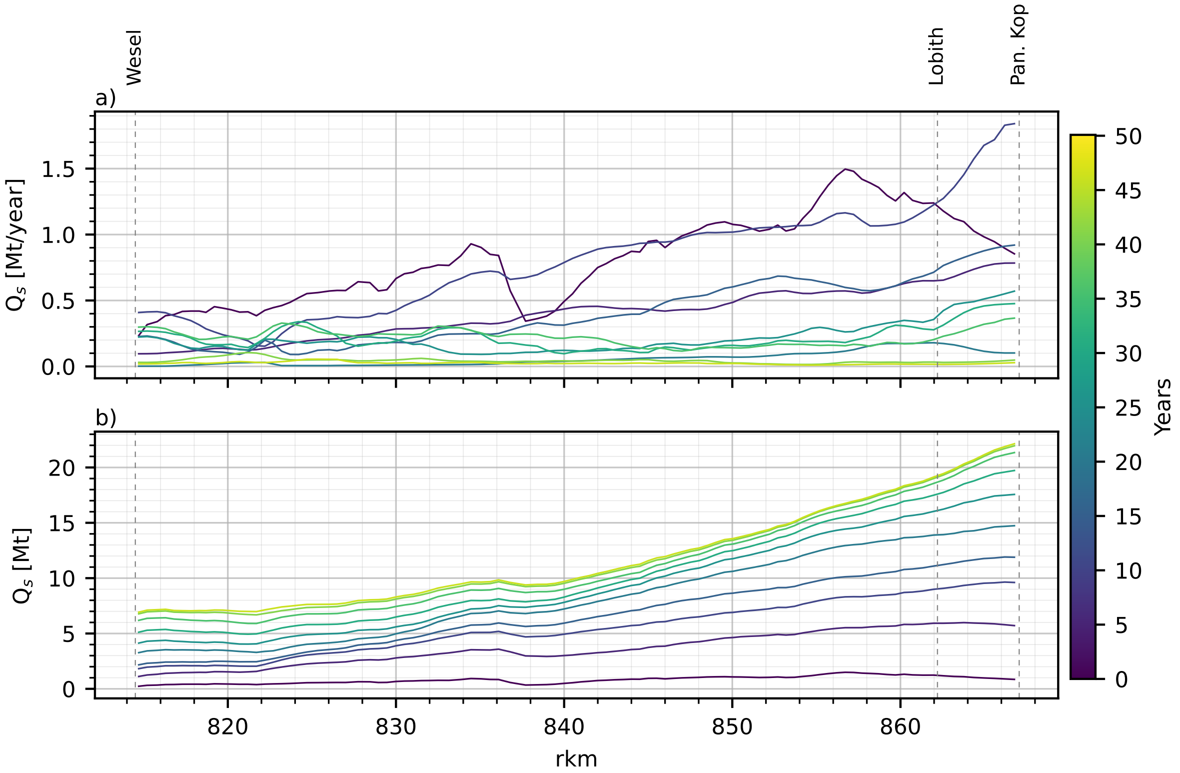


Fig. 7.5 a) Yearly sediment transport rate and b) cumulative sediment transport in the Rhein and Boven-Rijn.

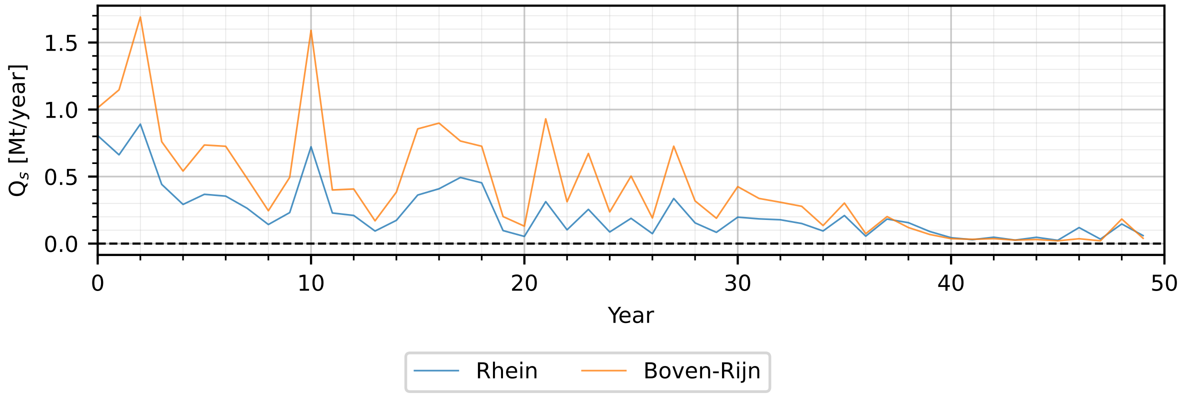


Fig. 7.6 Reach averaged development of the sediment transport rate in the Rhein and Boven-Rijn.

7.1.4 Bed Level Development of the Waal Reaches

The development of the bed level of the Waal is shown in Fig. 7.7a. Upstream of rkm 917.5, at Tiel Passewaaij, the Waal erodes. Downstream of this point, aggradation is visible. This can be seen as a counterclockwise rotation around this point, causing a decrease in the bed slope. Fig. 7.7b shows the development of the Waal with respect to the initial bed level. The erosion of the Boven-Waal and Midden-Waal, as well as the aggradation of the Beneden-Waal, agree with historical observations (Barneveld et al., 2020; Blom, 2016), other modelling studies (De Lange, 2022; Rorink, 2022), and predictions in Programma Integraal Riviermanagement (2021).

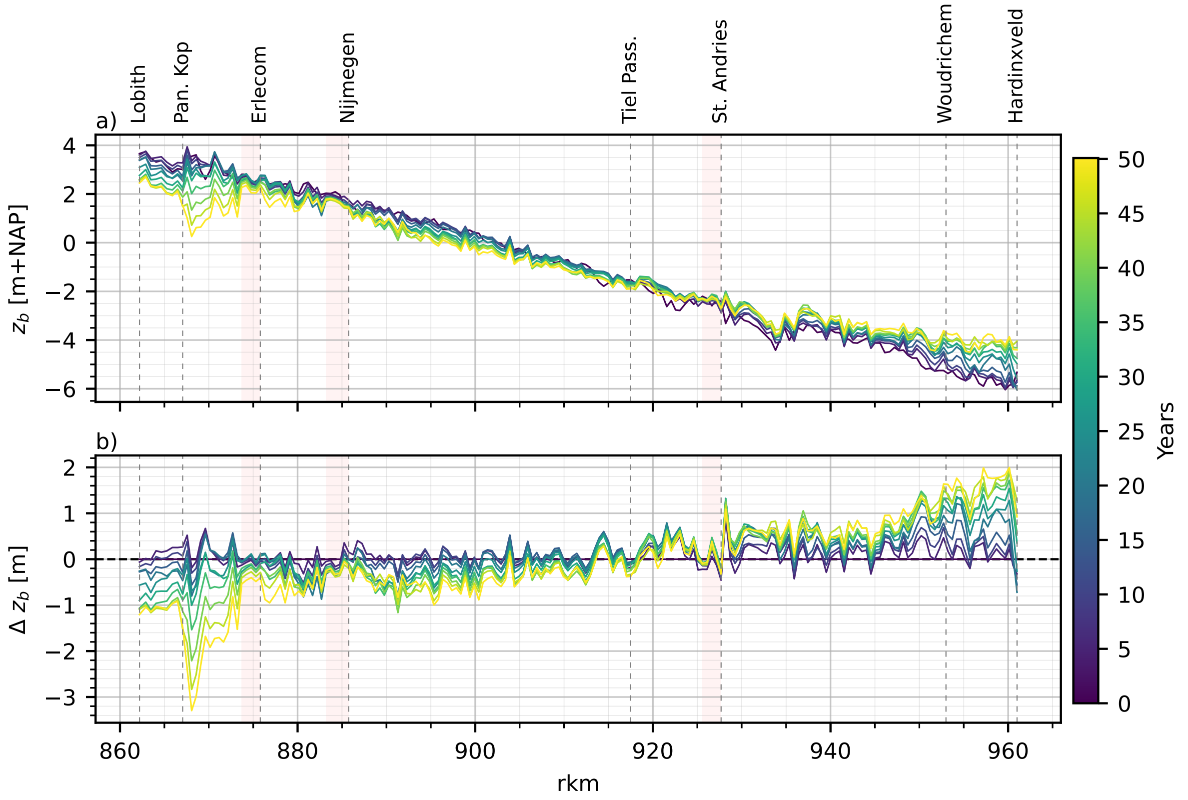


Fig. 7.7 a) Development of the main channel bed level and the b) absolute main channel bed level change in the Boven-Rijn and Waal. The red shaded area indicate the locations of fixed layers.

The average development of the bed level for the different reaches is presented in Fig. 7.8. In the Boven-Waal I, initially net aggradation occurs for the first 20.5 years, after which the bed erodes. During this net aggradation, there are some periods of erosion. This erosion occurs during the years when a higher discharge is applied upstream. In the first 30 years, the Boven-Waal I erodes 40 cm, or 1.3 cm/year. In the last 20 years, this is 1.6 m or 7.8 cm/year. Due to the lack of erodible sediment in the Boven-Rijn, large amounts of sediment are eroded from the Boven-Waal I. Initially, this is countered by the sediment that is deposited from the Boven-Rijn. This erosion wave then travels downstream to the Waal and Pannerdensch Kanaal. A similar behaviour is observed by Rorink (2022), De Lange (2022) and Paarlberg and Van Lente (2021).

In the Boven-Waal II, net aggradation occurs for the first 5.1 years. Hereafter, net erosion occurs. After 30 years, the Boven-Waal II has eroded 20 cm, or 0.7 cm/year. In the last 20 years, this has increased to 40 cm, or 2.0 cm/year. The first rate is less than the predicted rate of 1.9 cm/year by Programma Integraal Riviermanagement (2021). This is because the model models periods of aggradation due to the deposited finer sediment from upstream, lowering the erosion rate. The second rate is close to the predicted rate, but cannot be directly compared as this prediction is made for the first 30 years.

The Midden-Waal shows similar behaviour to the Boven-Waal II. Sedimentation occurs for the first 15.8 years, after which erosion takes over. In the first 30 years, 24 cm are eroded, or 0.8 cm/year. In the last 20 years, 16 cm of erosion takes place (0.8 cm/year). Therefore, the erosion rate has remained the same. These rates are lower than the erosion of 1.1 cm/year predicted by (Programma Integraal Riviermanagement, 2021). Again, in this reach, the model first shows a period of aggradation, which lowers the average erosion rate.

The Beneden-Waal indicates the point where the Waal starts to aggrade, with a predicted average rate of 0.1 cm/year (Programma Integraal Riviermanagement, 2021). The reference scenario shows an aggradation of 50 cm in the first 30 years, or 1.7 cm/year. For the last 20 years, this rate has reduced to approximately 0.3 cm/year. Both rates are still higher than the predicted and measured historical rates (Programma Integraal Riviermanagement, 2021; Ylla Arbós et al., 2019). This is due to the exclusion of (maintenance) dredging, which causes the bed level higher than reality. This dredging will continue until 2025, when net removal dredging contracts are set to terminate (Ylla Arbós et al., 2023).

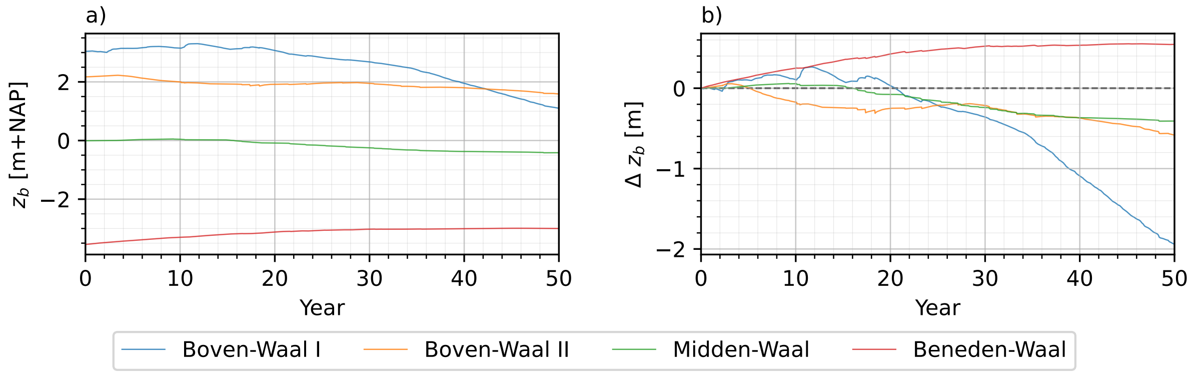


Fig. 7.8 a) Reach averaged development of the main channel bed level and the b) reach averaged absolute main channel bed level change in the Boven-Rijn and Waal.

7.1.5 Mean Grain Size Development of the Waal Reaches

The geometric mean grain size of the Boven-Rijn and Waal is presented in Fig. 7.9a. The change with respect to the initial grain size is presented in Fig. 7.9b. A wave is visible as coarser sediment flows in from upstream, causing an increase in the mean grain size. During the first 10-20 years a decrease in the mean grain size is observed in the upstream part of the Waal. This is due to the inflow of the finer sediment eroded from the Boven-Rijn.

The mean grain size development averaged over each Waal reach is shown in Fig. 7.10a. The mean grain size with respect to the initial mean grain size is presented in Fig. 7.10b. Initially, the Boven-Waal I fines up to 0.35 mm in the first two years. Up to year 28, the bed coarsens to a maximum of 0.4 mm. During this coarsening, periods of fining occur. These periods coincide with high discharge years in the upstream boundary. Between years 28 and 50, the Boven-Waal I fines again. In year 50, a net increase of 0.1 mm is reached in the mean grain size.

For the Boven-Waal II, the change in mean grain size roughly represents a sine wave and has an equal shape to the change in bed level (Fig. 7.7b). During the first 22 years a net fining occurs, with a maximum decrease of 0.15 mm. The second part of the simulation a net coarsing is present, with a maximum increase of 0.25 mm in year 36. In year 50, this has become 0.1 mm. This pattern occurs due to the finer sediment that flows in from the Rhein and Boven-Rijn. When an increase in bed is observed, an increase in mean grain size is observed as well.

The Midden-Waal shows a relatively stable change in mean grain size in comparison to the Boven-Waal. This is due to the fact that is less subject to the changes in the Rhein and Boven-Rijn, since the Boven-Waal is located in between them. In the first 2-3 years, an increase in the mean grain size is observed, after which it slightly decreases up until year 5. After 30 years, the bed has coarsened by 0.3 mm. Between years 18-24, a slight decrease is observed, after which the bed starts to coarsen again. After 50 years, this has increased to 1.7 mm. Similar as in the Boven-Waal, the overall coarsening of the bed is alternated with moments of fining, with magnitudes smaller than 0.01 mm.

The Beneden-Waal shows comparable behaviour to the Midden-Waal. In the first 30 years, the bed coarsens by 0.25 mm. In the last 20 years, this coarsening is further increased to 0.32 mm. Whereas the Boven-Waal and Midden-Waal contained some periods where the bed started to fine again, the Beneden-Waal only shows the small fluctuations at the same points in time as the Midden-Waal. Again, these fluctuations have a magnitude smaller than 0.01 mm.

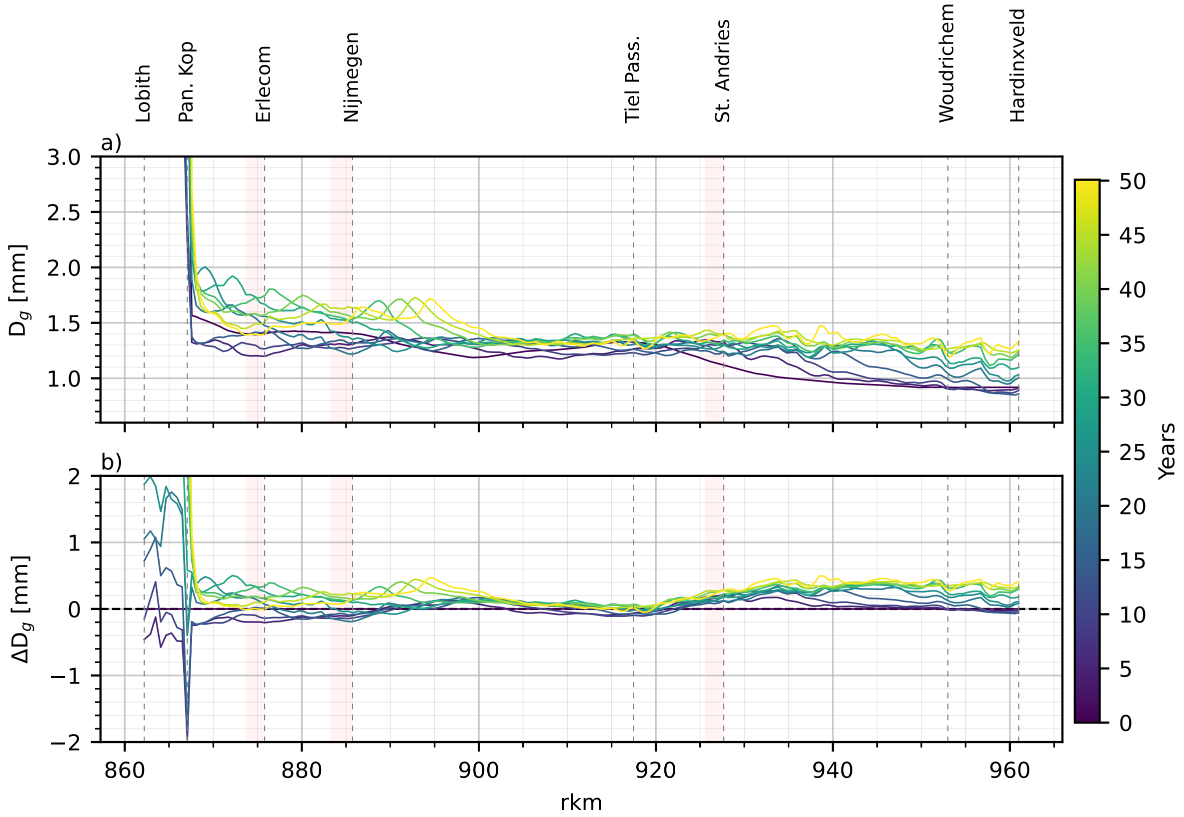


Fig. 7.9 a) Development of the geometric mean grain size and the b) geometric mean grain size change with respect to the initial geometric mean grain size in the Boven-Rijn and Waal. The red shaded area indicate the locations of fixed layers.

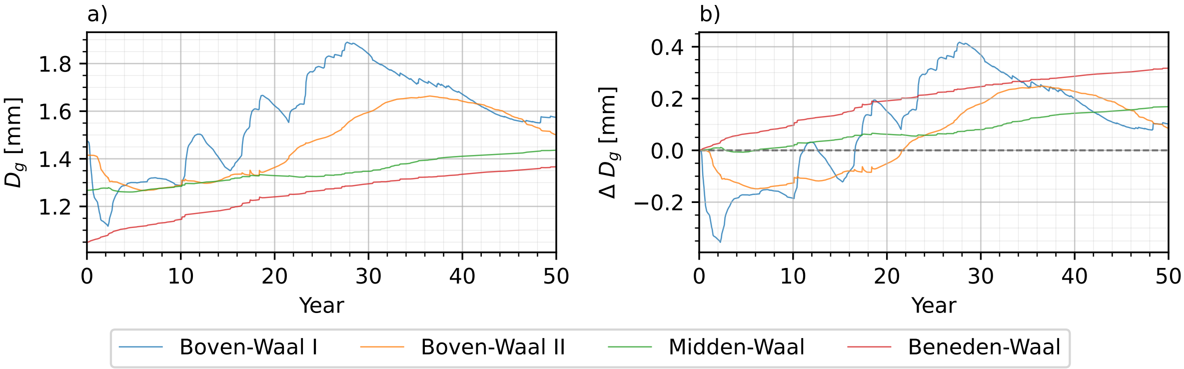


Fig. 7.10 a) Reach averaged development of the geometric mean grain size and the b) reach averaged geometric mean grain size change with respect to the initial geometric mean grain size in the Boven-Rijn and Waal.

7.1.6 Sediment Transport Development of the Waal Reaches

Fig. 7.11 presents an overview of the cumulative sediment transport and annual sediment transport rate patterns within the Boven-Rijn and Waal. In particular, the sediment transport rate demonstrates an increasing trend in the Boven-Waal and Midden-Waal sections as they progress downstream, while a decrease is observed in the Beneden-Waal section. This phenomenon corresponds to the initial degradation and subsequent aggradation processes. Over time, the distinctions in sediment transport rates between these sections gradually decrease, attributed to the declining bed slope. This reduction in bed slope, accompanied by an enlargement in grain size, also leads to a decrease in the yearly sediment transport rates. Temporal fluctuations in the sediment transport rate are driven primarily by variations in discharge travelling through the system due to the implementation of an unsteady hydrograph.

The yearly sediment transport rates per Waal reach are presented in Fig. 7.12. The behaviour of the transport is the same in the different reaches. However, they differ in magnitude. Initially, the sediment transport rate is highest in the Boven-Waal I & II, followed by the Midden-Waal and Beneden-Waal, as already mentioned. Over time, this order changes with no clear pattern. In general, the sediment transport rates decrease over time.

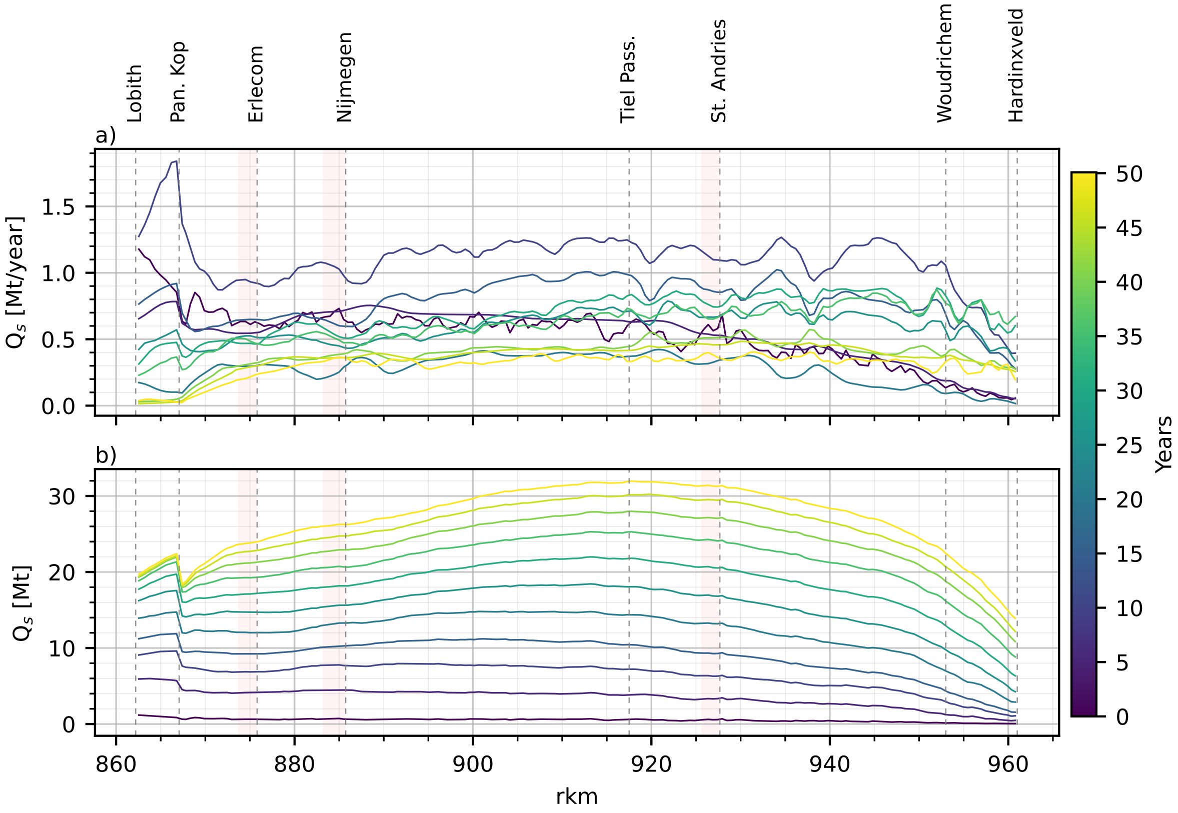


Fig. 7.11 a) Yearly sediment transport rate and b) cumulative sediment transport in the Waal. The red shaded area indicate the locations of fixed layers.

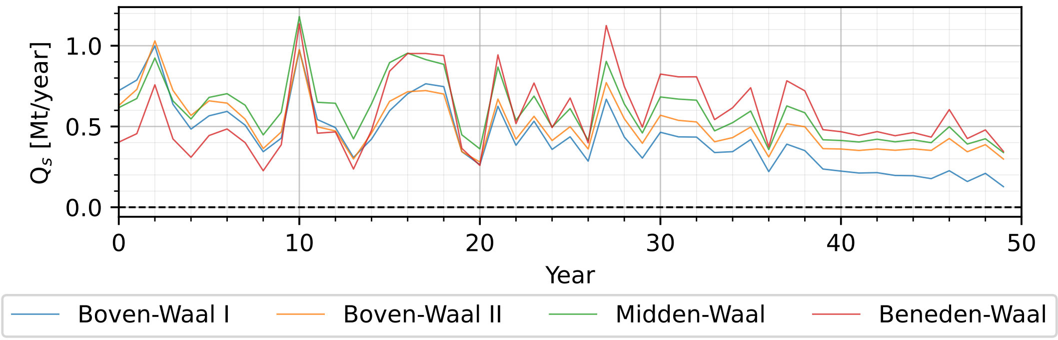


Fig. 7.12 Reach averaged development of the sediment transport rate in the Waal.

7.1.7 Discharge Distribution at the Pannerdensche Kop

In the previous sections it has been confirmed that the Waal continues to erode. When this happens, more discharge is routed to the Waal. This is more noticeable for lower discharges. Fig. 7.13 shows the evolution of the discharge distribution at the Pannerdensche Kop as a fraction of the discharge at Lobith. When the water level at Lobith reaches 8.65 m+NAP, the weir in Driel opens. This corresponds to a discharge of approximately 1,800 m^3/s. At this point, a bend in the distribution appears. Taking into account the low flow conditions (i.e., when the weir at Driel is closed) 78-79% of the discharge is directed to the Waal in year 0. In year 30, this range is 79-80%. In year 50, this range varies between 81-82%. Although no specific increase in discharge at OLA can be identified, it is visible that over time more discharge enters the Waal. The normal discharge at Lobith varies between 1,000-4,450 m^3/s (Waterinfo, 2023). For this discharge regime, the initial Waal discharge fractions vary between 67-72%. In year 30, this becomes 68-75%. Finally in year 50, this increases to 69-79%. For the higher discharges (>4,450 m^3/s), less data is available. Initially the distribution is very close to the agreed flow partitioning. During the 50 years of simulation, approximately 2% more discharge is routed to the Waal for the higher discharges. In year 50, $Q_{1,400}$ has increased from 78.7% to 81.4%, which is 2.7% or 38 m^3/s.

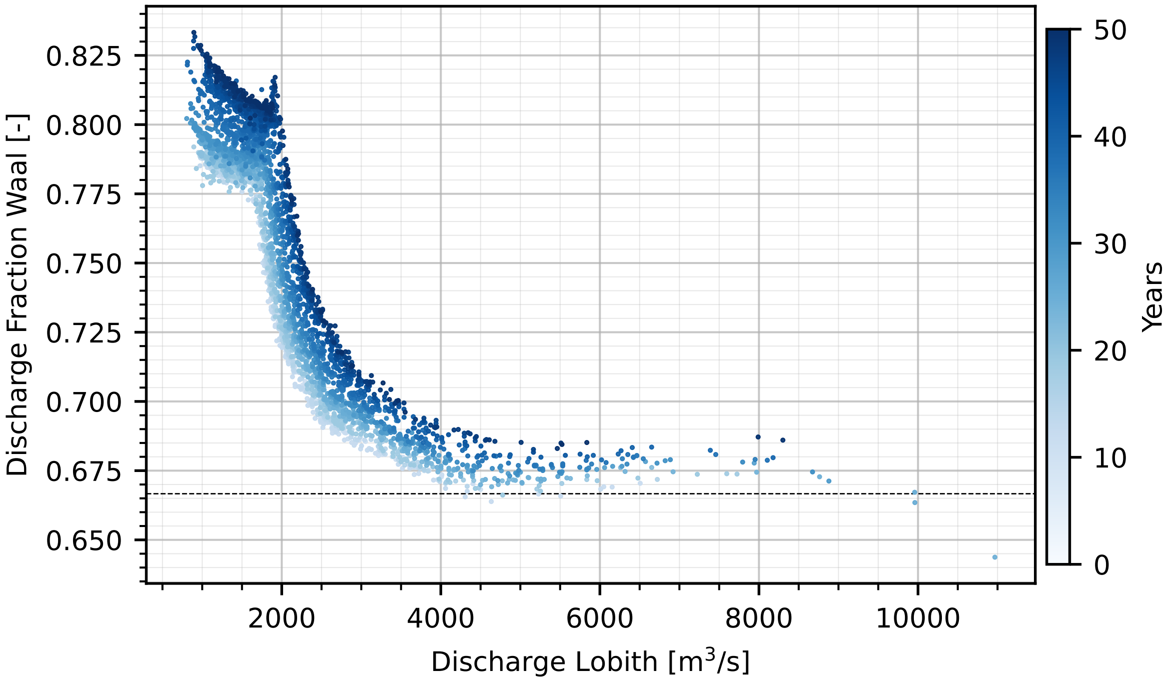


Fig. 7.13 Evolution of the discharge distribution at the Pannerdensche Kop. The horizontal line indicates the agreed flow partitioning of ⅔ towards the Waal.

7.2 Nourishments from Area Vision Midden-Waal

At the start of the simulation, the nourishments are imposed on the river bed as described in Table 6.1.

7.2.1 Spatial Bed Level Development

Fig. 7.14 shows the development of the bed level with respect to the initial bed level every 10 years. The nourishments are visible as rectangles at the nourishment locations (Fig. 7.14a). In year 10, the effect of the nourishments can be distinguished from the natural bed development (Fig. 7.14b). At the nourishment location, the bed is elevated sufficiently such that instead of erosion, sedimentation occurs. This is also the case in the subsequent Figs. 7.14c-f. As the sediment is supplied, it is transported downstream where erosion is also prevented, and even sedimentation occurs. The sediment also reaches the Beneden-Waal and, therefore, additional dredging is needed.

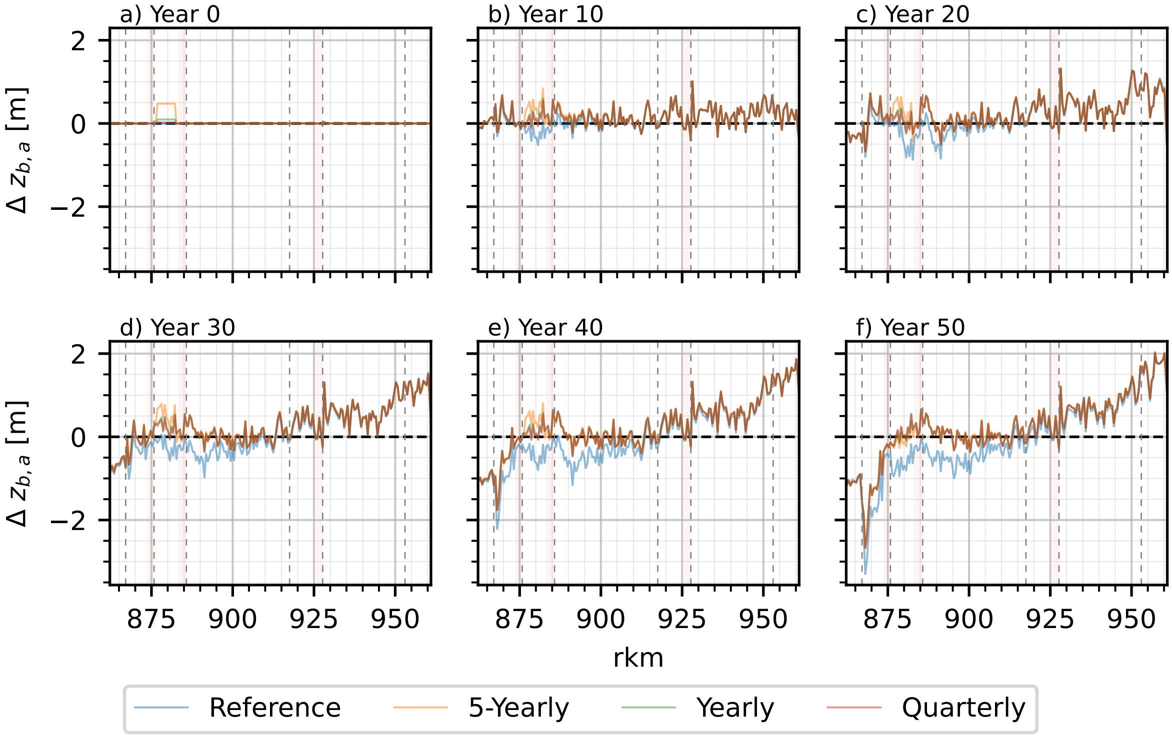


Fig. 7.14 Bed level change with respect to the initial bed level in the Waal for the Area Vision Midden-Waal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

The isolated effects of the different nourishment strategies are presented in Fig. 7.15. For the subsequent analysis, it is important to consider how the strategies differ. For the five-yearly strategy, the sediment is nourished in year 0, 5, 10, 15 and so on. For the yearly and quarterly strategies, the placement of this sediment is spread accordingly, but with their smaller volumes. This difference in nourished volume is visible at the placement of the first nourishments in Fig. 7.15a. In year 10 this difference persists, as the five-yearly peak is higher than the yearly peak, and the yearly peak is higher than the quarterly peak. (Fig. 7.15b). Over time, more sediment is added, which is transported downstream. Additionally, the backwater curve effects cause additional sedimentation upstream of the nourishment locations of about 10 cm. The front of the nourishments is located at around rkm 915. In year 20, upstream an increase of 20 cm is observed and the front of the nourishments has already reached the Beneden-Waal, causing additional sedimentation here (Fig. 7.15c). In the next period, upstream from the nourishments, sedimentation of about 1 cm/year occurs, such that after 50 years there is about 50-60 cm of additional sedimentation (Figs. 7.15d-f). All of the different nourishment strategies cause an increase of up to 80 cm in the Boven-Waal at the nourishment location after 50 years. Moving downstream, this becomes slightly smaller to a minimum of about 10 cm in the Beneden-Waal.

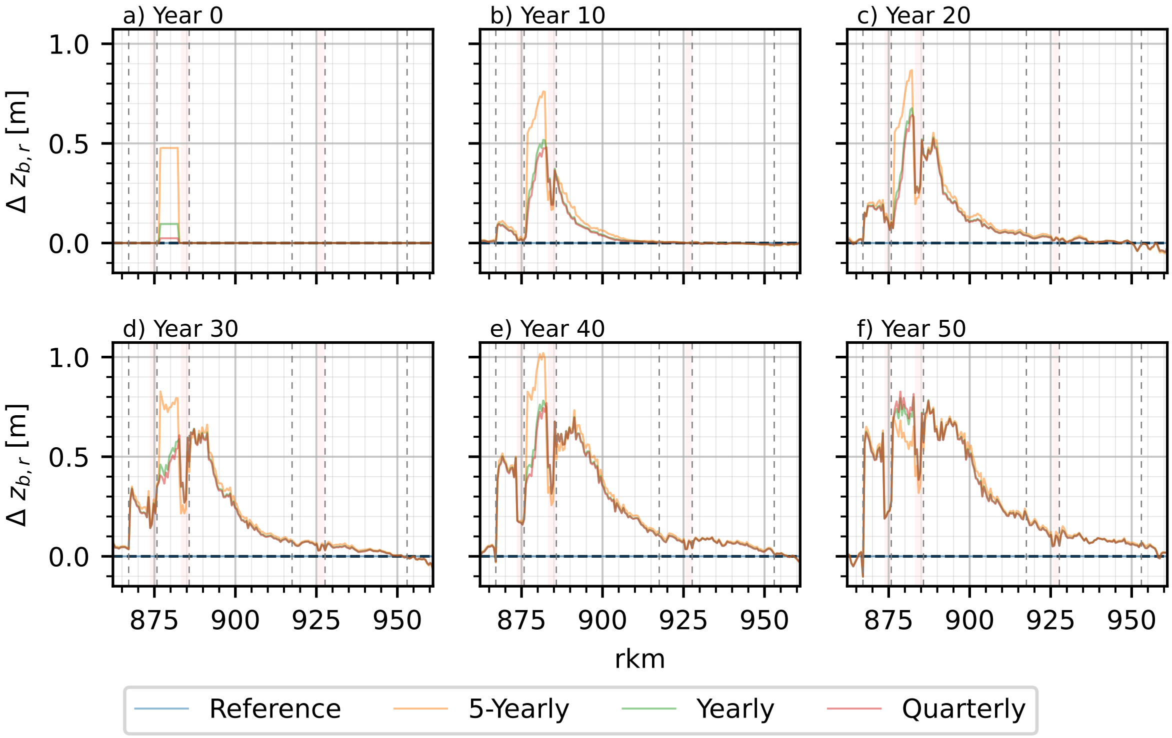


Fig. 7.15 Bed level change with respect to the reference bed level in the Waal for the Area Vision Midden-Waal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

The differences in bed level between the scenarios are presented in Fig. 7.16. When the nourishments are placed five-yearly instead of yearly or quarterly, initially more sediment is present in the system. Therefore, a higher bed level is observed (Fig. 7.16a). As this sediment is present earlier in the system, it has more time to be transported downstream. Therefore, an increase in the bed level is observed downstream of the nourishment location for both cases during the rest of the simulation (Figs. 7.16c-f). This hump has a height of approximately 10 cm and moves downstream for the rest of the simulation. Additionally, more sedimentation can take place upstream of the nourishment due to the increased backwater curve effect. This increase is about 2 cm throughout the entire simulation. After 50 years, a decrease in the bed level at the nourishment locations is observed (Fig. 7.16f). This is because the last five-yearly nourishment is executed in year 45, whereas this is respectively year 49 and 49.75 for the yearly and quarterly nourishments. Therefore, the five-yearly placed sediment is already moved downstream, as compared to the yearly and quarterly strategies.

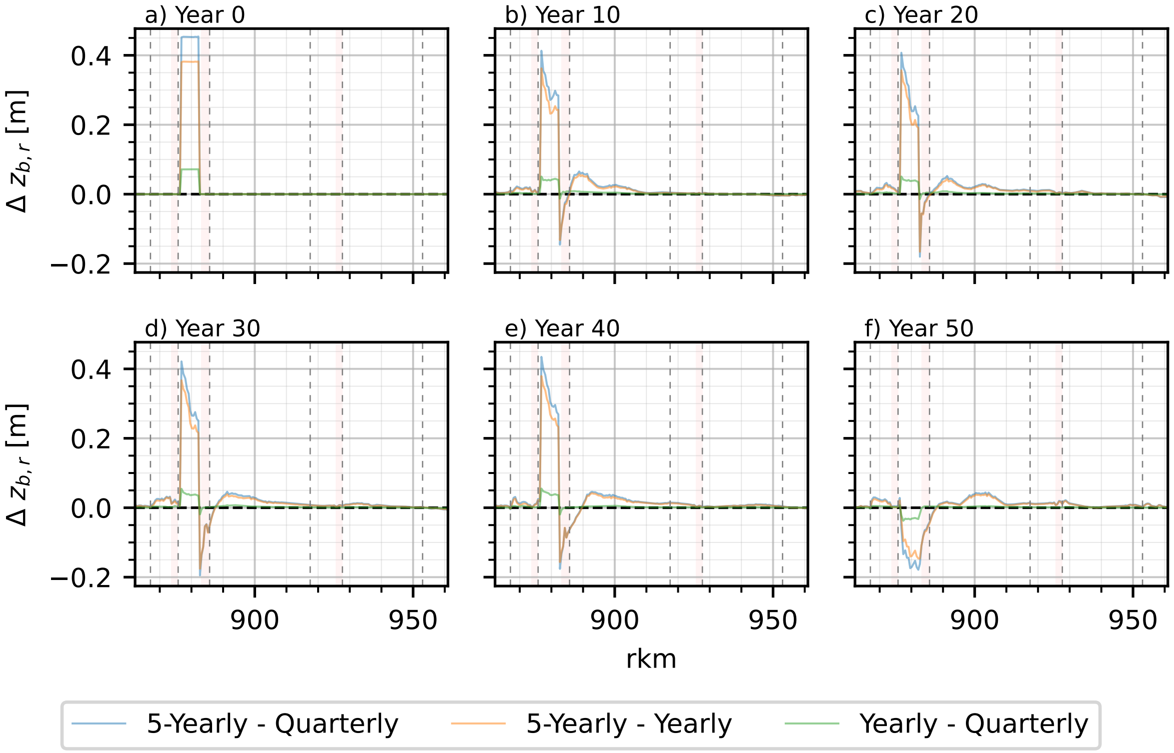


Fig. 7.16 Bed level differences between the different scenarios in the Waal for the Area Vision Midden-Waal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

7.2.2 Reach Averaged Bed Level Development

Figs. 7.17a-d show the change in the bed level averaged per reach with respect to the initial bed level over time for the different strategies. In the Boven-Waal I, the nourishment strategies delay erosion with 6.2, 5.2 and 4.7 years respectively (Fig. 7.17a). In the Boven-Waal II, all nourishment strategies prevent erosion from ever occurring as net sedimentation is present here (Fig. 7.17b). For the five-yearly strategy, this net sedimentation fluctuates between 0 and 40 cm. For the yearly and quarterly strategies, the sedimentation fluctuates between 10 and 30 cm. In the Midden-Waal, erosion is mostly prevented. However, there are periods where slight erosion is present (Fig. 7.17c). After 15 years, additional sedimentation takes place in the Beneden-Waal (Fig. 7.17d).

Figs. 7.17e-h show the isolated effect of the nourishments averaged over the reaches. Placing the nutrients causes an approximately linear bed level increase in the Boven-Waal I of 1 cm/year due to backwater curve effects (Fig. 7.17e). After 50 years, this results in an aggradation around 55 cm for the different strategies. The differences between the strategies are presented in Fig. 7.18. The five-yearly strategy causes an bed level increase of 2 cm with respect to the other scenarios during the entire simulation (Fig. 7.18a). The yearly strategy results in a few mm increase with respect to the quarterly strategy.

Placing the nourishments causes a sudden increase in the relative bed level change in the Boven-Waal II (Fig. 7.17f). This is 30, 6 and 1.5 cm for the five-yearly, yearly and quarterly scenarios respectively. For each strategy, the repetition time is clearly visible as a jump in the bed level. For the five-yearly strategy, a steep decrease in the bed level is observed immediately after nourishing. However, the applied volume is enough such that not all the sediment is eroded before the next nourishment. Therefore, a net bed level increase is observed. The combined effect of these repeated nourishments causes an increase in the bed level over time. The same holds for the yearly and quarterly strategies. For these, the fluctuation in bed level is less pronounced. The yearly and quarterly scenarios result in a bed level increase of approximately 70 cm after 50 years, whereas the five-yearly scenario results in a bed level increase of almost 60 cm. The differences between the strategies are presented in Fig. 7.18b. After around 2.5 years, no differences between the different strategies are observed for the bed level in the Boven-Waal II. This equality between the different strategies is repeated every five years. Placing the nourishments yearly instead of quarterly causes a fluctuation of about 2 cm every year (Fig. 7.18b).

From Fig. 7.17g, it is seen that it takes 1-2 years for the nourishment to increase the bed level in Midden-Waal. Over time, the average bed in the Midden-Waal increases linearly. The five-yearly strategy results in a bed level increase of 45 cm after 50 years, or 0.9 cm/year. When the nourishments are placed yearly or quarterly, this results in a bed level that is approximately 2 cm lower over the entire period as compared to the five-yearly strategy. During the simulation, a slight oscillation is present in these differences (Fig. 7.18c). When comparing the yearly and quarterly strategies, applying the yearly strategy results in a constant bed level increase of a few mm.

Additional sedimentation occurs in the Beneden-Waal after 10-15 years, which can be seen in Fig. 7.17h. The bed level increases linearly from this point on, up to 10 cm in year 50 for the five-yearly strategy. Compared to the five-yearly strategy, the yearly strategy results in a slightly lower bed level increase of about 7 mm (Fig. 7.18d). Again, the quarterly strategy results in a lower bed level than the yearly strategy. In the Beneden-Waal, this difference is 1-2 mm during the entire simulation period.

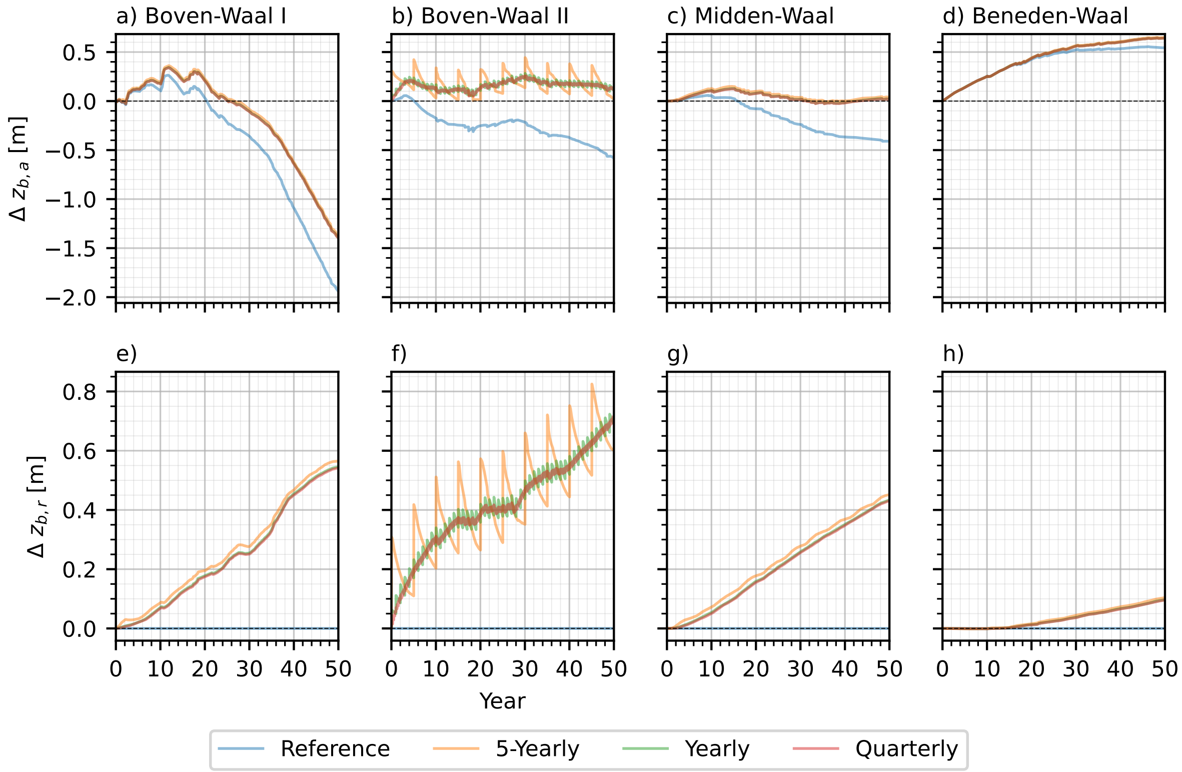


Fig. 7.17 Reach averaged bed level change with respect to the a-d) initial reach averaged bed level and e-h) reference reach averaged bed level in the Waal for the Area Vision Midden-Waal nourishments.

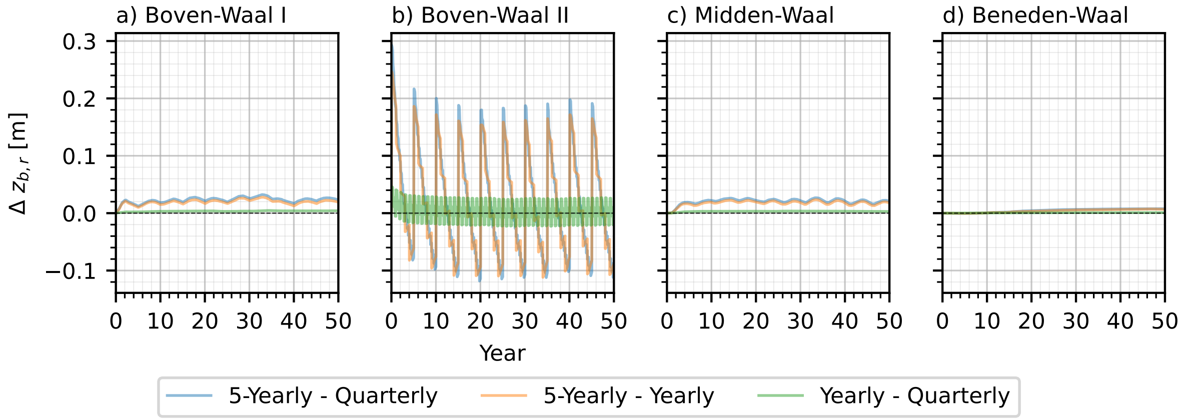


Fig. 7.18 Reach averaged bed level differences between the different scenarios in the Waal for the Area Vision Midden-Waal nourishments.

7.2.3 Spatial Grain Size Development

The isolated effect of the nourishments on the mean grain size is shown in Fig. 7.19. A decrease in mean grain size is observed in year 0. For the five yearly nourishment, this initially results in a decrease of approximately 0.24 mm. The yearly nourishment results in a decrease of 0.05 mm and the quarterly nourishment results in a decrease of 0.01 mm (Fig. 7.19a). In subsequent steps (Figs. 7.19b-f), this decrease in grain size spreads along the Waal under the effect of advection and diffusion. Since during the simulation period more sediment is nourished, the mean grain size decreases even further at and downstream of the nourishment location. In year 10, a hump forms for the different scenarios. From year 20, this hump separates in two humps. While they may look static from the snapshots, these humps move downstream over time. Whenever a new nourishment is placed, a new source of fine sediment is supplied, causing the initial hump in year 10. This is already a combined effect of multiple nourishments. As more nourishments are applied between years 10-20, they interfere with each other. The finer fractions are already washed away, such that the coarser (but still finer than the bed) remain as troughs. These troughs then move downstream. Whenever a new nourishment is placed, the finer fractions are introduced again. These finer fractions from the new nourishment are transported downstream faster than the coarser (but still finer than the bed) fractions, such that the troughs interfere even more. Directly upstream of the nourishment, no changes in mean grain size are observed. This is because the sediment that is deposited here, is riverine and thus similar to the original bed. At the Pannerdensche Kop, a decrease in mean grain size of 0.5 mm is observed in years 40 and 50, followed by an increase of 0.2 mm.

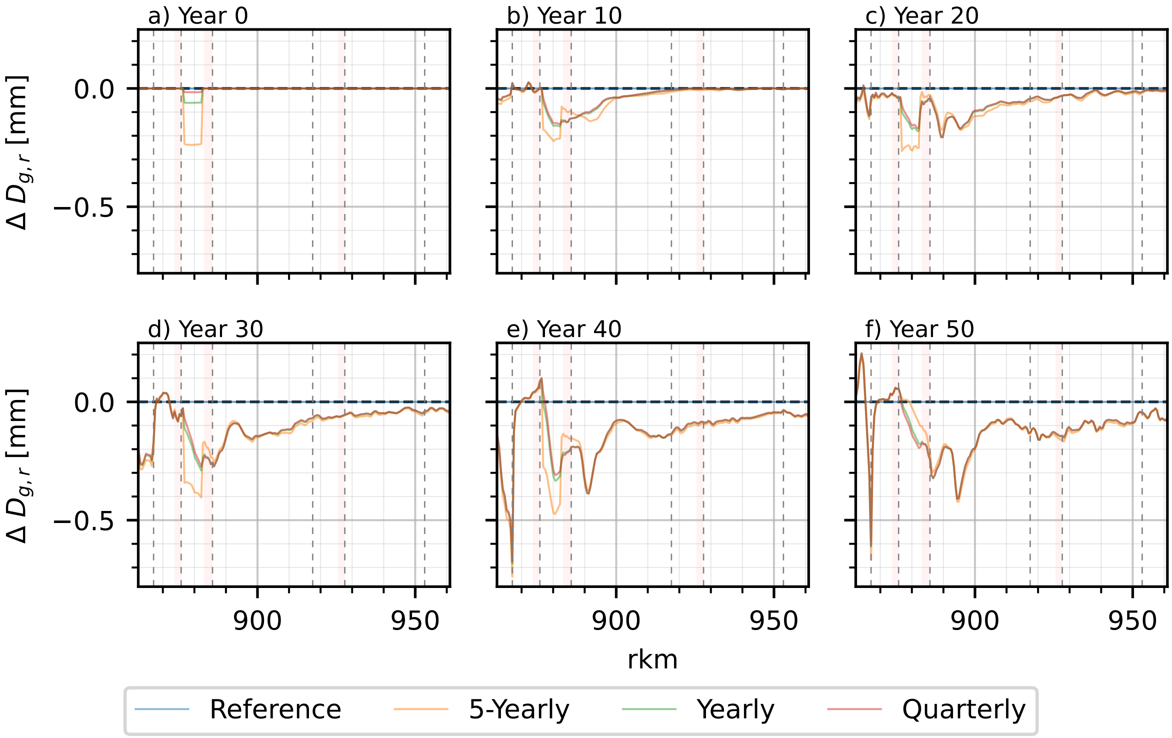


Fig. 7.19 Mean grain size change with respect to the reference mean grain size in the Waal for the Area Vision Midden-Waal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

The differences in mean grain size between the different strategies are presented in Fig. 7.20. In year 10, changes of up to 0.1 mm in mean grain size are observed between nourishing five-yearly and yearly (Fig. 7.20b). Similar differences occur between nourishing five-yearly and quarterly. The largest differences are located at the nourishment location. Due to the increased nourished volume at the snapshots for the five-yearly nourishments, a larger decrease in mean grain size is observed. This decrease travels downstream as a wave.

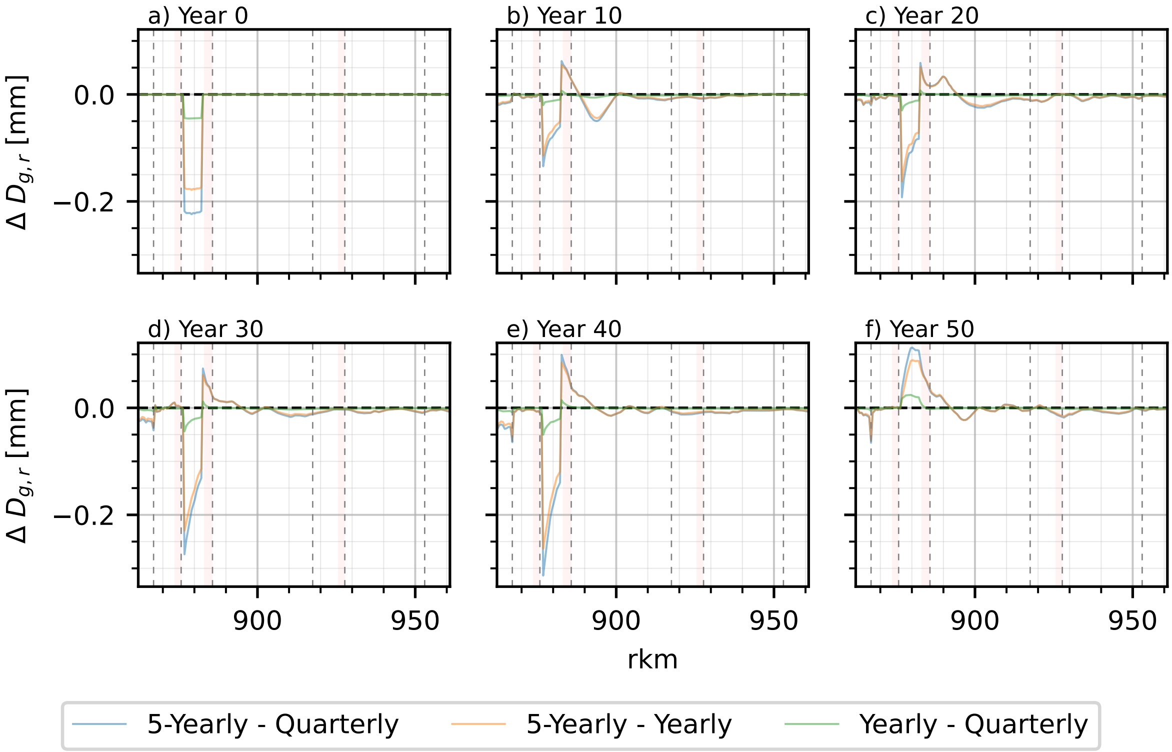


Fig. 7.20 Mean grain size differences between the different scenarios in the Waal for the Area Vision Midden-Waal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

7.2.4 Reach Averaged Grain Size Development

The isolated effect of the nourishments on the mean grain size is presented in Fig. 7.21 for the different nourishment strategies. For the mean grain size in the Boven-Waal I, no clear pattern is present. The mean grain size fluctuates between a maximum decrease of 0.05 mm and a maximum increase of 0.02 mm. This mean grain size is mostly influenced by what is happening upstream. Initially, the finer sediment that is eroded at the Boven-Rijn is deposited here during the first 30 years, with occasionally some coarsening. After 30 years, a net coarsening occurs. However, this coarsening does not show a clear pattern. In general, the five-yearly strategy results in a smaller mean grain size than the yearly and quarterly strategies (Fig. 7.22a). Nevertheless, the differences are less than 0.01 mm. When comparing the yearly strategy with the quarterly strategy, the mean grain size is also smaller, but the differences are negligible.

Placing the nourishments directly causes a decrease in the mean grain size for the different strategies in the Boven-Waal II (Fig. 7.22b). However, throughout the simulation, the decrease when a nourishment is placed differs. This is due to the development of the bed itself: since the mean grain size of the bed changes over time, the relative effect of a nourishment on the mean grain size changes. The change in mean grain size follows the same pattern as the change in bed level. Its period is the same as the nourishment interval. In general, a decreasing trend is observed. As the sediment from the five-yearly strategy has more time to be transported downstream, its mean grain size fluctuates more than the yearly and quarterly strategies. This is highlighted in Fig. 7.22b. Here, the differences between the strategies show fluctuating differences with an amplitude varying between 0.04 and 0.12 mm between the five-yearly and the other strategies. Between the yearly and quarterly strategies, a fluctuation of about 0.02 mm occurs.

In the Midden-Waal, the placement of the nourishments causes a fining over time (Fig. 7.21c). As was observed in the Boven-Waal II, the fluctuations in bed and mean grain size were more severe for the five-yearly strategy. This sediment was transported downstream, as visible in the lower mean grain size of the five-yearly strategy. Five-yearly nourishments cause a decrease in mean grain size up to 0.02 mm with respect to the other scenarios (Fig. 7.22c). Between the yearly and quarterly strategies, a slight decrease in mean grain size is observed throughout the simulation. The overall progression of the different scenarios follows a similar pattern. After 50 years, the scenarios result in a decrease of 0.17 mm.

The Beneden-Waal fines somewhere between 5-10 years (Fig. 7.21d). This coincides with the observed increase in bed level. Between years 10-40, the mean grain size decreases by about 2.5 μm per year. In year 50, the mean grain size has decreased with 0.11 mm for the five-yearly scenario. The yearly and quarterly scenarios show a slightly higher mean grain size of about 0.005 mm (Fig. 7.22d). Again, the yearly strategy results in a slightly finer mean grain size than the quarterly strategy, but these differences are negligible.

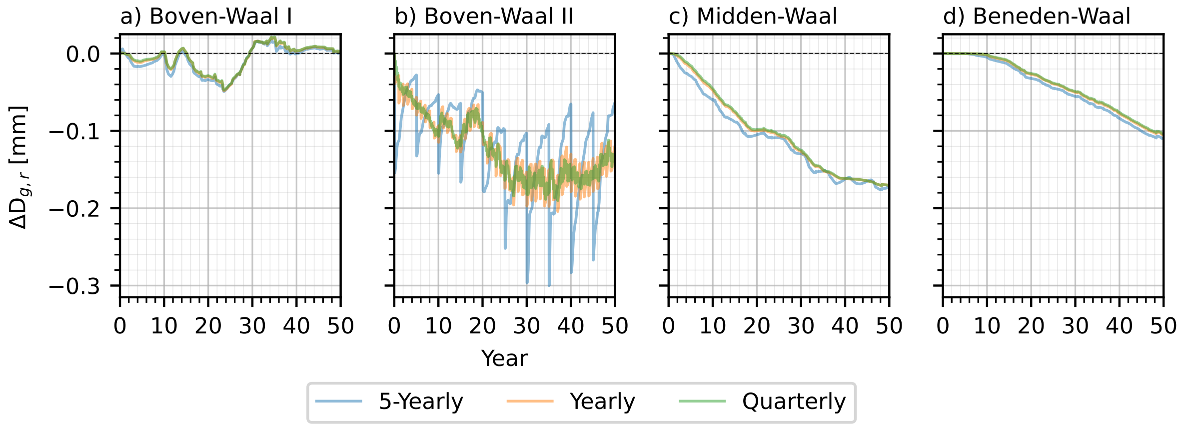


Fig. 7.21 Reach averaged mean grain size change with respect to the reference mean grain size in the Waal for the Area Vision Midden-Waal nourishments.

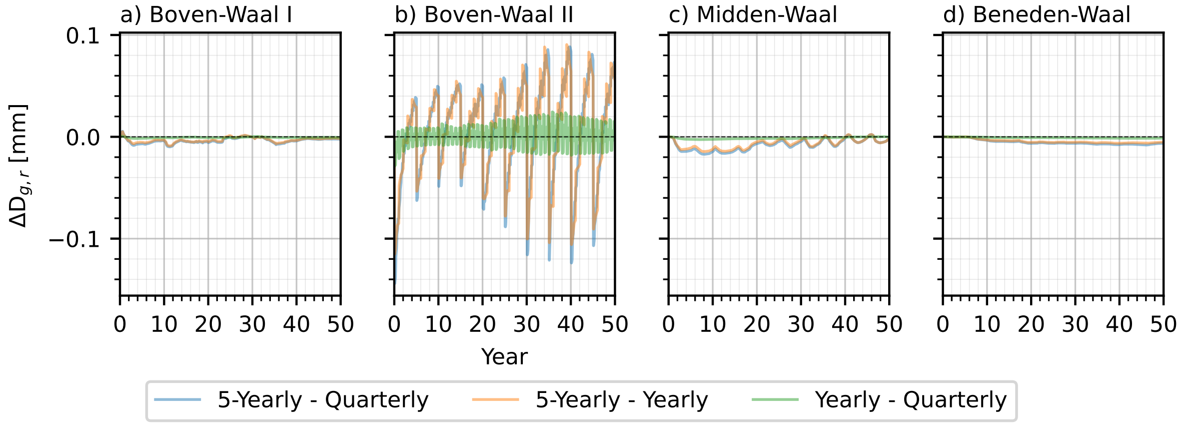


Fig. 7.22 Reach averaged mean grain size differences between the different scenarios in the Waal for the Area Vision Midden-Waal nourishments.

7.2.5 Influence on the Discharge Distribution

The effect of the five-yearly nourishment strategy on the discharge distribution is presented in Fig. 7.23. Overall, placing the nourishments causes a decrease of discharge towards the Waal, with the exception of some points at 1,800 m^3/s. These points are positive since the weir is partially open at this point, causing some fluctuations. As the discharge increases up until 1,800 m^3/s, the effect of the nourishment on the distribution decreases. This forms a sharp peak between 1,800-2,000 m^3/s where the effect increases. For the discharges higher than 2,000 m^3/s, the effect gradually decreases again.

The five-yearly repetition time is also reflected in the distribution. The effect of the first initial nourishment is located at the orange arrow, showing an initial higher influence. As the height of the nourishment reduces over time, so does its influence on the discharge distribution. This change in height is slower for the years 2-5, which is seen as a clustering of the yearly distributions at the blue arrow. As the bed level in the Boven-Waal II decreases, so does the effect on the discharge distribution. This pattern repeats for every additional nourishment. For the yearly and quarterly strategies this pattern is also present, but more subtle as the differences between subsequent nourishments are less (Appendix C.1). In year 50, the five-yearly nourishment strategy reduces $Q_{1,400}$ by 3.0%. For the yearly and quarterly strategies, this is 3.2%.

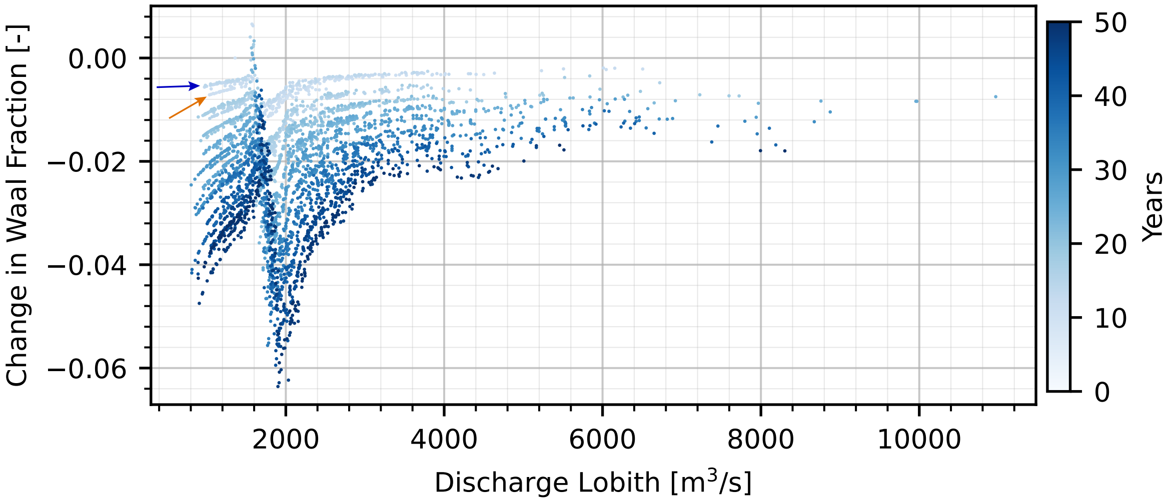


Fig. 7.23 Changes in discharge distribution for the five-yearly nourishment strategy relative to the reference scenario. The orange arrow indicates the effect in the first year after a nourishment, whereas the blue arrow indicates the effect in the following 4 years.

7.3 Nourishments from Spijk

At the start of the simulation, the nourishments are imposed on the river bed as described in Table 6.1.

7.3.1 Spatial Bed Level Development

Fig. 7.24 shows the development of the bed level with respect to the initial bed level every 10 years. Initially, the nourishments are visible as rectangles (Fig. 7.24a). In year 10, the effect of the nourishments have already become indistinguishable from the natural bed development (Fig. 7.24b). Since the changes in bed level are larger in magnitude than the nourishments, the mitigating effect of the nourishments is drowned out by the natural development of the bed. This is also the case in the subsequent Figs. 7.24c-f.

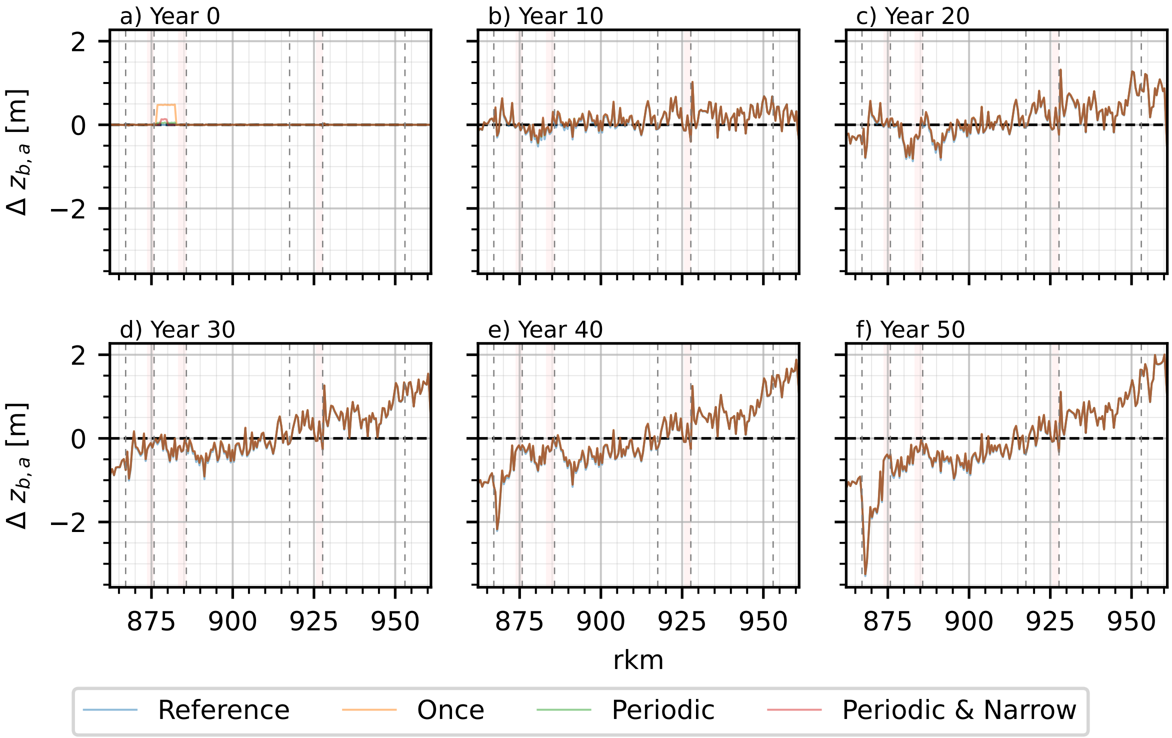


Fig. 7.24 Bed level change with respect to the initial bed level in the Waal for the Spijk nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

The bed level change relative to the reference bed level is presented in Fig. 7.25. Again, the nourishments are visible as rectangular shapes in year 0 in Fig. 7.25a. In year 10, the shapes of the nourishments have changed significantly (Fig. 7.25b). At this point, additional nourishments have been carried out for the periodic strategies, such that the total nourished volume is the same after this point for the different strategies. The nourishment heights are reduced and their lengths have increased by diffusion. Additionally, sediment humps are moved downstream by advection, causing sediment to enter the Midden-Waal and Beneden-Waal and even flow out of the system. In year 10, the maximum height of the singular nourishment has decreased to 10 cm and has moved downstream to rkm 884. The nourishment is similarly shaped for the periodic strategies. Upstream of the nourishments, an increase in the bed level of 5 cm is observed for the different scenarios. In years 20-50 (Figs. 7.25c-f) the nourishments travel further downstream and diffuse more. Most of the finer sediment has already moved to the Midden-Waal and Beneden-Waal, such that only the coarser fractions remain in the Boven-Waal. Coarser fractions have also spread along the other Waal reaches, such that no clear peak is present in the nourishment height. Therefore, it is difficult to determine the propagation rates of the nourishments.

The differences in bed level between the scenarios are presented in Fig. 7.26. When the nourishments are placed at once instead of periodic, a wavelike pattern in the bed level differences occurs. A similar pattern is observed when the periodic nourishments are placed on a narrower area. For both cases, this pattern has a non-constant amplitude that varies between a few mm and a cm, which decays over time.

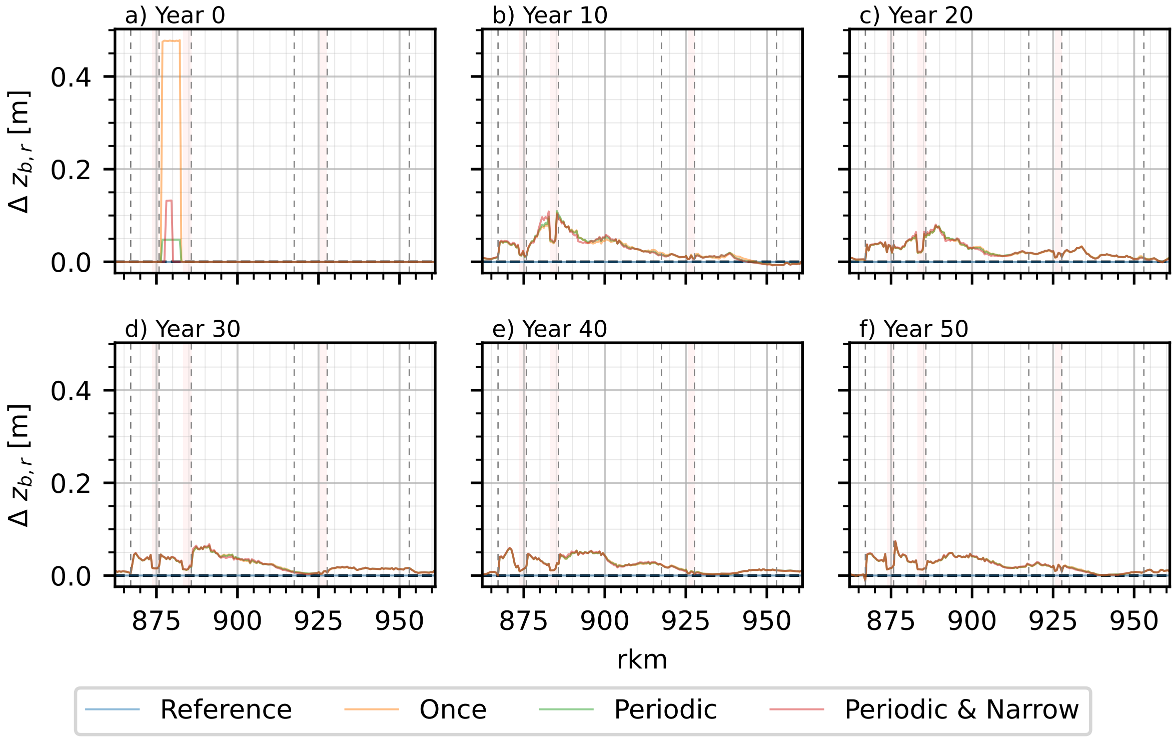


Fig. 7.25 Bed level change with respect to the reference bed level in the Waal for the Spijk nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

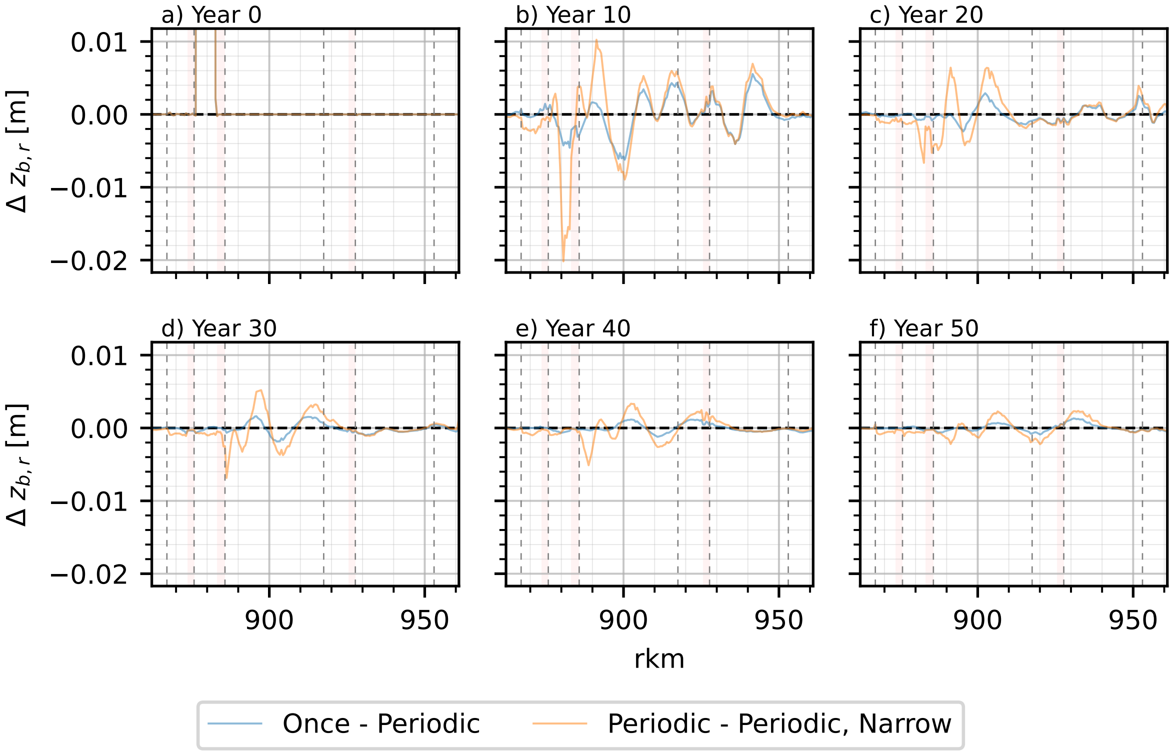


Fig. 7.26 Bed level differences between the different scenarios in the Waal for the Spijk nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

7.3.2 Reach Averaged Bed Level Development

Figs. 7.27a-d show the change in the bed level averaged per reach with respect to the initial bed level over time for the different strategies. In the Boven-Waal I, the nourishment strategies all result in a delay of the erosion of half a year (Fig. 7.27a). In the Boven-Waal II, erosion is delayed by 1.6, 1.8 and 1.8 years for the respective strategies (Fig. 7.27b). In the Midden-Waal, all strategies delay the erosion with 1.5 years (Fig. 7.27c). Additional sediment occurs in the Beneden-Waal due to the nourishments (Fig. 7.27d).

Figs. 7.27e-h show the isolated effect of the nourishments averaged over the reaches. Placing the nourishments cause an increase in the Boven-Waal I of 2-3 cm in the first two years (Fig. 7.27e). Over time, this slightly increases to 4 cm after 10 years. For the rest of this simulation, the net increase fluctuates around 4 cm. Between the different strategies, only minor differences are present in the first few years of less than 1 cm (Fig. 7.28a).

Placing the singular nourishment causes a sudden increase in the relative bed level change in the Boven-Waal II of 32 cm. Initially, a steep decrease in bed level is observed as the finer fractions leave the Boven-Waal II. Over time, this decrease becomes less rapid. Since the finer fractions have left the Boven-Waal II, the coarser fractions remain. As these are less easily transported, the decrease in bed level slows down. After 20-30 years, the increase in the Boven-Waal II stabilises to approximately 4 cm. The differences in bed level between the different strategies are presented in Fig. 7.28. In the first two years, differences of up to 8 cm are visible in the bed level for the different nourishment strategies in the Boven-Waal II (Fig. 7.28b). These differences occur here, since the nourishments are applied in the Boven-Waal II and the strategies differ in the first two years. When all the sediment is nourished at once, initially more sediment is applied and thus the average and local mitigation will be higher in the first two years. After 10 years, no significant differences are present in the Boven-Waal II anymore.

From Fig. 7.27g, it is seen that it takes 1-2 years for the sediment to increase the bed level in the Midden-Waal. After 5 years, a maximum increase of 4 cm in the Midden-Waal is obtained as well. Over the rest of the simulation, this fluctuates between 3 and 4 cm. Only during the first 5 years, differences between the different strategies are present in the Midden-Waal, of 1 cm (Fig. 7.28c).

After 5 years the sediment enters the Beneden-Waal, which is seen in Fig. 7.27h. After 20 years, a maximum increase of 1.8 cm is present in the Beneden-Waal. At this point, the change in bed level decreases as sediment flows out of the Beneden-Waal into the Merwede. 20 years later, in year 40, the increase in bed is reduced to 1 cm in the Beneden-Waal. Up until year 50, this slightly increases to 1.1 cm. No significant differences in bed level are observed between the different nourishment strategies in the Beneden-Waal (Fig. 7.28d).

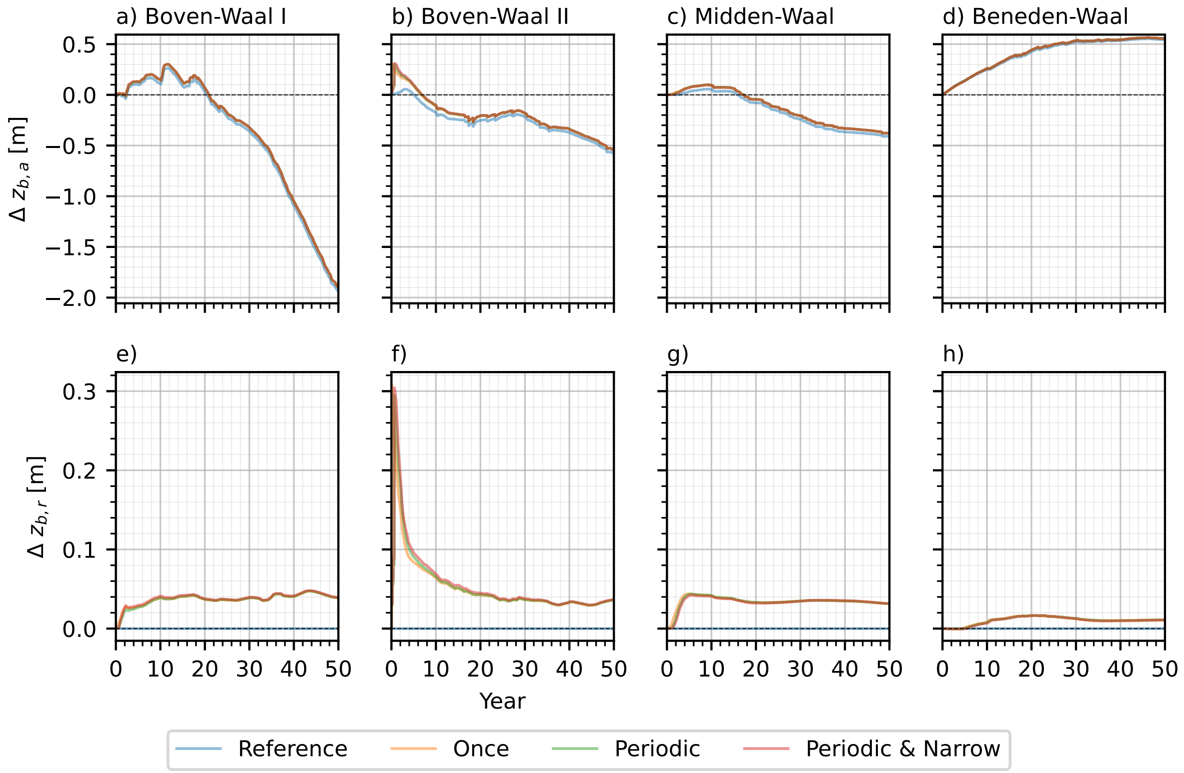


Fig. 7.27 Reach averaged bed level change with respect to the a-d) initial reach averaged bed level and e-h) reference reach averaged bed level in the Waal for the Spijk nourishments.

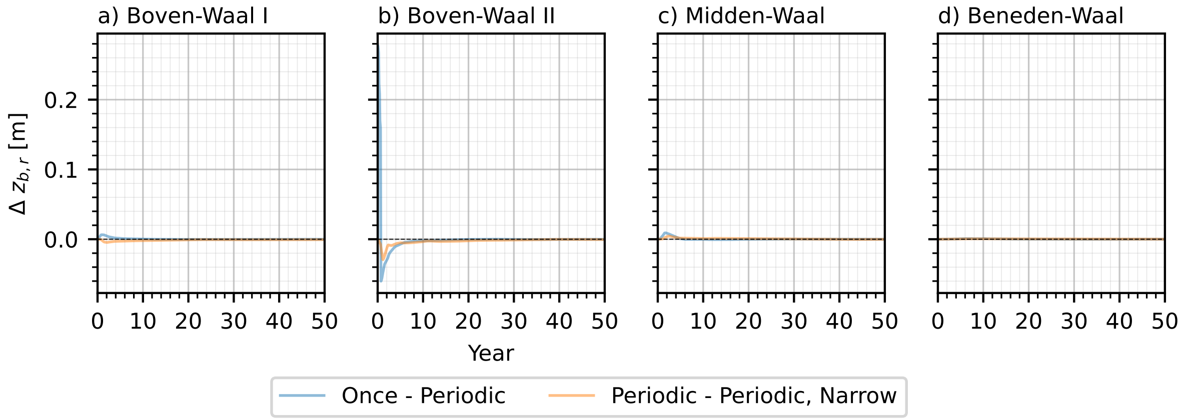


Fig. 7.28 Reach averaged bed level differences between the different scenarios in the Waal for the Spijk nourishments.

7.3.3 Spatial Grain Size Development

The isolated effect of the nourishments on the mean grain size is shown in Fig. 7.29. A decrease in mean grain size is observed in year 0. For the singular nourishment, this initially results in a decrease of approximately 0.38 mm. The (single) periodic nourishment causes a decrease of 0.05 mm, and the (single) narrow periodic nourishment a decrease of 0.14 mm. In subsequent steps, this decrease in grain size spreads along the Waal as the nourishment is transported downstream and diffuses. Over a greater length the grain size is decreased, but more gentle. This can be seen as a 'fining' wave travelling through the system. In year 10, the maximum decrease in mean grain size has moved approximately 25 km downstream to rkm 905 and has been reduced to approximately 0.1 mm. This maximum decrease corresponds to a 'hump' in the bed level (Fig. 7.25b). Additionally, an increase of 0.05 mm in the mean grain size is observed at the nourishment location for all the different strategies. This increase coincides with an increase in the bed level (Fig. 7.25b). When considering the average composition of the nourishment, it is finer than the bed. However, the sediment from Spijk contains a small amount of sediment that is coarser than the bed. Initially, the finer fractions outweigh these coarser fractions, and thus a decrease in grain size is observed. However, since finer sediment is transported more easily, it is washed away earlier, such that coarser fractions remain. This causes an increase in the mean grain size. In subsequent time steps, the decrease in mean grain size travels downstream and spreads out under the effects of diffusion and advection. The increase in grain size that originates from the nourishment location also travels downstream. As the fining wave leaves the system, an additional hump of increased grain size appears at rkm 900 in year 30 (Fig. 7.29d-f). Again, this hump moves downstream. Upstream of the nourishment, where sedimentation takes place due to the backwater curve, only minor changes (up to 0.05 mm) in the grain size are observed.

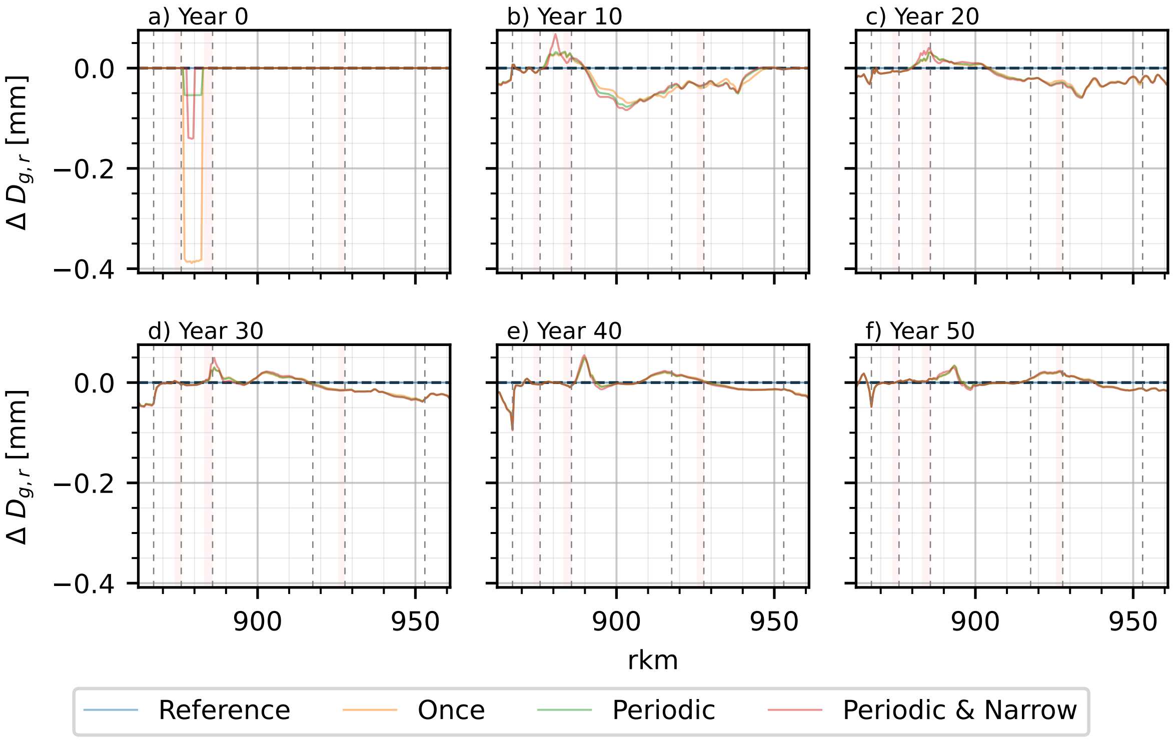


Fig. 7.29 mean grain size change with respect to the reference mean grain size in the Waal for the Spijk nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

The differences in mean grain size between the different strategies are presented in Fig. 7.30. In year 10, changes of up to 0.02 mm in mean grain size are observed between nourishing at once and periodic (Fig. 7.30b). Similar differences occur when the repeated nourishments are placed on a narrower area. The largest differences are located at the nourishment location: for the narrow placement, the largest increase in grain size is observed. This is because the coarser fractions are placed on a narrower area, resulting in a spike. Along the rest of the Waal, a wavelike pattern is observed similar to the differences in bed level. In year 10, it has a maximum amplitude of 0.02 mm, which reduces to 0.005 mm after 50 years. For comparison, the reach averaged mean grain size varies between 1.1 and 1.7 mm in the Waal.

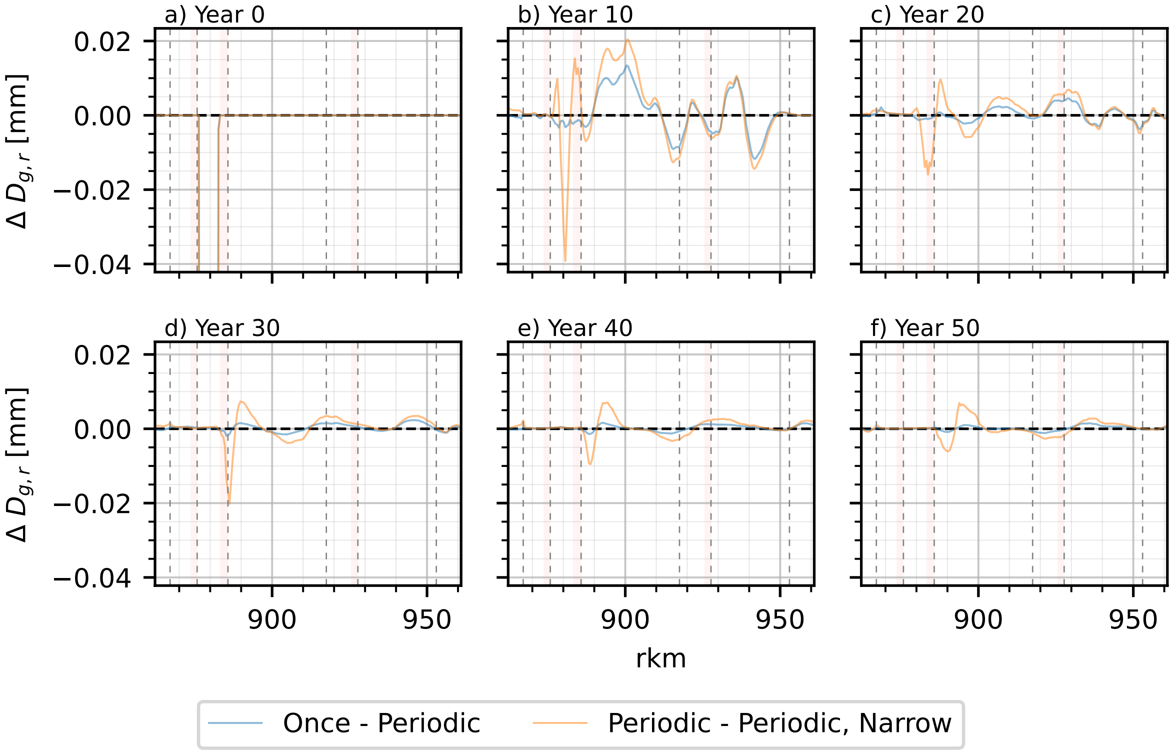


Fig. 7.30 Mean grain size differences between the different scenarios in the Waal for the Spijk nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

7.3.4 Reach Averaged Grain Size Development

The isolated effect of the nourishments on the mean grain size is presented in Fig. 7.31 for the different nourishment strategies. The sedimentation that occurs in the Boven-Waal I, causes a fining with a maximum of 0.02 mm after 6 years (Fig. 7.31a). Over the rest of the simulation period, a slight fining is observed between 0 and 0.02 mm. Since the sediment that is deposited here is riverine, no major changes were expected here. Between the different strategies, only a very small difference (less than 0.01 mm) is observed in the first two years (Fig. 7.32a).

Placing all of the sediment at once causes a maximum average decrease of 0.25 mm in the Boven-Waal II (Fig. 7.31b). For the periodic nourishments, this peak occurs slightly later (when all the sediment is placed) and has a maximum of 0.24 mm. When the nourishment is placed on the narrow area, the maximum decrease is 0.21 mm. In the first 4 years, the fine sediment is still present in the Boven-Waal II , which decreases the mean grain size. This is also the period in which the differences in grain size between the different strategies are present (Fig. 7.32b). With the exception of the initial placement, the strategies cause differences of up to 0.1 mm. Immediately after nourishing, the grain size in the Boven-Waal increases again since the finer fractions are transported downstream to the Midden-Waal. The differences between the strategies also decrease: after 10 years, no significant differences are present. After 5 years, most of the fine sediment has eroded from the Boven-Waal and the presence of the remaining coarser sediment fractions causes an increase in the grain size. These coarser fractions are also moved downstream out of the Boven-Waal, causing it to fine again. After 20 years, the mean grain size of the Boven-Waal is equal to the reference scenario. No major changes are visible from here on.

In the Midden-Waal, the influx of fine sediment causes a decrease in the mean grain size in the first 5 years (Fig. 7.31c). After this period, the Midden-Waal coarsens again. This is a combined effect of the coarse sediment that enters from the Boven-Waal, and fine sediment that leaves the Midden-Waal. In year 20, the relative change passes zero, after which a net increase in the mean grain size is observed. This reaches a maximum of 0.01 mm between years 30-40, after which it decreases again. In the Midden-Waal, placing the nourishment at once instead of periodic causes a smaller mean grain size with a maximum of 0.02 mm for the first 4 years (Fig. 7.32c). This is because more of the fine sediment is already transported downstream. Analogously, more of the fine sediment will leave the Midden-Waal earlier, such that there is a maximum increase in mean grain size of 0.01 mm in year 6. This difference then linearly decreases up until year 18, after which no visible changes are present. A similar pattern occurs when a nourishment is placed on a narrow area.

The Beneden-Waal fines after 5 years due to the inflow of fine sediment (Fig. 7.31d). In year 15, the maximum decrease of 0.03 mm is reached for the different scenarios. From this point on, up until the end of the simulation, the bed coarsens. In year 50, the average grain size has increased with 0.002 mm. The differences between the strategies are presented in Fig. 7.32c. Between years 6-10, a small decrease (< 0.01 mm) is observed. This is due to the faster influx of finer sediment. After this period, an increase in the mean grain size is observed for the different scenarios.

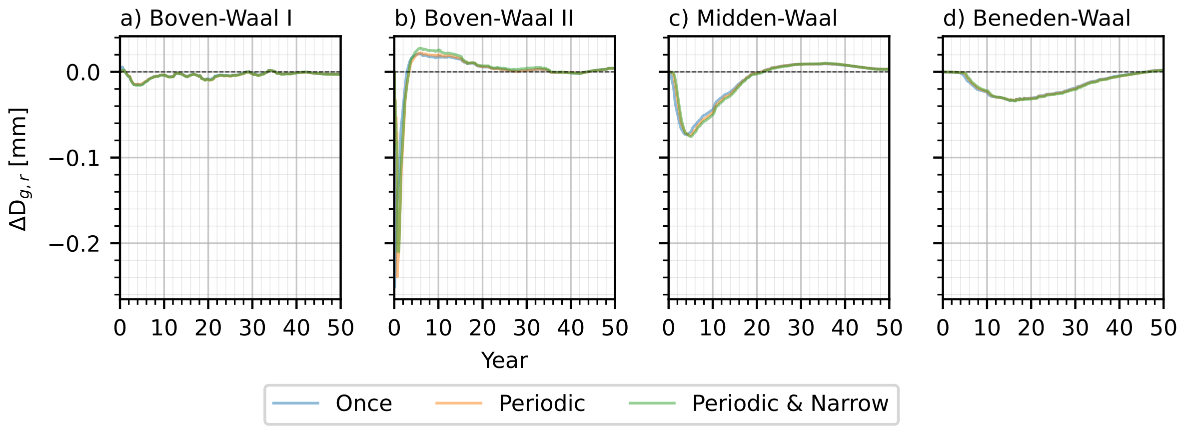


Fig. 7.31 Reach averaged mean grain size change with respect to the reference mean grain size in the Waal for the Spijk nourishments.

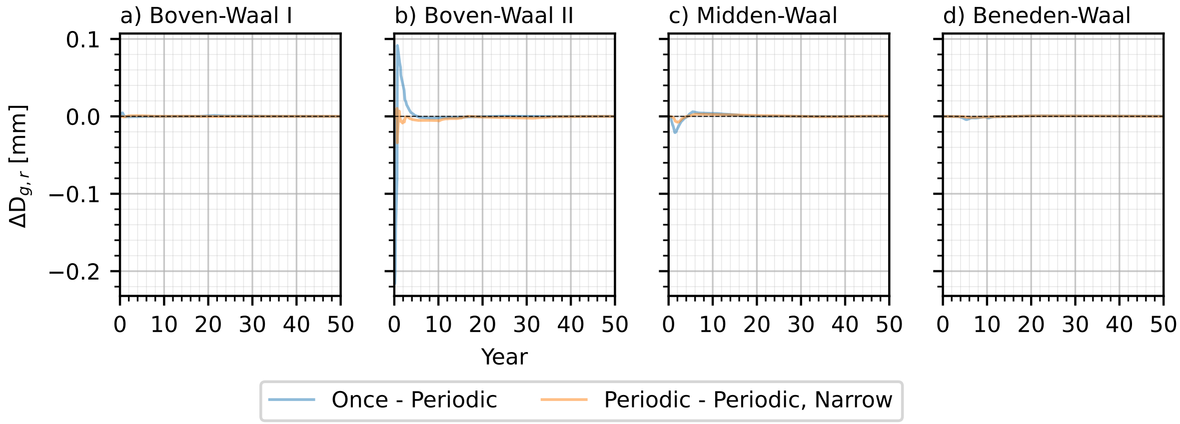


Fig. 7.32 Reach averaged mean grain size differences between the different scenarios in the Waal for the Spijk nourishments.

7.3.5 Influence on the Discharge Distribution

The effect of the singular nourishment is presented in Fig. 7.33. Overall, placing the nourishments causes a decrease of discharge towards the Waal, with the exception of some points at 1,800 m^3/s. Over time, the changes decrease as the height of the nourishment decreases. For the periodic strategies, a similar behaviour is observed (Appendix C.3). In year 50, the singular and periodic nourishment strategies reduce $Q_{1,400}$ by 0.18%. For the periodic, narrow strategy this is slightly higher at 0.19%.

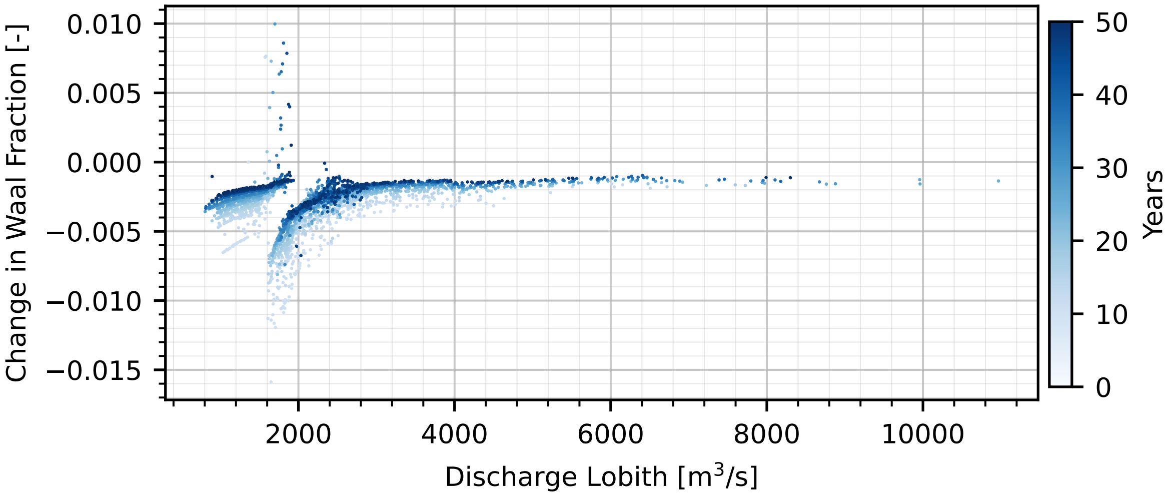


Fig. 7.33 Change in discharge distribution due to the singular nourishment from Spijk relative to the reference scenario.

7.4 Nourishments from the Maas-Waal Canal

At the start of the simulation, the nourishments are imposed on the river bed as described in Table 6.1.

7.4.1 Spatial Bed Level Development

Fig. 7.34 shows the development of the bed level with respect to the initial bed level every 10 years. The nourishments can be identified in Fig. 7.34a. In year 10, the effect of both nourishments have become indistinguishable from the natural bed development (Fig. 7.34b). This is also the case in the subsequent Figs. 7.34c-f.

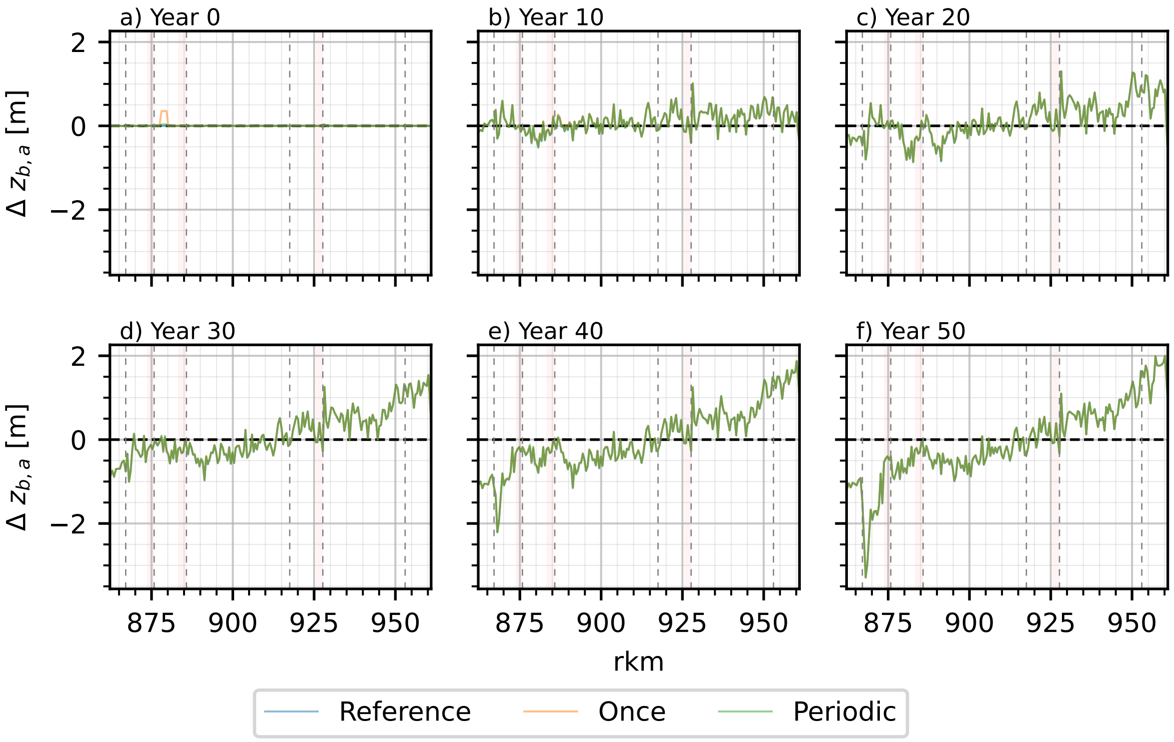


Fig. 7.34 Bed level change with respect to the initial bed level in the Waal for the Maas-Waal Canal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

The isolated effect of the nourishments is presented in Fig. 7.35. Here, both nourishments are visible as rectangular shapes in year 0 in Fig. 7.35a. Is important to note that for the periodic strategy every five years sediment gets added. The snapshots presented are right after the placement of these nourishments, such that at the nourishment location an increase is observed. In year 10 (Fig. 7.35b) the singular nourishment has already decreased to a maximum of 4 cm and has moved downstream. With the exception of the nourishment location, the periodic nourishment has a height up to 1 cm and has also moved downstream. Upstream of the nourishment location, additional sedimentation of 1-2 cm has occured for the singular nourishment. In years 20-50 the nourishments travel further downstream and diffuse more (Figs. 7.35c-f). During this period, additional sedimentation occurs for the periodic strategy. After 50 years, the aggradation upstream of the nourishment is equal to the singular nourishment strategy. The differences between the different strategies are presented in Fig. 7.36. When the nourishments are placed at once instead of periodic, a wavelike pattern in the bed level differences occurs. In year

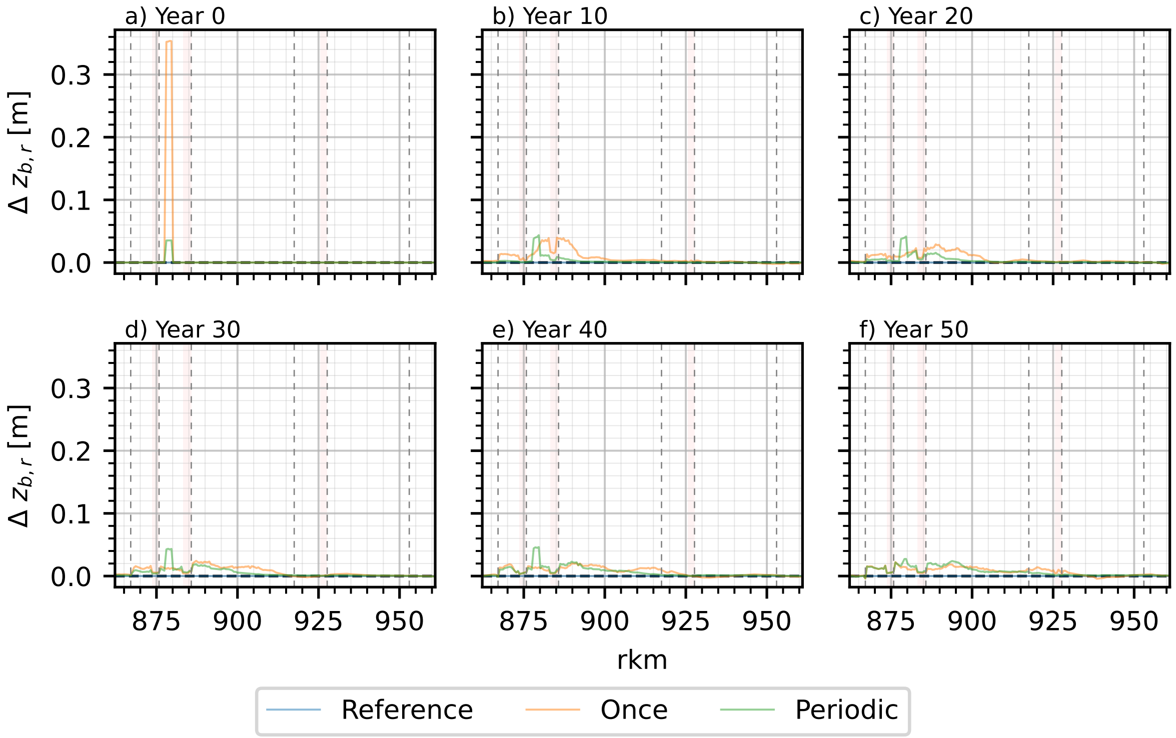


Fig. 7.35 Bed level change with respect to the reference bed level in the Waal for the Maas-Waal Canal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

10 (Fig. 7.36a), the singular nourishment results in higher bed levels everywhere with a maximum of 2.5 cm. This is not the case for the nourishment location, since new sediment is added here every 5 years for the periodic strategy. Over time, a wavelike pattern develops that travels downstream. In year 20 (Fig. 7.36c), the relative increase has moved downstream, and has diffused. This continues until the end of the simulation. Eventually, the singular nourishment results in locally lower bed levels than the periodic strategy. This is visible in years 40-50 (Figs. 7.36e-f), close to the nourishment location. While the sediment from the singular strategy has already moved downstream, the sediment from the periodic strategy did not have time to do so. Therefore, applying a periodic strategy results in more sediment close to the nourishment location in comparison to a singular strategy. Upstream of the nourishments, the difference disappear as over time additional sedimentation takes place for the periodic strategy. After 50 years, the nourishments have an effect of up to 1-2 cm.

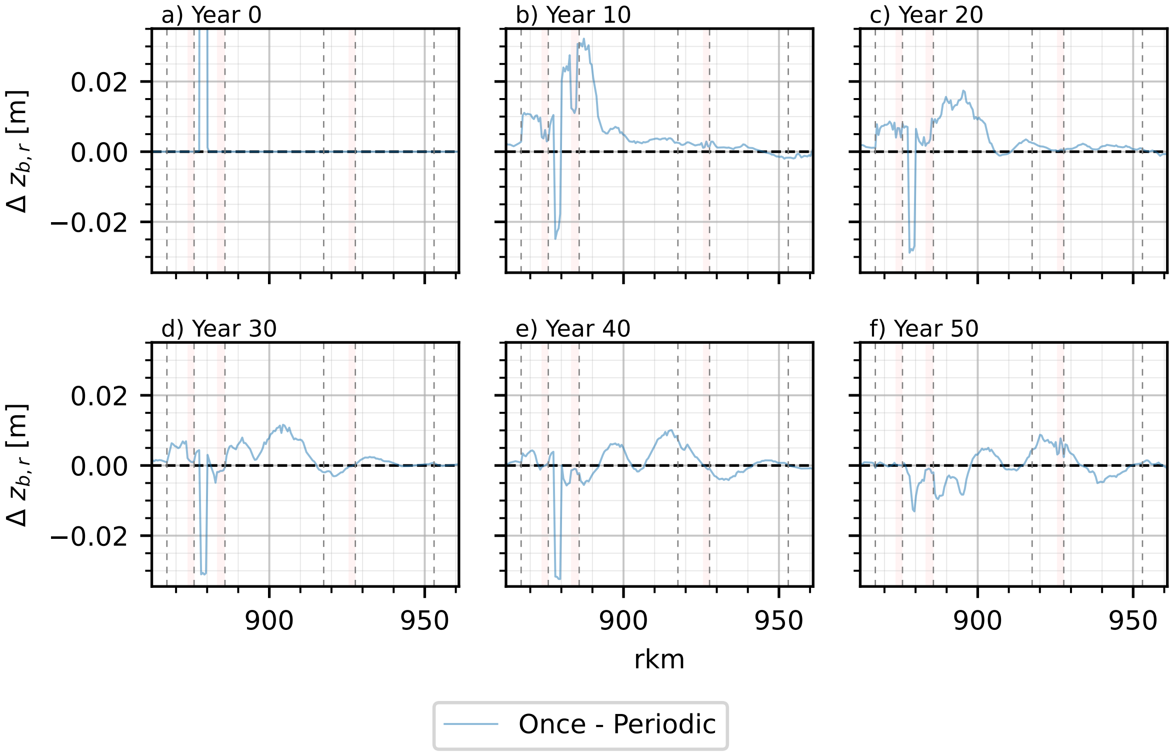


Fig. 7.36 Bed level differences between the different scenarios in the Waal for the Maas-Waal Canal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

7.4.2 Reach Averaged Bed Level Development

Figs. 7.37a-d show the change in the bed level averaged per reach with respect to the initial bed level over time for the different strategies. For the strategies based on the Maas-Waal Canal, the mitigating effect is small due to the small volume applied. In the Boven-Waal I, nourishing at once delays erosion with 2 months, whereas nourishing periodicially reduces erosion with 1 month (Fig. 7.37a). In the Boven-Waal II, erosion is prevented with 0.6 or 0.2 years for the respective strategies (Fig. 7.37b). In the Midden-Waal, erosion is delayed with 0.6 or 0.3 years. (Fig. 7.37c). In the Beneden-Waal, additional sedimentation occurs (Fig. 7.37d).

Figs. 7.37e-h show the isolated effect of the nourishments averaged over the reaches. After 50 years, 1.5 cm of aggradation occurs in the Boven-Waal I for both cases (Fig. 7.37e). For the singular strategy, most of this sedimentation occurs in the first 10 years, whereas the periodic strategy shows an approximately linear increase over time. These differences are highlighted in Fig. 7.38a.

Placing the singular nourishment causes a sudden increase in the relative bed level change in the Boven-Waal II of 8.4 cm (Fig. 7.37f). Initially, a steep decrease in bed level occurs as sediment leave the Boven-Waal II. Over time, this decrease becomes less rapid. Since the finer fractions have left the Boven-Waal II, the coarser fractions remain. Similar to Spijk, the composition from the Maas-Waal Canal contains small fractions of sediment that are coarser than the bed, which are less easily transportable. After 20-30 years, the increase in the Boven-Waal II stabilises to approximately 1-1.5 cm. For the periodic strategy, placing a nourishment results in a bed level increase of 0.84 cm (Fig. 7.37f). Each subsequent nourishment causes a net increase in the bed level. In year 50, the singular strategy results in an increase of 1.24 cm, whereas the periodic strategy causes an increase of 1.9 cm. These differences are also highlighted in Fig. 7.38b.

From Fig. 7.37g, it is seen that it takes 1-2 years for the sediment to increase the bed level in the Midden-Waal. After 10 years, the bed level has increased with 1 cm for the singular nourishment. Between years 30-40, a maximum is reached of around 1.4 cm, after which the change in bed level reduces to 1 cm in year 50. For the periodic strategy, the increase is approximately linear. In year 50, this strategy also results in an increase of 1 cm. The differences between the two strategies are highlighted in Fig. 7.38c.

While both strategies have an influence of the bed level in the Beneden-Waal, their effect is contained to a minimum (Fig. 7.37h). At no point in time do they increase the bed level with more than 0.05 cm. The differences are highlighted in Fig. 7.38d.

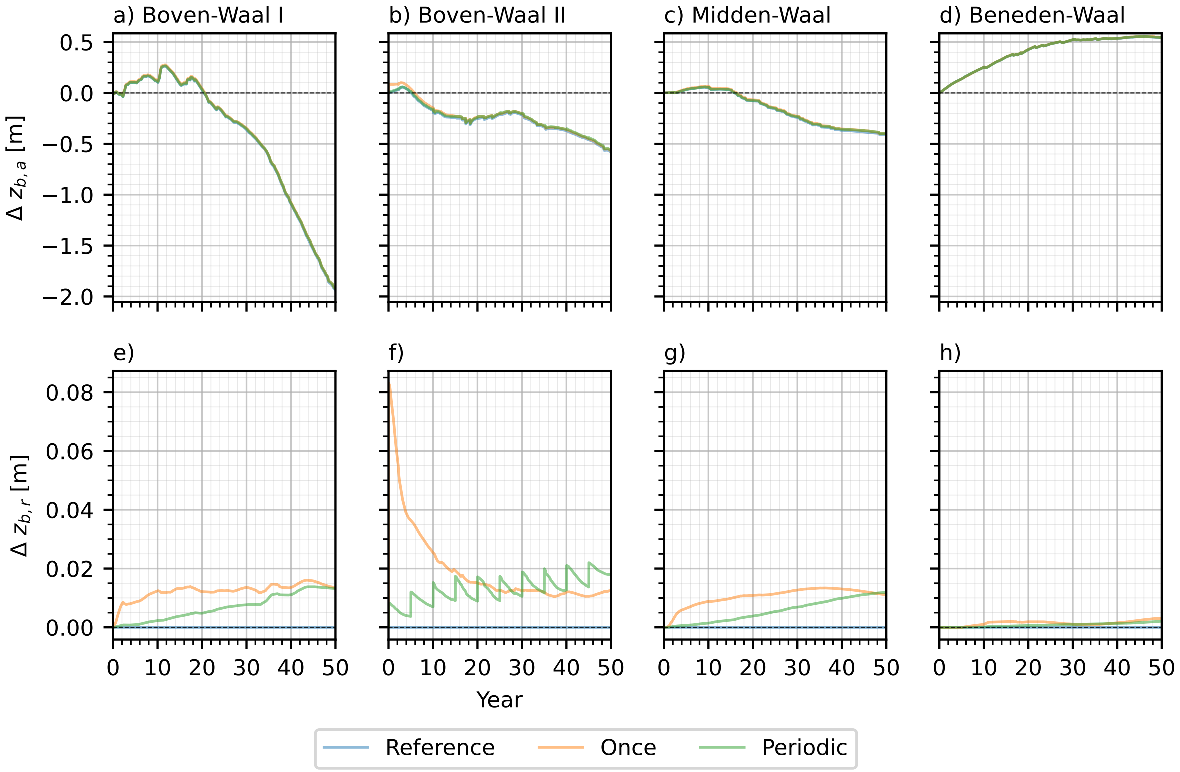


Fig. 7.37 Reach averaged bed level change with respect to the a-d) initial reach averaged bed level and e-h) reference reach averaged bed level in the Waal for the Maas-Waal Canal nourishments.

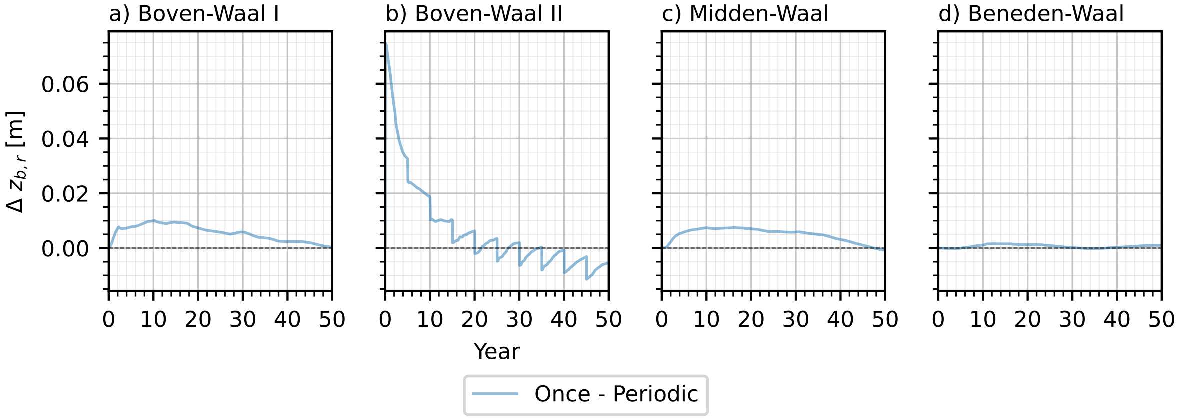


Fig. 7.38 Reach averaged bed level differences between the different scenarios in the Waal for the Maas-Waal Canal nourishments for the Maas-Waal Canal nourishments.

7.4.3 Spatial Grain Size Development

The isolated effect of the nourishments is shown in Fig. 7.39. A decrease in mean grain size is observed in year 0. For the singular nourishment, this initially results in a decrease of approximately 0.15 mm. The periodic nourishment causes a decrease of 0.02 mm. For subsequent time steps, the singular nourishment shows behaviour equal to the singular nourishment from Spijk. In year 10, the maximum decrease in mean grain size has moved downstream to rkm 895 and has been reduced to approximately 0.02 mm. Downstream of this point, the grain size is also decreased. Upstream from rkm 895, an increase in the mean grain size is observed. Similar to Spijk, this is due to the remaining coarser fractions from the nourishments. In subsequent time steps, the changes are transported downstream and spread out (Figs. 7.39). For the periodic nourishment, a similar behaviour is observed. However, due to the periodic placement, the initial effect is less severe as less sediment is placed. Over time, as more sediment is placed, this effect increases. Upstream of the nourishments, changes up to 0.02 mm occur due to the sediment that deposits here. The differences between the strategies are presented in Fig. 7.40.

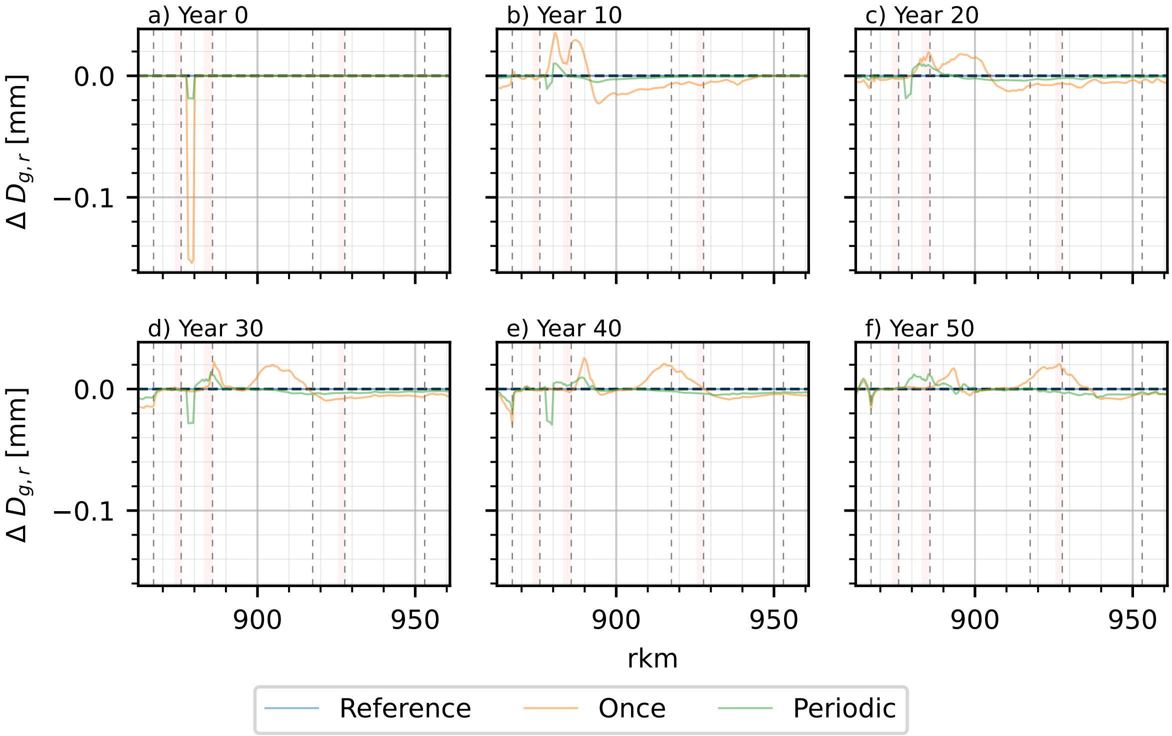


Fig. 7.39 Mean grain size change with respect to the reference mean grain size in the Waal for the Maas-Waal Canal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

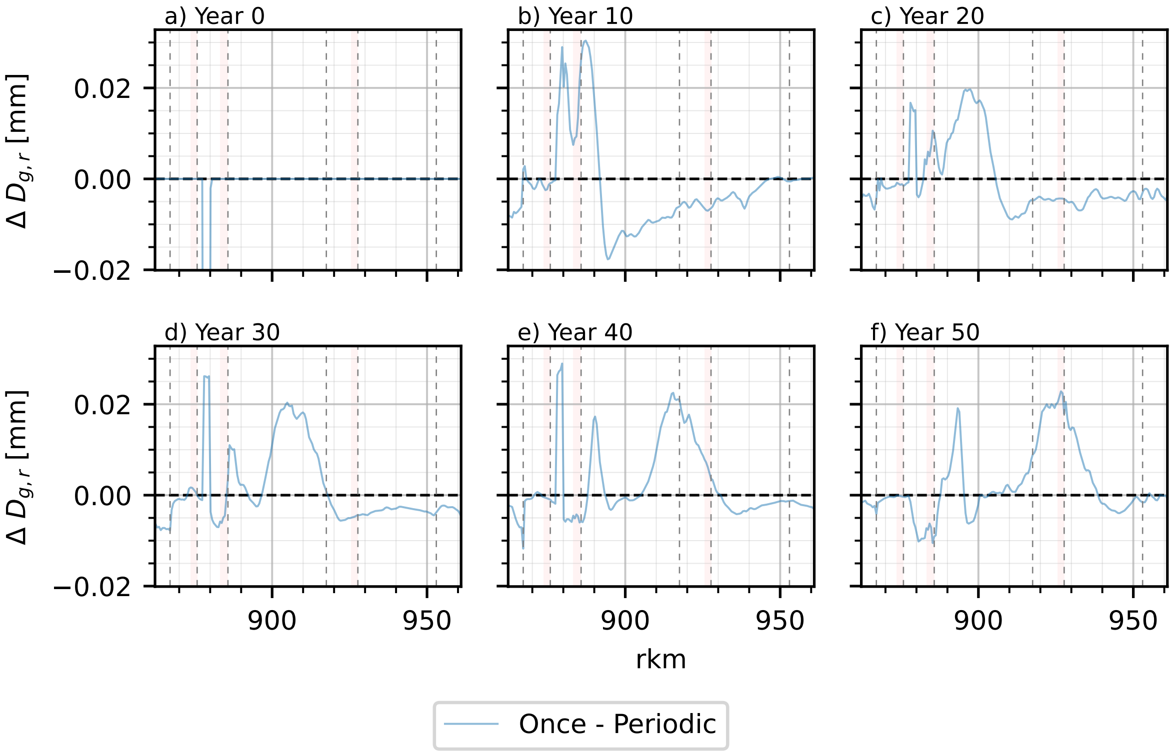


Fig. 7.40 Mean grain size differences between the different scenarios in the Waal for the Maas-Waal Canal nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

7.4.4 Reach Averaged Grain Size Development

The isolated effect of the nourishments on the mean grain size is presented in Fig. 7.41 for the different nourishment strategies. The sedimentation that occurs in the Boven-Waal I, causes a fining with a maximum of 0.005 mm after 6 years (Fig. 7.41a). Over the rest of the simulation period, a slight fining is observed between 0 and 0.002 mm. Since the sediment that is deposited here is riverine, no major changes were expected here. Between the different strategies, only a very small difference (less than 0.005 mm) is observed in the first two years (Fig. 7.42a).

Placing all of the sediment at once causes a maximum average decrease of 0.035 mm in the Boven-Waal II (Fig. 7.41b). For the periodic nourishments, initially a decrease of 0.005 mm is observed. After this, coarsening occurs in both cases(Fig. 7.41f). When the finer sediment is moved downstream, a maximum increase of 0.02 mm is observed in year 5 for the singular strategy. This increase then proceeds to reduce to 0 in year 40, and end with a slight increase in year 50. Every nourishment from the periodic strategy results in a decrease of the mean grain size. However, as the nourishment is is transported downstream, the mean grain size increases again. This pattern is repeated for each nourishment. Throughout the periodic strategy, the mean grain size increase fluctuates mostly between 0.0 and 0.005 mm. The differences are highlighted in Fig. 7.42b.

The fine sediment that is transported from the Boven-Waal II, enters the Midden-Waal. For both strategies, this is visible as a decrease in the mean grain size (Fig. 7.41c). When nourishing once, a decrease is observed in the first 16 years, with a maximum of 0.15 mm. After these 16 years, the bed starts to coarsen as the coarser sediment is also transported in. The coarsening reaches a maximum of 0.01 in year 32, after which the mean grain size increases to 0.0024 mm in year 50. For the periodic strategy, the grain size changes are less severe. In the first 35 years, a maximum decrease of 0.035 mm is reached, after which a negligible coarsening occurs. The differences are highlighted in Fig. 7.42c.

For both nourishment strategies, the Beneden-Waal fines after 5 years due to the inflow of fine sediment (Fig. 7.41d). The singular nourishment shows a similar behaviour to the Midden-Waal: initially a fining occurs, followed by a coarsening. The fining occurs up until year 42, after which coarse sediment flows in. The maximum decrease in the Beneden-Waal is 0.006 mm, whereas the maximum increase is 0.024 mm for the singular nourishment. When nourishing periodically, only a decrease in the Beneden-Waal is observed. This reaches a maximum of 0.005 mm in year 50. For the periodic strategy, no coarsening is observed. This is because, for periodic placement, insufficient coarse material has reached the Beneden-Waal yet to increase the grain size. The differences between the strategies are presented in Fig. 7.42d.

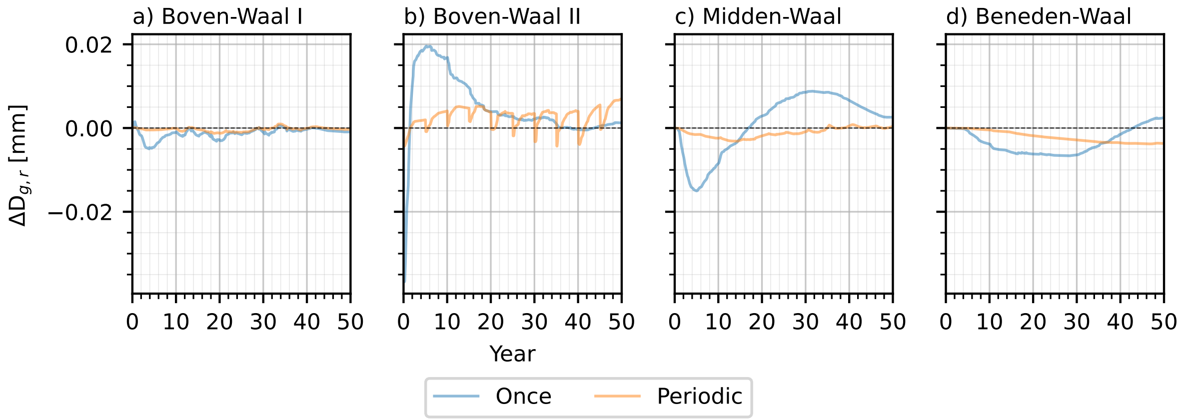


Fig. 7.41 Reach averaged mean grain size change with respect to the reference mean grain size in the Waal for the Maas-Waal Canal nourishments.

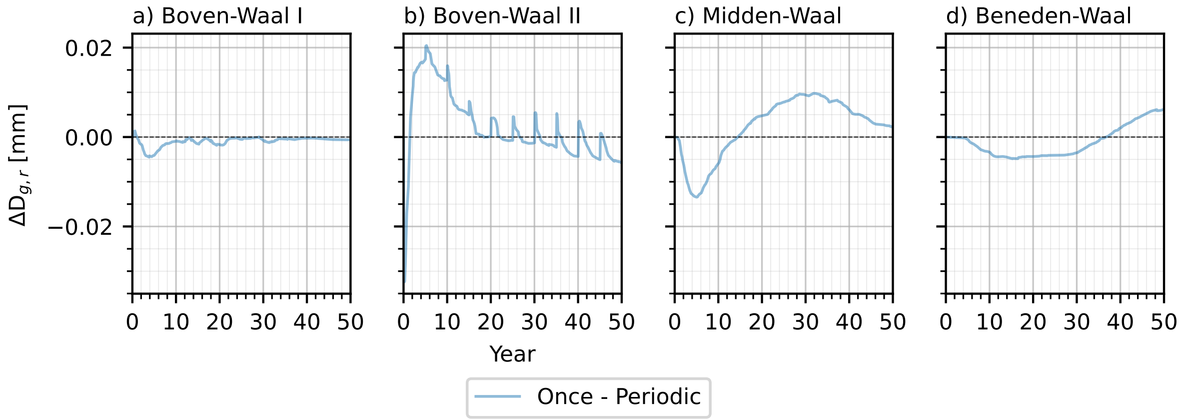


Fig. 7.42 Reach averaged mean grain size differences between the different scenarios in the Waal for the Maas-Waal Canal nourishments.

7.4.5 Influence on the Discharge Distribution

The effect of the singular nourishment is presented in Fig. 7.43. Overall, placing the nourishments causes a decrease of discharge towards the Waal. Next to the points around 1,800 m^3/s, additional negative values are found between 2,000-3,000 m^3/s. This is also believed to be an effect of the weirs as they operate in this discharge regime. These outliers are more apparent because the changes induced by the Maas-Waal Canal nourishments are small and of the same order of magnitude. Over time, the effect of the nourishment on the discharge distribution decreases as the height of the nourishment decreases. For the periodic strategies, an inverse behaviour is observed (Appendix C.4). As more sediment is nourished, the change in Waal fraction increases. In year 50, the singular and periodic nourishment strategies reduces $Q_{1,400}$ by 0.064%. For the periodic strategy this is slightly higher at 0.075%.

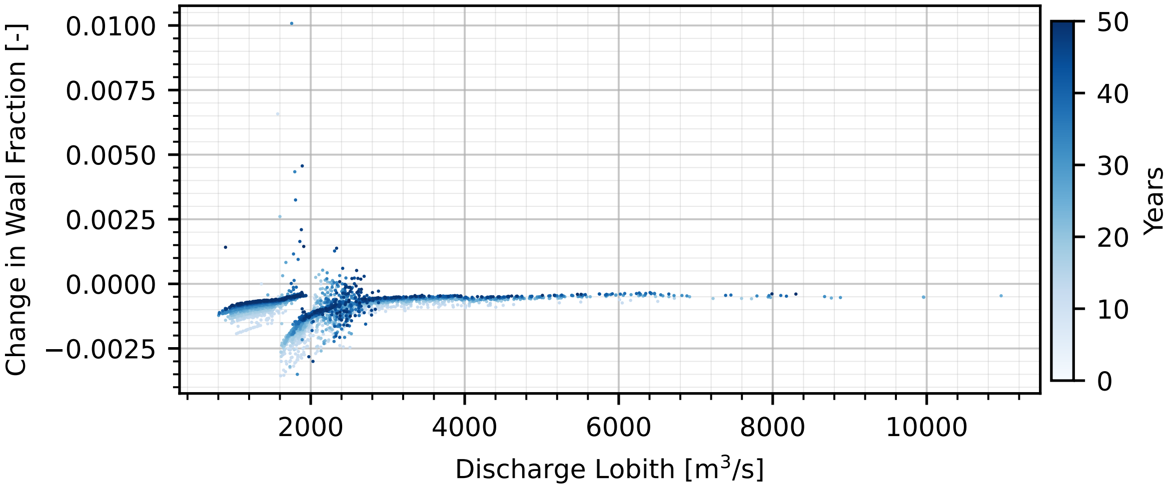


Fig. 7.43 Change in discharge distribution due to the singular nourishment from the Maas-Waal Canal relative to the reference scenario.

7.5 Nourishments from Downstream Aggradation

At the start of the simulation, the nourishments are imposed on the river bed as described in Table 6.1.

7.5.1 Spatial Bed Level Development

Fig. 7.44 shows the development of the bed level with respect to the initial bed level every 10 years. In year 10, the effect of the nourishments have already become indistinguishable from the natural bed development (Fig. 7.44b). This is also the case in the subsequent years (Figs. 7.44c-f).

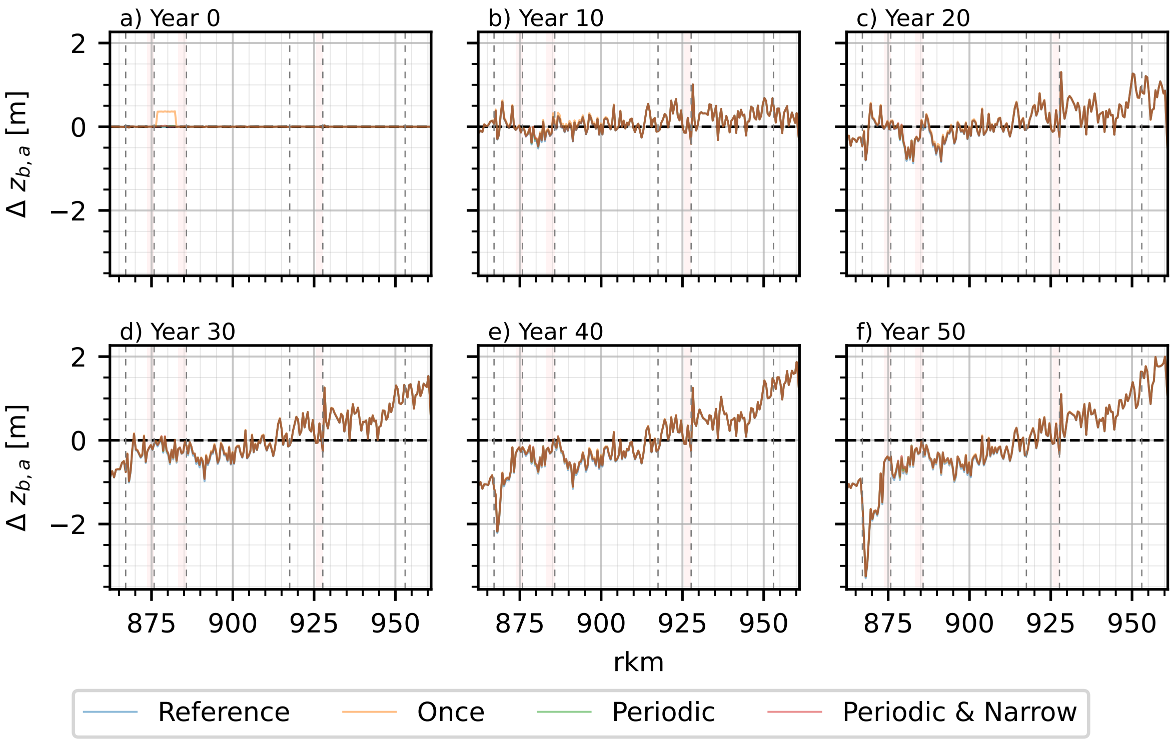


Fig. 7.44 Bed level change with respect to the initial bed level in the Waal for the downstream aggradation nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

The relative bed level change is presented in Fig. 7.45. Again, the nourishments are visible as rectangular shapes in year 0 in Fig. 7.45a. It should be noted that for the periodic strategies, every year sediment is nourished. In year 10 the shapes of the nourishments have changed significantly under the influence of advection and diffusion (Fig. 7.45b). The singular nourishment behaves similarly to the singular nourishment from Spijk, since their characteristics (volume and grain size distribution) are comparable. As more sediment is nourished for the periodic nourishments, their mitigating effect increases. Over time, the singular nourishment moves downstream and spreads out (Figs. 7.45b-f). For the periodic nourishment, more sediment is located upstream compared to the singular nourishment. At the end of the simulation, the bed level increase varies between 3-6 cm in the Boven-Waal and Midden-Waal (Fig. 7.45f). For the periodic strategy, this is the same range.

The differences in bed level between the scenarios are presented in Fig. 7.46. When the nourishments are placed at once instead of periodic, a wavelike pattern in the bed level differences occurs. This wavelike pattern behaves in a similar way as the pattern observed in the scenarios from the other sources. When placing nourishments on a narrower area, the only differences are found at the nourishment location.

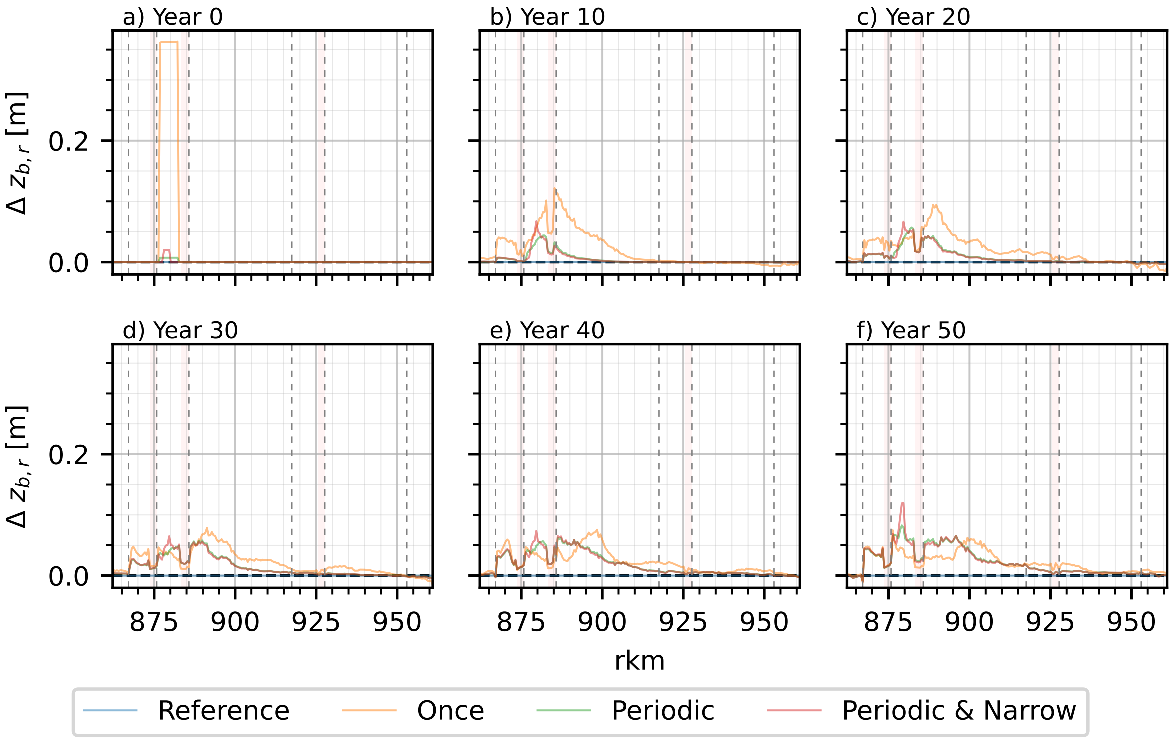


Fig. 7.45 Bed level change with respect to the reference bed level in the Waal for the downstream aggradation nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

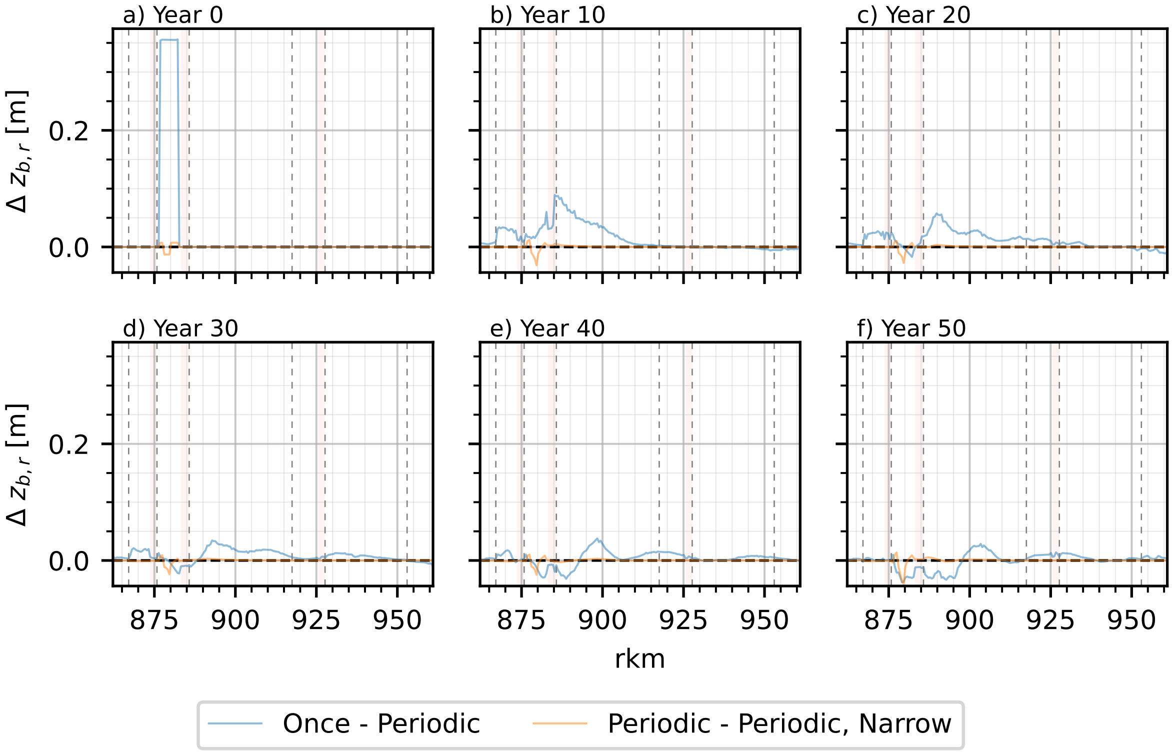


Fig. 7.46 Bed level differences between the different scenarios in the Waal for the downstream aggradation nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

7.5.2 Reach Averaged Bed Level Development

Fig. 7.47 shows the isolated effect of the nourishments averaged over the reaches. For all strategies, placing the nourishments causes an increase in the Boven-Waal I of about 4 cm in year 50 (Fig. 7.47a). For the singular nourishment, most of this sedimentation occurs in the first 10 years. For the periodic nourishments, this sedimentation occurs approximately linearly over time. These differences are highlighted in Fig. 7.48a. For the periodic nourishments, no differences are observed between the two (Fig. 7.48a).

Placing the singular nourishment causes a sudden increase in the relative bed level change in the Boven-Waal II of 23 cm (Fig. 7.47b). After nourishing, a steep decrease in bed level is observed as the sediment is transported to the Beneden-Waal. After 20 years, this stabilises to 3-4 cm. For the periodic nourishments, the bed level increases over time in a sawtooth pattern. After 50 years, the bed increases by 6 cm for both periodic scenarios. When placing the nourishment on a narrow area, a slight increase is observed (Fig. 7.48b).

From Fig. 7.47c, it can be seen that it takes 1-2 years for the sediment to increase the bed level in the Midden-Waal. When nourishing at once, a maximum bed level increase of 4 cm is obtained after 15 years. For the rest of the simulation, this stays roughly the same. When nourishing periodically, the bed level increases linearly. After 50 years, this reaches 4 cm as well. The differences between the strategies are presented in Fig. 7.48c.

After 15 years, the nourishments increase the bed in the Beneden-Waal (Fig. 7.47d). The singular nourishment results in an increase of 1 cm after 50 years, whereas the periodic nourishments result in an increase of 0.8 cm. Equal to the additional sediment in the Midden-Waal, nourishing at once results in more sediment that is transported to the Beneden-Waal. This results in a few mm increase throughout the simulation (Fig. 7.48d). Between the periodic strategies, no differences are observed.

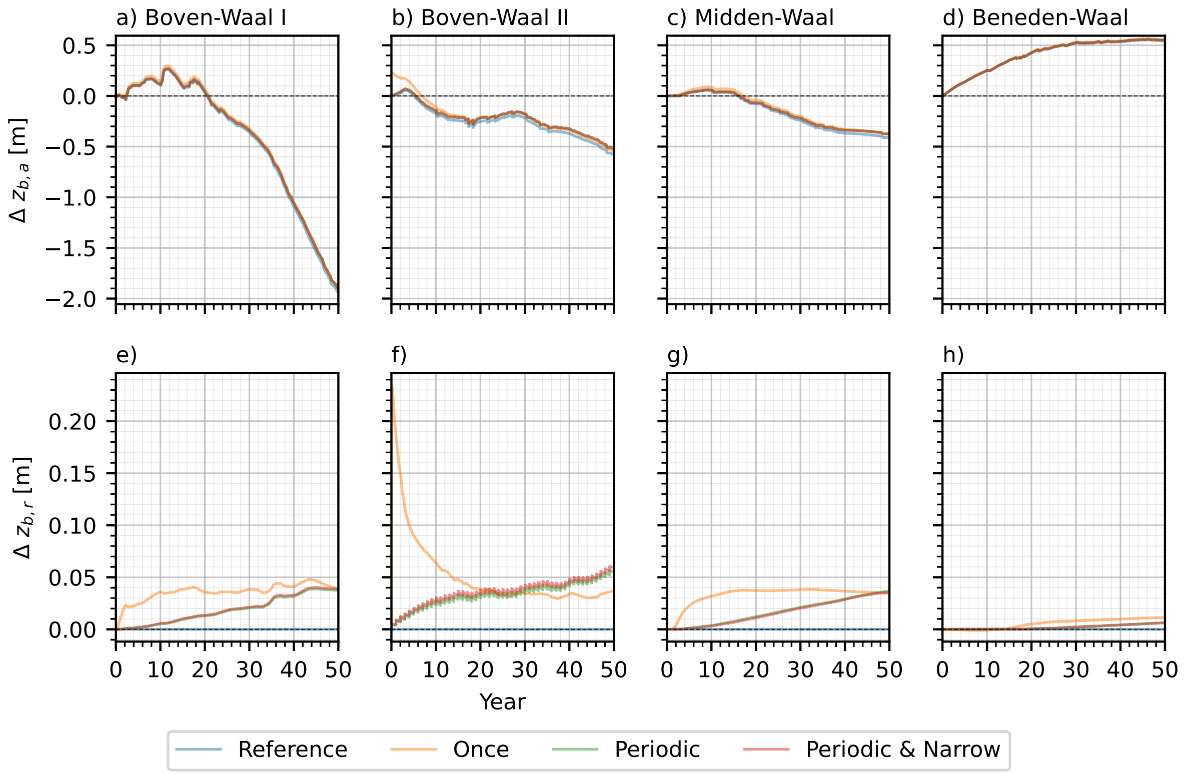


Fig. 7.47 Reach averaged bed level change with respect to the a-d) initial reach averaged bed level and e-h) reference reach averaged bed level in the Waal for the downstream aggradation nourishments.

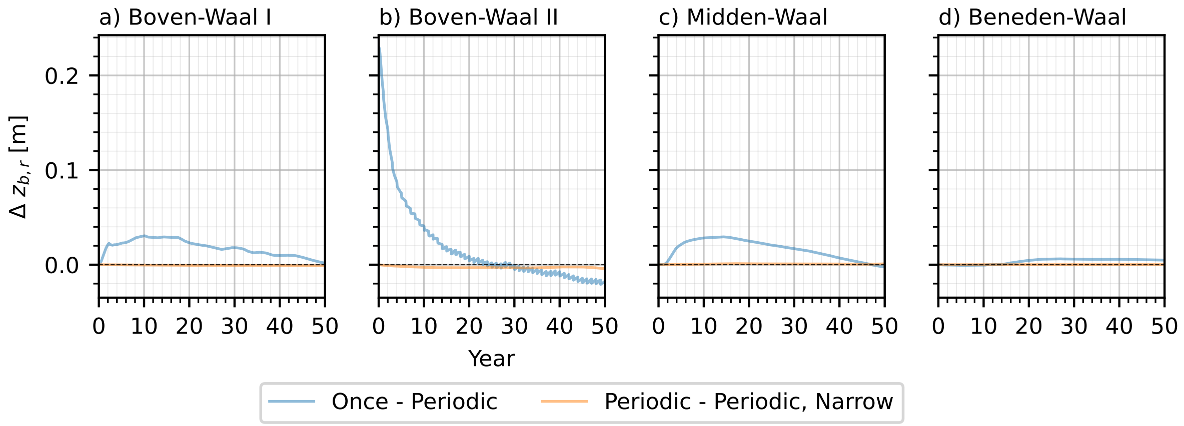


Fig. 7.48 Reach averaged bed level differences between the different scenarios in the Waal for the downstream aggradation nourishments.

7.5.3 Spatial Grain Size Development

The isolated effect of the nourishments on the mean grain size is shown in Fig. 7.49. A decrease in mean grain size is observed in year 0 (Fig. 7.49a). For the singular nourishment, this initially results in a decrease of approximately 0.11 mm. The (single) periodic nourishment causes a decrease of 0.002 mm, and the (single) narrow periodic nourishment a decrease of 0.009 mm. In subsequent steps (Figs. 7.49b-f), this decrease in grain size spreads along the Waal as the nourishment is transported downstream and diffuses. Due to the periodic nourishments, a pattern of spikes occurs over time. Between the periodic strategies, the only differences are present at the nourishment location (Fig. 7.50). When nourishing at once instead of periodically, initially a fining 'hump' travels through the system (Fig. 7.50). As the finer sediment is moved downstream, coarser sediment remains such that a coarsening 'hump' forms that moves downstream (Figs. 7.50d-f).

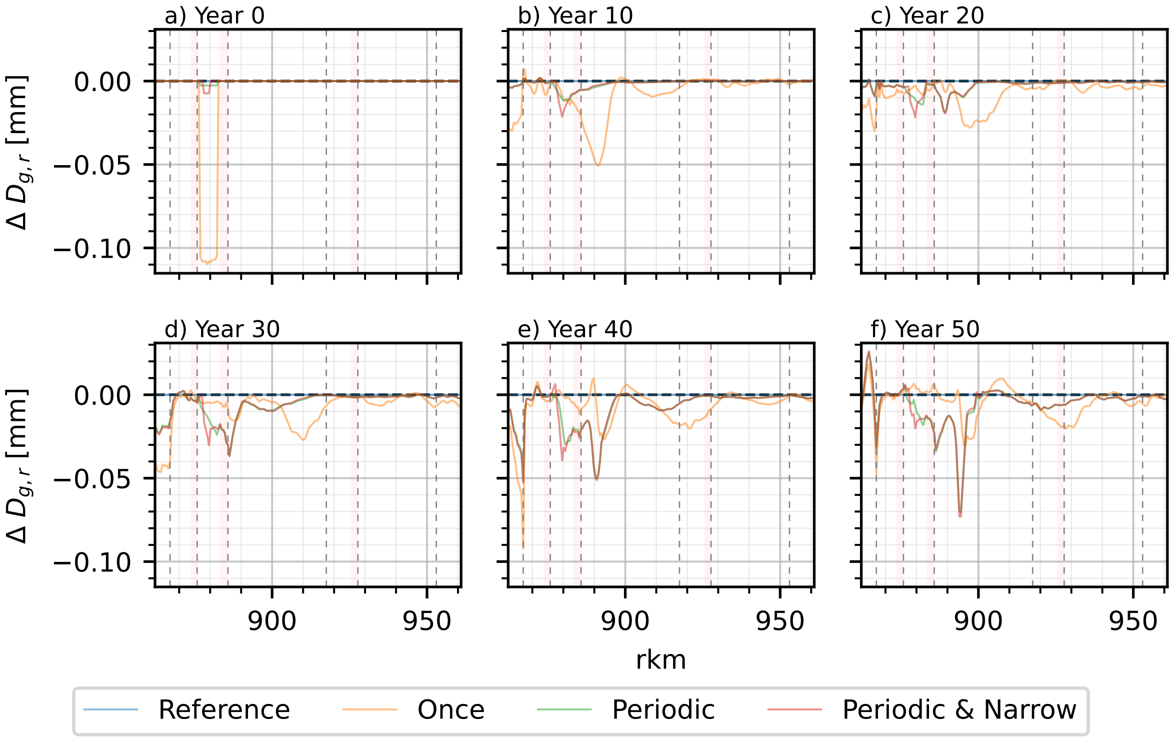


Fig. 7.49 mean grain size change with respect to the reference mean grain size in the Waal for the downstream aggradation nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

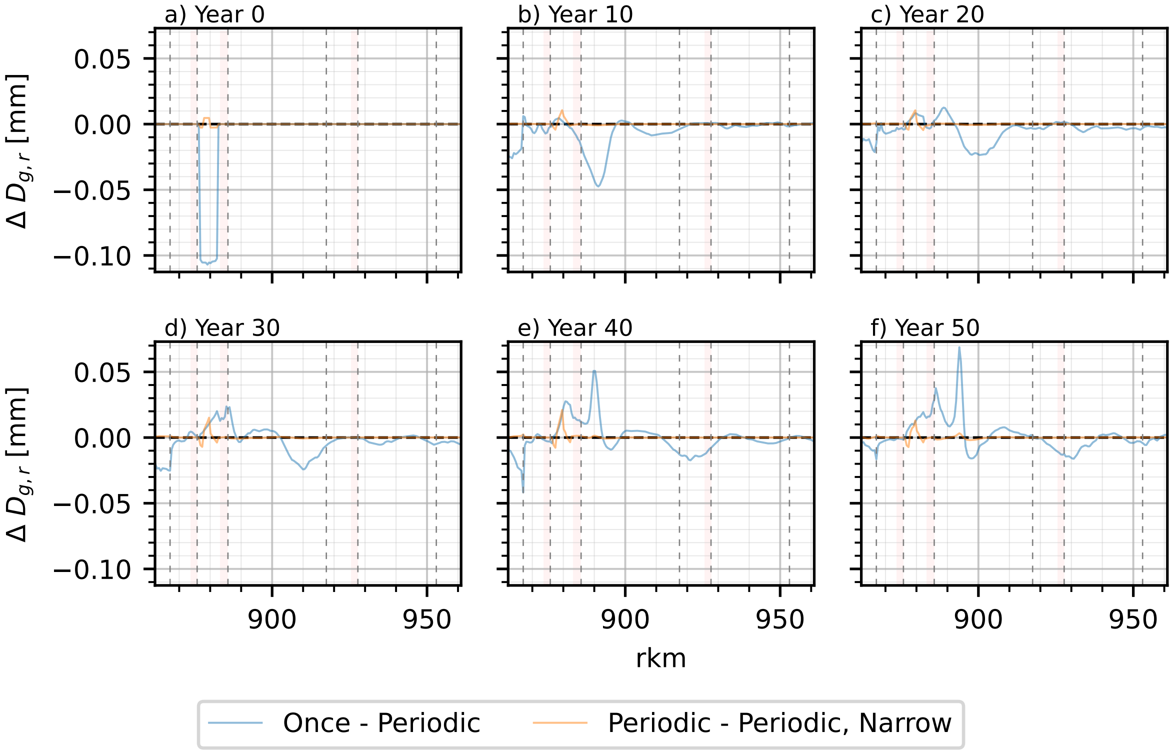


Fig. 7.50 Mean grain size differences between the different scenarios in the Waal for the downstream aggradation nourishments for the downstream aggradation nourishments. The dashed lines indicate the boundaries between reaches and the red marked areas the fixed layers implemented in the model.

7.5.4 Reach Averaged Grain Size Development

The isolated effect of the nourishments on the reach averaged mean grain size is presented in Fig. 7.51 for the different nourishment strategies. In the Boven-Waal I, the singular nourishment causes a maximum decrease of 0.13 mm in year 4 (Fig. 7.51a). Afterwards, there are fluctuations of up to 0.01 mm. For the periodic nourishments, these fluctuations are up to 0.005 mm. The differences are presented in Fig. 7.52a.

In the Boven-Waal II, the singular nourishment results in a decrease of 0.07 mm directly after placing the nourishment (Fig. 7.51b). For the periodic nourishments, this is 0.002 mm. For the singular nourishment, the mean grain size increases rapidly in the first 10 years, such that the decrease is 0.005 mm. In years 10-50, the mean grain size fluctuates around this value. In year 50, the mean grain size increased by 0.024 mm. For the periodic strategies, the mean grain size decreases in the first 30 years with about 0.015 mm. In years 30-50, the decrease fluctuates between 0.01 and 0.02 mm. The narrow placement results in a higher decrease of approximately 0.005 mm throughout the simulation (7.52b).

In the Midden-Waal, the influx of fine sediment causes a decrease in the mean grain size (Fig. 7.49c). For the singular nourishment, this results in a maximum decrease of 0.15 mm after 10 years, after which the bed coarsens. In year 50, a decrease of 0.005 mm is observed. For the periodic strategies, only fining is observed. In year 50, a maximum decrease of 0.01 mm is reached for both periodic strategies. As presented in Fig. 7.50c, no differences are observed between the periodic strategies.

The Beneden-Waal fines after 10 years due to the inflow of fine sediment for all scenarios (Fig. 7.49d). In year 50, more fine sediment has reached the Beneden-Waal from the singular nourishment than the periodic nourishments. This is represented in the differences in mean grain size decrease. For the singular nourishment, the mean grain size decreased with 0.8 mm, whereas both periodic nourishments result in a decrease of 0.4 mm. Again, no differences between the periodic strategies are observed (Fig. 7.50d).

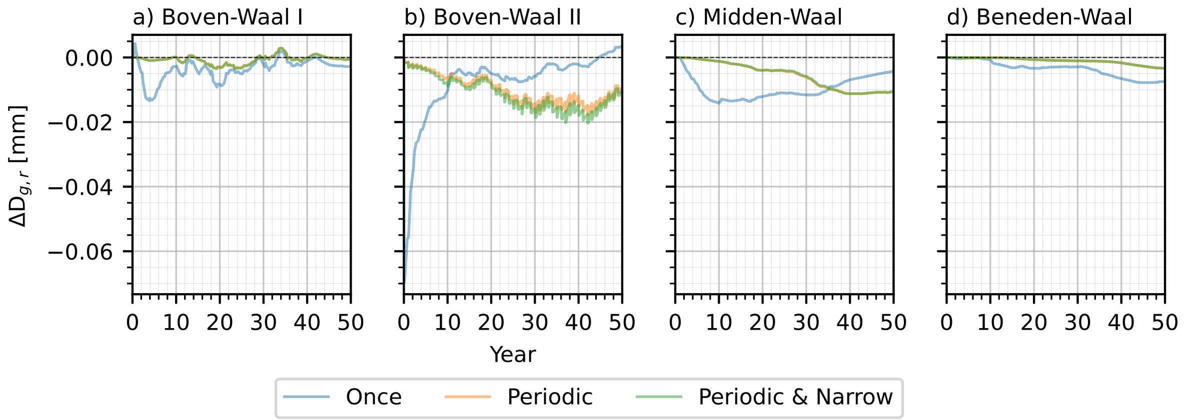


Fig. 7.51 Reach averaged mean grain size change with respect to the reference mean grain size in the Waal for the downstream aggradation nourishments.

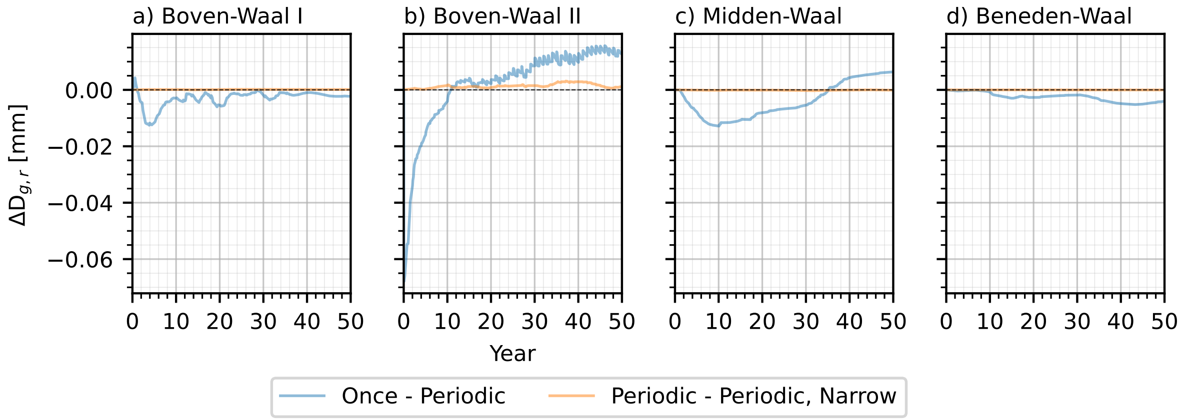


Fig. 7.52 Reach averaged mean grain size differences between the different scenarios in the Waal for the downstream aggradation nourishments.

7.5.5 Influence on the Discharge Distribution

The effect of the singular nourishment is presented in Fig. 7.53. Overall, placing the nourishments causes a decrease of discharge towards the Waal. Overall, placing the nourishments causes a decrease of discharge towards the Waal, with the exception of some points at 1,800 m^3/s. This is believed to be an effect of the weirs as they operate in this discharge regime. Over time, the changes in distribution decrease as the height of the nourishment decreases. For the periodic strategies, an inverse behaviour is observed (Appendix C.2). As more sediment is nourished, the change in Waal fraction increases. No major differences are observed when the nourishments are placed on a narrow area. In year 50, the singular nourishment strategy reduces $Q_{1,400}$ by 0.19%. For the periodic strategies this is slightly higher at 0.23% and 0.24% for the regular and narrow placement, respectively.

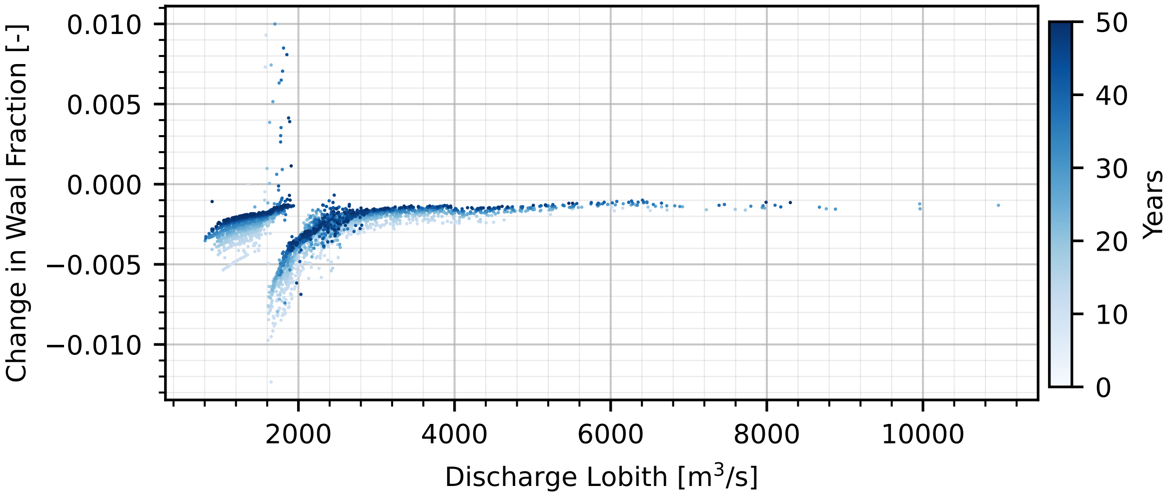


Fig. 7.53 Change in discharge distribution due to the singular nourishment from downstream aggradation relative to the reference scenario.

7.6 Morphological Effects of Nourishment Scenarios

The research question that is answered by this chapter is "*What are the morphological effects of the different nourishment strategies?*"

In the previous sections, the morphological development of the different nourishment strategies were analysed in both space and time. Changes in bed level, geometric mean grain size, and discharge distribution due to the strategies were examined per sediment source. Table 7.1 contains an overview of the morphological effects of the different nourishment strategies.

Table 7.1 Long-term and average morphological effects of the different nourishment strategies. For some parameters, two values are presented: The first value represents the average over the entire simulation. The second represents the value at the end of the simulation, after 50 years. Included are the total applied nourishment volume (V), the relative reach averaged bed level increase ($\Delta z_{b,r}$), the delay in net erosion ($\Delta t_{erosion}$) and the relative change in the reach averaged mean grain size ($\Delta D_{g,r}$). Finally, the changes in $Q_{1,400}$ are listed. All the changes in discharge have a standard error of 1% of the presented change in discharge. For example, the yearly strategy from Area Vision Midden-Waal has an interval of $0.1 \cdot 3.17 = 0.032$. Thus, the value is 3.17 ± 0.032 and ***not*** 3.17 ± 1%.

			Boven-Waal I			**Boven-Waal II**			**Midden-Waal**			**Beneden-Waal**		
ID	**V (Mm^3)**	**N (-)**	**$\Delta z_{b,r}$ (cm)**	**$\Delta t_{erosion}$**	**$\Delta D_{g,r}$ (µm)**	**$\Delta z_{b,r}$ (cm)**	**$\Delta t_{erosion}$**	**$\Delta D_{g,r}$ (µm)**	**$\Delta z_{b,r}$ (cm)**	**$\Delta t_{erosion}$**	**$\Delta D_{g,r}$ (µm)**	**$\Delta z_{b,r}$ (cm)**	**$\Delta D_{g,r}$ (µm)**	**$\Delta Q_{1,400}$ (%)**
1-I AVMW (5-Yearly)	7.5	10	26.5/56.5	6.2 y	-8.8/1.1	43.6/59.9	Prevented[1]	-118.1/-62.7	22.5/45.2	Slight (5.5 y)[2]	-111.0/-172.7	3.7/10.4	-46.1/-110.7	-1.85/-2.99
1-II AVMW (Yearly)	7.5	50	24.6/54.6	5.2 y	-5.8/2.9	42.0/68.6	Prevented[1]	-122.7/-117.9	20.7/43.5	Slight (11.1 y)[2]	-104.2/-171.2	3.3/9.7	-41.7/-105.6	-1.73/-3.17
1-III AVMW (Quarterly)	7.5	200	24.2/54.2	4.7 y	-5.1/3.5	41.6/70.6	Prevented[1]	-123.8/ -132.1	20.4/43.2	Slight (11.8 y)[2]	-102.9/-171.0	3.2/9.6	-40.8/-104.3	-1.75/-3.18
2-I Spijk (Once)	0.75	1	3.7/3.9	6 mo	-3.8/-2.8	5.3/3.7	1.6 y	0.7/4.2	3.5/3.1	1.5 y	-10.2/3.3	1.0/1.1	-15.3/2.1	-0.25/-0.18
2-II Spijk (Periodic)	0.75	10	3.7/3.9	6 mo	-4.0/-2.9	5.3/3.7	1.7 y	0.5/4.2	3.4/3.1	1.5 y	-10.3/3.2	1.0/1.1	-15.3/1.7	-0.25/-0.18
2-II Spijk (Periodic, Narrow)	0.75	10	3.8/3.9	6 mo	-4.2/-2.9	5.5/3.7	1.8 y	2.3/4.2	3.4/3.1	1.5 y	-10.8/3.1	1.0/1.1	-15.5/1.7	-0.26/-0.19
3-I MWC (Once)	0.20	1	1.2/1.3	2 mo	-1.3/-0.9	2.0/1.3	0.6 y	4.9/1.2	1.0/1.1	0.6 y	1.3/2.6	0.1/0.3	-3.3/2.5	-0.084/-0.064
3-II MWC (5-Yearly)	0.20	10	0.7/1.3	1 mo	-0.3/-0.3	1.3/1.8	0.2 y	2.7/7.1	0.6/1.2	0.3 y	-1.1/0.4	0.1/0.2	-2.1/-3.7	-0.047/-0.075
4-I DA (Once)	0.57	1	3.6/3.9	6 mo	-3.6/-2.8	5.2/3.7	1.7 y	-7.8/3.4	3.3/3.4	1.5 y	-9.5/-4.2	0.6/1.1	-3.6/-7.4	-0.24/-0.19
4-II DA (Yearly)	0.57	50	1.8/3.8	2 mo	-0.6/-0.5	3.3/5.9	0.3 y	-9.9/-11.3	1.7/3.7	0.6 y	-5.6/-10.5	0.2/0.6	-1.0/-3.4	-0.13/-0.23
4-III DA (Yearly, Narrow)	0.57	50	1.9/3.9	2 mo	-0.7/-0.6	3.6/6.4	0.3 y	-11.2/-12.3	1.6/3.6	0.6 y	-5.5/-10.4	0.2/0.6	-1.0/-3.4	0.13/-0.24

[1] No erosion occurs throughout the simulation.

[2] Around year 30, net erosion occurs in the Midden-Waal for a while. The value represents the erosion duration.

8 Discussion

This chapter discusses the results obtained from this study. An evaluation of the identified sources and other possibilities is discussed in Section 8.1. The design of the nourishment scenarios is discussed in Section 8.2. Then, Section 8.3 provides a discussion of the effectiveness of the different investigated nourishment strategies. Finally, a discussion of the methods applied and the assumptions made is provided in Section 8.4.

8.1 Supply-Driven Sediment Sources

In this research, four different sources were identified. In reality, sediment can be obtained from many more sources. Therefore, it is of interest to identify other possible sources. As already mentioned, the WFD and PAGW contain projects where sediment becomes available. During such projects, it would be beneficial to track the properties (composition, volume, quality) of the sediment that is extracted from these areas. The development of the soil flow model (Section 5.2) provides a first step in identifying what sediment is actually available. Next to these 'conventional' projects, efforts can also be made to make sediment available. A specific possibility mentioned by Van Vuren (2023) is to close or narrow the openings in the downstream existing longitudinal dams at Wamel. Low water levels are then increased by the narrowing. Then, sediment can be extracted from this riparian channel between rkms 901-911, with a height equal to the low water level setup of the longitudinal dams. Considering a set-up of 15-20 cm, a width of 150 to 200 m and a length of 10 cm, she estimates that this can result in 225,000-400,000 m^3 of sediment.

Another factor to consider in the availability of sediment from supply-driven sources is its current intended use. For example, the sediment of Spijk was used to finance the construction of the overnight mooring facility. If instead it was used to perform nourishments in the Waal, the construction would have become much more expensive (Wieggers, 2023). The sediment from the Maas-Waal Canal was used to fill the scour hole near St. Andries (Reneerkens, 2023). Furthermore, the sediment from Area Vision Midden-Waal will be sold on the open market. In this research, the sediment cost was not incorporated. This may also be one of the main contributing factors in reality on how achievable a nourishment actually is.

8.2 Design of Modelling Scenarios

The design of a nourishment strategy consists of numerous variables such as volume per nourishment, dimensions, grain size distribution, and placement location. In this study, the volume per nourishment was determined by the source. It can, however, be decided whether such a source is used immediately, or distributed over time. This is discussed in the next section. The grain size distribution of a nourishment is also inherent to a source. However, a source can be pre-processed. Some of the sediment sources (Spijk and the Maas-Waal Canal) contained small parts of very coarse material (Appendix B.3). These coarse fractions may result in local armouring, which can result in unwanted morphological effects. It can therefore be desirable to filter out these coarse fractions. Currently, groyne field nourishments are executed in parts of the Waal. To prevent armouring, the sediment that is nourished here is not allowed to contain grains with a diameter larger than 6 mm (Van Leeuwen, 2023).

The nourishment location was kept the same in this research, centred around rkm 879. Therefore, individual nourishments from a temporally spaced strategy were always placed at the same location. It would be possible to change the placement of a nourishment throughout the simulation, based on the effect of previous nourishments. For example, if more sediment is needed upstream or downstream, the nourishment can be placed accordingly. However, this requires the need of using restart files. In earlier studies, this was found to result in faultive behaviour of the model (De Lange, 2022). It may also be of interest to see what would happen if the nourishments were placed even more upstream. In this study it was found that the nourishments from Area Vision Midden-Waal resulted in additional aggradation in the Boven-Waal II, while net erosion still occured in the Boven-Waal I. Placements of nourishments here could prevent erosion in this reach as well. Additionally, as nourishments are placed closer to the bifurcation, their influence on the discharge distribution will increase.

In this study, nourishments were implemented using only the dumping part of the dredge and dump module. Therefore, nourishments based on downstream aggradation could be designed using a predetermined volume and sediment composition. Both the nourished volume and the sediment composition are modelled as constant, which is a simplification. If the downstream dredging is based on the annual sedimentation rate of 1 mm, the amount of sediment dredged will already differ as the width of the river varies with its depth. Furthermore, dredging 1 mm per year along the entire Beneden-Waal is not realistic. A more realistic approach would be, for example, dredging specific parts of the Beneden-Waal up to a specific level with respect to OLR. The sediment composition is not constant either: based on where the dredging occurs (river bed fines when travelling downstream) and at which point in time (river bed coarsens over time), the sediment composition changes. When downstream dredging is implemented, these properties are captured more accurately. However, when implementing nourishments this way, both morphological responses from the nourishment and the dredging occur in the system. Therefore, the effect of the nourishment cannot be isolated anymore.

Sediment from different sources was not combined in a single nourishment strategy. If this were to be modelled, temporal availability should be taken into account: the sediment from one source may not become available at the same point in time as another source. This is also one of the major factors in the soil flow model of Rijkswaterstaat: if sediment cannot be used immediately, it has to be stored somewhere.

8.3 Morphological Effects of the Nourishment Strategies

The four sources identified in this research differed in their available sediment volume and sediment composition. Furthermore, the ways in which they were modelled differed as well. Therefore, it is not possible to provide a direct comparison between all of the different strategies. Instead, properties of the different strategies are discussed throughout this section.

8.3.1 Nourishment Volume and Temporal Spacing

In the scenarios from Area Vision Midden-Waal, a variation in the ratio between the nourishment volume and the temporal spacing was applied. Either 37,500 m^3 was placed quarterly, 150,000 m^3 yearly, or 750,000 m^3 five-yearly.

Since the different strategies used the same nourishment length of 6 km, nourishments had to vary in height. For each individual nourishment, this was 2.4, 9.6, and 47.8 cm, respectively. When a nourishment is placed in the Boven-Waal II, the initial bed level differences are larger for the five-yearly nourishments compared to the quarterly and yearly strategies (Fig. 7.17b). Immediately after nourishing, the height of an individual nourishment decreases (Fig. 7.17b). For the five-yearly scenario, the effect of the nourishment decreases in the first five years and is only increased after 5 years, when a new nourishment is placed. For the quarterly and yearly strategies, the behaviour is similar. However, these nourishments are repeated with a higher frequency. While all strategies show a net increase of the bed level over time in the Boven-Waal II, this increase shows less fluctuations for the quarterly and yearly strategies (Fig. 7.17b).

Increasing the nourishing frequency also increases the amount of times the river bed is disturbed and how frequently ships carrying the sediment have to travel over the river. While yearly nourishment results in a better morphological response, it disrupts the river more frequently but less severely compared to the larger five-yearly nourishments. Since the river also has a function as a habitat for numerous species, these species will underfind hindrance from the execution of nourishments. It is important to prevent too large disruptions or other forms of damage to this habitat when carrying out nourishments (Programma Integraal Riviermanagement, 2023). At this point, it is not certain whether a larger, less frequent nourishment is more damaging than a smaller, more frequent nourishment to this river function. Additionally, the fairway will be hindered more often than a five-yearly nourishment strategy.

8.3.2 Repeated Nourishments and Singular Nourishments

In this research, different scenarios investigated the effect of nourishing a larger volume at once or by splitting this larger volume into smaller repeated nourishments.

In general, placing a larger nourishment results in larger initial effects. An example is generating the backwater curve that causes sedimentation upstream of the nourishment in the Boven-Waal I. For the singular placements, the maximum aggradation is reached earlier for a singular nourishment in comparison to repeated nourishments for the Maas-Waal Canal and downstream aggradation scenarios (Figs. 7.37e and 7.47e). At the end of the simulation however, the different strategies result in similar aggradation in the Boven-Waal I. For the repeated scenario from Spijk, the differences with the singular nourishment are small and only present in the first few years of the simulation (Figs. 7.27e). This is because the strategies only differ in the first two years. It is desired to reach this maximum aggradation in the Boven-Waal I as fast as possible, as it maximises the positive effect on the discharge distribution and countering bed degradation.

Placing a singular nourishment introduces all of the sediment at the beginning of the simulation. Therefore, the bed level in the Boven-Waal II is initially higher. This sediment is than transported downstream. Opposed to the repeated strategies, this gives the river more time to transport the sediment downstream, eventually leading in lower bed levels in the Boven-Waal II for the singular nourishments compared to the repeated strategies (Figs. 7.37f and 7.47f). Initially, this results in higher bed levels in the Midden-Waal for the singular nourishments (Figs. 7.37g and 7.47g). However, at the end of the simulation the bed levels in the Midden-Waal are similar for the singular and periodic strategies (Figs. 7.37g and 7.47g). Furthermore, the singular strategies result in higher bed levels in the Beneden-Waal (Figs. 7.37h and 7.47h). This increases the need for maintenance dredging.

When considering whether to place one larger nourishment or smaller repeated nourishments, the first is deemed more optimal. While a singular nourishment results in a higher need for dredging in the Beneden-Waal compared to the periodic strategies, its morphological effects are maximised earlier during the nourishment strategy.

8.3.3 Nourishment Dimensions

The effect of changing the ratio between the nourishment length and nourishment height was investigated for the scenarios from Spijk and downstream aggradation. Nourishments were placed with a length of 2 or 6 km. For Spijk, the differences are all accumulated in the first two years of the simulation, which do result in a noticeable difference (Fig. 7.28). However, these differences only persist in the first few years. For downstream aggradation, the differences between the placements are negligible (Fig. 7.48).

8.3.4 Nourishment Effects on the Mean Grain Size

In general, the Waal coarsens over time. This varies between 0.1-0.3 mm for the different branches during the entire simulation (Fig. 7.10b). Placing a nourishment influences the grain size distribution of the river bed. As the nourishments in this research consisted of sediment that is finer than the Waal, placement initially caused a decrease in the mean grain size. For the nourishments from Area Vision Midden-Waal and Spijk, the change in mean grain size is of the same order as the natural development. The scenarios from Area Vision Midden-Waal result in a decrease of approximately 0.1 mm in the different branches throughout the simulation (Fig. 7.21). As a negative consequence, this fining may make the bed more erodable. For the nourishments from Spijk, the differences reduce to 0 mm at the end of the simulation (Fig. 7.21). Therefore, the sediment from Spijk does not influence the mean grain size on the long-term. For the scenarios from the Maas-Waal Canal and downstream aggradation, the change in mean grain size is about ten times smaller (0.02 mm), limiting its effect on the mean grain size of the river.

In general, significant changes in the mean grain size are not observed upstream of the Boven-Waal II as sediment that is deposited here does not originate from the nourishments. However, for the nourishments from Area Vision Midden-Waal, large changes (0.5 mm) are observed at the bifurcation point (Fig. 7.19). This is believed to be an artefact of the nodal point relation and not an actual physical process. It is also observed that while initially placing a nourishment causes a decrease in the mean grain size, an increase is observed at a later point in the simulation. This is the case for Spijk and the Maas-Waal Canal (Figs. 7.31 and 7.41). When considering only the mean grain size, it is smaller than the river mean grain size. However, small fractions of very coarse sediment are present in these sources (Table 5.1). When the finer fractions are transported downstream, the coarser remaining fractions increase the mean grain size. As these coarser fractions are eroded less easily, it is possible that erosion pits form downstream of them.

De Lange (2022) executed nourishments that were coarser than the river bed at roughly the same location in the Boven-Waal. After 50 years, this locally resulted in an increase of 0.1 mm for a nourishment of 250,000 m^3. Given its volume, this effect is much larger than the changes in mean grain size observed in this research. A reason for this is that the coarser nourishments erode less and thus remain longer in place, whereas the finer nourishments from this research are eroded much faster.

8.3.5 Nourishment Effects on the Discharge Distribution

As nourishments are placed in the Waal, they affect the discharge distribution at the Pannerdensche Kop. In the reference scenario, $Q_{1,400}$ decreases by 2.7% during the entire simulation (Fig. 7.13). Placing a nourishment always has a positive effect on this discharge distribution, as $Q_{1,400}$ always decreases (Table 7.1). For the scenarios from Area Vision Midden-Waal, the effect of the nourishment on $Q_{1,400}$ is even greater than the reference change of 2.7%. However, it should be taken into account that this model is not calibrated for hydrodynamic calculations. This effect may even be further increased when nourishments are placed further upstream. This was done by Becker (2021), who placed nourishments in the outer bend at rkm 870.

8.3.6 Deciding on an Optimal Strategy

When considering the morphological effects of a nourishment strategy, it can be evaluated both in terms of efficiency and effectiveness. To quantify the efficiency of a nourishment strategy, the obtained average bed level changes from Table 7.1 are normalised by the total nourished volume of the individual strategies (Fig. 8.1a). The effectiveness of a nourishment strategy is expressed by the obtained average bed level changes (Fig. 8.1b).

The singular strategies from downstream aggradation and the Maas-Waal Canal show the highest efficiency. As the scenarios differ in more than one variable (grain size distribution, nourished volume, placement in time), the differences in efficiency cannot directly be attributed to a specific characteristic of the strategy. Nevertheless, the singular strategies have a higher efficiency compared to their periodic counterparts. This suggests that singular nourishments are preferred to smaller repeated ones. As was found by De Lange (2022), a nourishment coarser than the bed showed better morphological results than a riverine nourishment. It could be the case that the grain size distribution from downstream aggradation and the Maas-Waal Canal result in a better morphological response. To confirm this, additional simulations can be performed.

The most efficient strategy in this research is not the most effective strategy. This is the case for the Area Vision Midden-Waal scenarios. This is expected, as these scenarios contain much more sediment than the other scenarios. In general, nourishing more sediment results in better mitigation as the bed level increases more. However, from the normalised mitigation rates, it is found that using more sediment is not an optimal solution on its own. To increase efficiency, a more suitable grain size distribution may be used.

When looking for an optimal strategy, it is desired to nourish large volumes at once. A larger nourishment volume increases the nourishment height, which increases the morphological fluctuations. It may be possible to reduce these morphological fluctuations by placing a longer nourishment instead of a higher nourishment. A guideline for the nourishment height is 35-50 cm (Klijn et al., 2022). Furthermore, the required nourishment volumes can possibly be reduced by using a source with a more suitable grain size distribution. The sediment from the Maas-Waal Canal showed the most promising results, but it is uncertain whether this is still the case when the nourished volume is increased. The second most promising source is downstream aggradation. Therefore, it may be of interest to investigate how sediment from the Beneden-Waal can be extracted in larger quantities, similar to Area Vision Midden-Waal, so that a larger scale strategy can be realised. Furthermore, this sediment does not have to be purchased, since it is already present in the system.

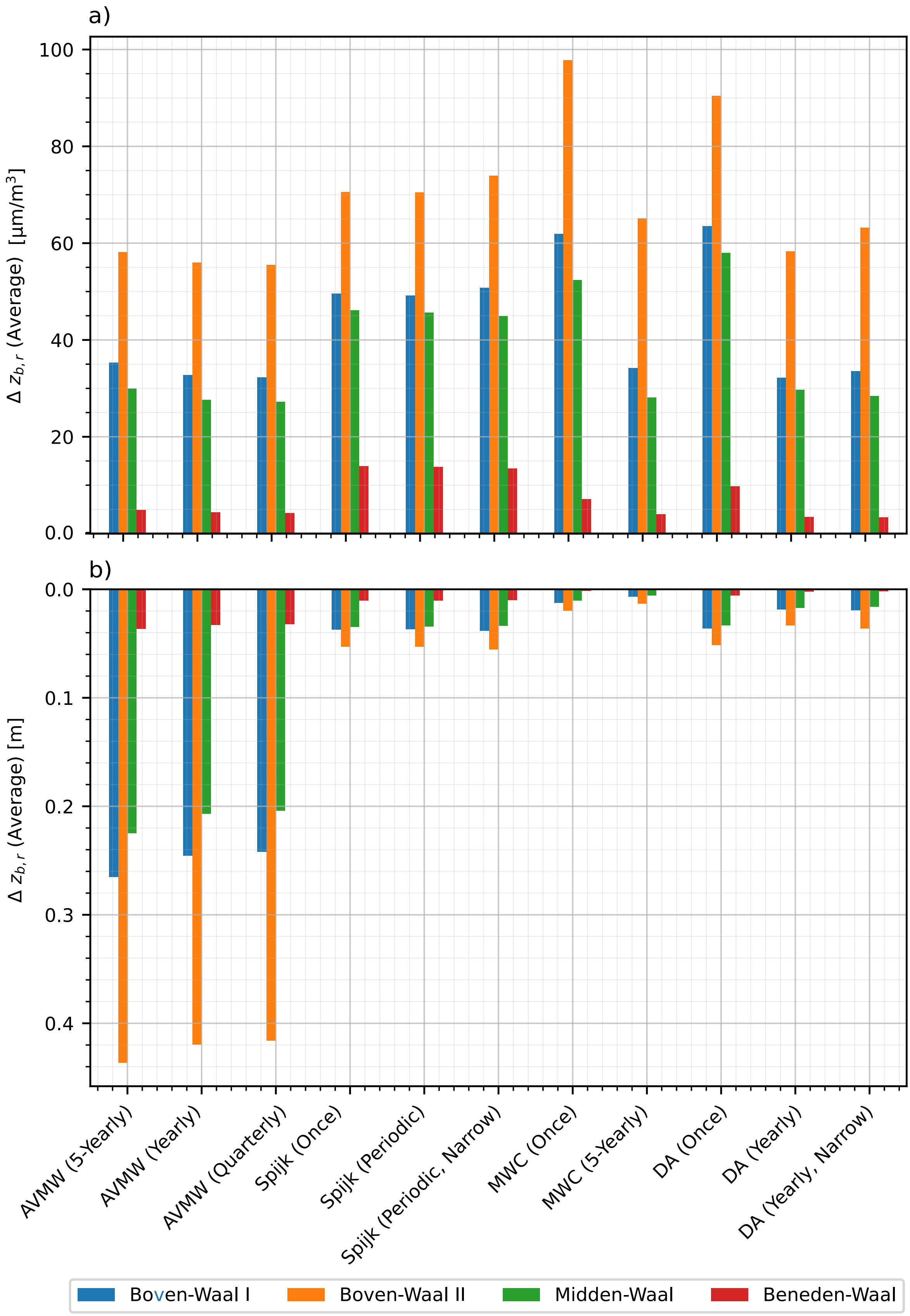


Fig. 8.1 a) Average mitigation rate over 50 years per reach normalised by the total nourished volume per nourishment strategy (Efficiency) and the b) average mitigation per reach (Effectiveness). For the Boven-Waal and Midden-Waal higher values are better. For the Beneden-Waal, lower values are better.

8.4 Reflection on the Used Model and Methods

8.4.1 Sediment Transport and Morphology

The 1D Rhine branches model uses two different sediment transport formulas for sand and gravel. In the formula for sand from Engelund and Hansen (1967), hiding-exposure effects are not considered. On the contrary, the formula for gravel of Meyer-Peter and Müller (1948) incorporates hiding-exposure effects by adjusting the critical bed shear stress. Consequently, sand particles affect the mobility of gravel, while gravel particles do not significantly affect the mobility of sand (Chavarrías et al., 2020). In reality, both sand and gravel influence each other. The hiding-exposure relation that is currently incorporated in the model is that of Ashida and Michiue (1972). This relation was chosen as it is completely on or completely off and thus cannot be partially active (Chavarrías, 2023). There are other hiding-exposure relations, which can be partially active by defining a coefficient between 0 and 1 that determines the 'strength' of the relation. Chavarrías (2023) mentions that a hiding-exposure relation that can be partially activated introduces an additional calibration parameter, which adds additional complexity during model calibration. Therefore, the relation of Ashida and Michiue (1972) was implemented, since it excludes such an additional coefficient. It can be interesting to see how hiding-exposure relations with a coefficient influence the morphological behaviour. A suggestion mentioned by the creators of the model is the relation of Parker et al. (1982), where an initial coefficient of 0.5 is applied (Chavarrías, 2023).

Using two different sediment transport formulas for sand and gravel impacts the model results. When a nourishment consists of both sand and gravel fractions, the difference in its behaviour can be attributed not only to the variation in grain size but also to the different sediment transport formulas. However, there is no single sediment transport formula that accurately predicts sediment transport for all grain sizes (Gomez and Church, 1989). Therefore, a formula must be chosen and calibrated to represent real-world behaviour. When results are analysed, the potential effects of using separate equations should be kept in mind. During this research, it was repeatedly observed that the effect of the nourishment appeared to split into two separate 'humps'. To gain a better understanding of the usage of separate transport formulas, it may be interesting to explore the development of a nourishment consisting of all sediment fractions and track how the sand and gravel fractions progress.

Due to the 1D nature of the model, 2D effects that occur in reality are not captured. In this study, only the main channel morphology is included. In reality, spiral flow and sorting effects have a great influence on flow, which causes the inner and outer bends of a river to develop differently (Clayton, 2010). As the nourishments are all placed in the Boven-Waal, which is characterised by four successive river bends, this can significantly influence the nourishment. Furthermore, these effects also influence how sediment is divided at a bifurcation such as the Pannerdensche Kop (Kästner and Hoitink, 2019).

The 1D Rhine branches model incorporates the active layer concept of Hirano (1971). This concept can only reproduce the behaviour of armour layers to a certain extent. De Lange (2022) also emphasises this, as she used nourishments that were coarser than the river bed. Such a nourishment would shelter the underlying river bed. The nourishments investigated in this research were composed of sediment that was finer than the river bed. In that case, it could be possible that the finer sediment makes the river bed more mobile, so that erosion is actually enhanced as the gravel particles are more exposed to the flow (Czapiga et al., 2022; Miwa and Parker, 2017). How this behaviour is captured in the model, depends on the hiding-exposure relations used.

The active layer thickness has an important impact with respect to the celerity at which changes in the grain size distribution propagate (Chavarrías et al., 2020). A smaller active layer results in faster changes in its grain size distribution. Analogously, a larger active layer results in slower changes in its grain size distribution. When the sediment distribution becomes more uniform, the thickness of the active layer becomes less significant. However, when a fine nourishment is added, the sediment distribution locally becomes less uniform and the active layer thickness becomes more influential. Chavarrías et al. (2020) investigated the effect of halfing (0.5 m) and doubling (2.0 m) the active layer during a 15-year morphological simulation. They found that for all thicknesses, the results are within an acceptable band (Chavarrías et al., 2020). It may be interesting to investigate how changing the active layer thickness influences the modelled effect of nourishments on longer-term calculations, as opposed to the investigated 15 years. However, it should be noted that for such a period, no measured data is available (yet).

8.4.2 Morphological Spin-Up Time

In this study, the spin-up conditions defined by De Lange (2022) were implemented. During the first 7 days of the simulation, changes in the bed level or bed composition are disabled. This spin-up time is based on the time it takes for the model to fill up with water, as it starts empty.

It may be beneficial to adjust the spin-up properties of the model, as strong initial reactions of the model are observed. For example, the model calculates an average aggradation of 20 cm in the Boven-Rijn in the first 2 years. This seems to be a deviation from what is realistic. First, because in reality the bed is eroding, and second, because the rate at which this occurs is much higher than the current trends of a few cm/year. This goes paired with a very strong coarsening in the Rhein and Boven-Rijn. A possible explanation for these strong reactions is the implementation of bathymetries from different years for the Rhein (2012) and Dutch Rhine branches (2019). Additionally, the sediment composition from 1995 is used. The usage of an older sediment composition means that a finer river bed is implemented, as the Rhine coarsens over time (Ylla Arbós et al., 2019). As a heavy coarsening is observed in the Rhein in the first few years of the simulation, it may be of interest to change the spin-up conditions. A possibility could be to only allow changes in the grain size distribution for 17 or 24 years, such that the composition of the bed would be more compatible with the applied bathymetries. These years represent the differences between the measurement of the grain sizes (1995) and the bathymetries (2012 and 2019) used in the model.

8.4.3 Distributions at Bifurcations

The discharge is distributed according to the conservation equations of momentum and mass (Appendix A.1.1). This distribution plays a crucial role when modelling morphodynamics. Although the model has undergone extensive calibration, it is crucial to acknowledge the constraints of the data used for calibration (Chavarrías et al., 2020). It is expected that between 2010 and 2020, the discharge distribution has changed due to conducted river interventions (Chavarrías et al., 2020). At the same time, Qh relations have not been updated (Chavarrías et al., 2020). Therefore, uncertanties in the actual discharge distribution may persist.

The distribution of sediment in a bifurcation is modelled by the nodal-point relation (Appendix A.1.3). This relation is calibrated for the sand and gravel fractions individually, based on sediment transport loads estimated by Frings et al. (2019). Chavarrías et al. (2020) point out that, due to the computational time, they were unable to explore a wide range of calibration factors, and that further adjustments may reduce the discrepancy between the modelled sediment transport loads and the loads estimated by Frings et al. (2019). However, the modelled values are acceptable, especially when taking into account the variability in the data from Frings et al. (2019). Next to this uncertainty in the calibration, the nodal-point relation forms a highly simplified representation of reality. Presently, reducing this uncertainty is challenging due to the significant uncertainty associated with nodal-point relationships, coupled with the limited and uncertain field data available for calibration (Ylla Arbós et al., 2023).

8.4.4 Implementation of Nourishments

Placement of Nourishments
In this study, nourishments are implemented using the dredgde and dump module. By using this module, nourishments are placed immediately on the bed. In reality, a nourishment would be executed by a ship that dumps sediment from the top of a river. When this happens, a part of the sediment will be transported downstream under the influence of the flow. Therefore, the aggradation close to the nourishment location may be overestimated and underestimated further downstream.

Nourishment Rate
For simplicity, every (separate) nourishment was executed with a duration of one day. In this research, single nourishments varied between 20,000 and 750,000 m^3, which is a factor of 37.5 difference. Since the nourishment time was kept equal, the nourishment rate differed. In reality, the nourishment rate is limited by the capacity of the vessels that carry the sediment. Therefore, the nourishment rates applied in this research may be higher than actually feasible. This means that in reality, the nourishments would take more than one day to realise. However, it is expected that on the timescale of this research these differences would only be visible close to the nourishing moment. Nevertheless, these differences may accumulate so that a significant difference persists when performing repeated nourishments.

Nourishment Height and Length
In this research, the thinnest nourishment (ID 4-II) has a height of 0.73 cm. In reality, this height is not achievable. As mentioned above, the sediment would be transported downstream when nourished by a ship. For such a small nourishment height, it could be possible that none of the sediment settles at the intended nourishment location. A logical step to prevent this limited height is to decrease the nourishment length. Currently, nourishment 4-II has a length of 6 cm. If this length is reduced to 125 m, its height becomes 35 cm. However, due to the coarse grid size (500 m), this is not possible. Additionally, when the nourishment is composed of too little grid cells, numerical diffusion will become more apparent. Chavarrías (2023) estimates that a length of five cells introduces an error of at least 10% in the calculated morphological effects. Therefore, it is not recommended to use this model to simulate smaller volumes. As these smaller volumes are not that effective in preventing large-scale erosion, a better possibility would be to model their effect on a smaller scale. This could be, for example, filling in erosion holes or eroded bends.

Exclusion of System Changes
All sediment sources considered in this research are in some way connected to the Waal. Therefore, the extraction of these sources has an impact on the system. The sediment extracted at Spijk causes a local widening, which is not included in the model. However, these changes in flow conditions are expected to be only local and will thus not have a major influence on the rest of the system. Additionally, in the 1D Rhine branches model the floodplains are not erodable. Therefore, they cannot be a source of sediment. The same arguments hold for the extractions performed at Area Vision Midden-Waal. However, the amount of sediment that is extracted here is much larger. While still local, its effect is expected to be greater. The third sediment source originates from the Maas-Waal Canal. Given its relatively small volume (20,000 m^3) and its distance from the Waal, it is expected that its extraction does not significantly influence the Waal. While the Maas-Waal

Canal is connected to the Waal in reality, it is not included in the model since lateral flows are ignored. Therefore, sediment extraction from this canal cannot be included in the model. What could be included in the 1D model is the downstrem dredging for the downstream aggradation nourishments. Currently, the nourishments are added as additional sediment by only nourishing. Using the dredge and dump module, it is possible to designate a dredging area downstream, which can be used as actual source of sediment. If this is done, no additional sediment is added. Using this method, a cycle of dredging and nourishing can be applied. An added benefit from using this method is that the sediment composition is actually the sediment composition that is present downstream, rather than an average.

8.4.5 Exclusion of Anthropogenic Factors

The Waal is heavily modified by human works. However, not all these factors were included in the model. An example is the maintenance dredging that is performed throughout the year. In 2022, 837,156 m^3 of sediment was moved between Lobith and Gorinchem in the shipping channel to maintain a navigable depth (Heijmans, 2022). This sediment is redistributed in deeper parts of the river by ploughs or suction hoppers. Another form of dredging that still occurs is the extraction of sediment from the river for commercial use. This sediment is not redistributed into the system and thus results in a net extraction (Programma Integraal Riviermanagement, 2021). This is estimated to be 5,000 m^3/year up until 2025 (Ylla Arbós et al., 2023).

The Waal is one of the busiest rivers in Europe. In 2022, more than 120,000 ships passed its busiest section (Eusterbrock, 2023). Through the turbulence induced by the propellers of these ships, sediment can become entrained by the flow. Especially at low discharges, this may have a significant effect as ships are closer to the river bed. This is also considered one of the components responsible for the differences between measured and modelled behaviour of the nourishment in the Boven-Rijn (Niesten and Becker, 2018). It should be noted that this effect is highly local and occurs on a scale much smaller than the spatial resolution of the model, and can therefore not (directly) be implemented.

Finally, no future training works or changes in operational policies are included in the model. As was seen in the RftR projects, large training works were executed to regulate the flow. It is very plausible that future training works will be implemented within the modelled period. However, since they are not known yet, they cannot be implemented. Another possibility of change is that Rijkswaterstaat changes their policies on managing the weirs. For example, it could be possible that they will be managed based on a discharge, rather than a water level (Programma Integraal Riviermanagement, 2021).

8.4.6 Boundary Conditions

Upstream Hydrograph

In this research, the boundary conditions of De Lange (2022) were applied. The upstream boundary conditions were designed using bootstrap resampling of historical hydrological years. This means that the applied hydrograph does not contain periodicity, which can be interpreted as random behaviour. This variability in the hydrograph adds an additional layer of complexity to the analysis of the morphological development. When a cycled hydrograph is applied, such noise can be reduced. This approach was followed by Ylla Arbós et al. (2023). Furthermore, she adjusted the cycled hydrographs for different climate scenarios by the KNMI and IPCC. Another possibility is to use a hydrograph consisting of a series of constant discharges based on the average annual discharge hydrograph of the Rhine. This approach was used by Ottevanger et al. (2015) and Becker (2021). Using such repeated hydrographs allows for a quantitative comparison of the influence of the nourishments on the discharge distribution at the Pannerdensche Kop.

Upstream Sediment Influx

The influx of sediment is governed using a ghost cell which has a fixed bed level and sediment composition. Therefore, the sediment influx is governed by the upstream boundary flow conditions. In reality, German management of the Rhein also influences what happens upstream. The combined effect of bed degradation and coarse nourishments cause changes in this upstream boundary. Ylla Arbós et al. (2023) investigated the effect of the upstream sediment influx by considering different scenarios. They used the lower and upper bounds of the uncertainty range from sediment fluxes found by Frings et al. (2014) to define different scenarios. The model they used, only considered five grain sizes. Therefore, it may be of interest to apply similar changes in the upstream sediment influx in the 1D Rhine branches model to see how these upstream changes behave in a more sophisticated model.

Downstream Boundaries

At the downstream boundaries, a Qh-relation was applied. In the Beneden-Waal, there is a sedimentation of 2 m in a span of 50 years. As the downstream boundary is characterised by a specific water level, not the water depth, an increase in the bed level results in a reduction in water depth as time goes on. This leads to the fact that an equal volume of water needs to traverse through a narrower passage, causing the water's speed to increase. The increased flow velocity contributes to erosion. Consequently, it is possible that sedimentation at the downstream edge is underestimated due to the chosen downstream boundary conditions.

9 Conclusions and Recommendations

This chapter gives an answer to the main research question posed in this research in Section 9.1. Additionally, Section 9.2 offers suggestions for further research on the application of sediment nourishments to mitigate bed degradation.

9.1 Conclusions

This study seeks to determine the morphological effects of nourishment strategies that are based on supply-driven sediment strategies in the Waal, and to demonstrate how these nourishments can be used to mitigate bed degradation. To do this, different sources of sediment are identified. Based on the characteristics of these sources, nourishment strategies are developed and 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, the main research question can be answered:

What is the optimal nourishment strategy to mitigate bed degradation in the Waal based on sediment availability in nearby sources?

Natural development of a river results in the coarsening of the river bed over time. For the Waal, the geometric mean grain size increases between 0.1 and 0.3 mm after 50 years. Placement of nourishments influences this geometric mean grain size. As the average composition of all of the sources is finer than the river bed, placement of a nourishment results in a fining of the bed. This makes the river bed more erodable. For the largest source, Area Vision Midden-Waal, this results in a decrease of about 0.1 mm after 50 years. For the smaller sources, this change is a factor 10 to 100 smaller. While the geometric mean grain size of the nourishments are smaller than that of the river bed, small fractions of very coarse sediment can be present in a nourishment. The presence of these coarser fractions can possibly result in local armouring. While not observed in this study, it is possible that coarse patches cause erosion pits downstream of them.

The nourishments from different sources are modelled to investigate their efficacy in mitigating bed degradation. Comparing the various strategies is challenging, as they differ in several aspects. This makes it difficult to identify a single best strategy. However, when considering an equal nourishment volume, it is found that a singular, larger nourishment is preferred to repeated, smaller nourishments when possible. Both strategies result in similar aggradation upstream of the nourishment at the end of a simulation, but for the singular nourishment the maximum bed level change is reached faster. This earlier maximum sedimentation also maximises the positive effect on the discharge distribution at the Pannerdensche Kop. On the long-term, placing a singular nourishment causes more sediment to reach the already aggrading part of the Waal, resulting in an increased need for maintenance dredging.

Singular nourishments delay bed erosion, but do not completely prevent it. As they will eventually erode, repeated nourishments are necessary to maintain the bed. Among others, this research includes three different scenarios (Area Vision Midden-Waal) in which the ratio between nourishment frequency and nourishment volume is varied. From an ecological point of view, it may be desired to nourish as few times as possible, as this causes less disruption to the ecological systems within a river. For the investigated Area Vision Midden-Waal nourishments the placement length is kept the same, so the nourishment heights have to increase for larger volumes. This results in a stronger initial morphological reaction for larger nourishments, causing higher fluctuations in bed levels. For the smaller nourishments with a higher nourishment frequency, this fluctuation is less severe. For the investigated Area Vision Midden-Waal scenarios, a yearly nourishment scenario seems the best trade-off between morphological results and disruptions due to the nourishment itself. As nourishments only counter symptoms of bed erosion, infrastructural changes are needed to prevent erosion.

Although the scenarios from Area Vision Midden-Waal are the most effective, they are not the most efficient. This is the case for the singular nourishment from the Maas-Waal Canal, followed by the singular nourishment from downstream aggradation. These higher efficiencies cannot directly be coupled to a specific property of the different nourishment strategies due to the differences in multiple strategy aspects. A possible explanation is that the grain size distributions of the Maas-Waal Canal and downstream aggradation are more favourable. If this is the case, the amount of sediment needed to mitigate bed degradation may be reduced when a suitable source or grain size distribution is chosen.

9.2 Recommendations

This study demonstrated that sediment nourishments are able to mitigate bed degradation in the Waal. To better understand sediment nourishments and to increase knowledge about them, various recommendations are made for further research.

The nourishments in this research were modelled using the average grain size distributions of the respective sources. It is recommended to investigate which possibilities are available to adjust the grain size distributions of the sources. An example is filtering out the coarser fractions, such that the nourishment has an upper grain size limit. For example, the grains in the Waal groyne field nourishments have an upper limit of 6 mm (Van Leeuwen, 2023). Another possibility is to tweak the ratio of the three different products from the Area Vision Midden-Waal nourishments to improve the morphological results. As these different products have different prices, different ratios will result in different costs. This is a factor that can also be included in further research.

In this research, nourishments from downstream aggradation were designed based on the average sediment composition from the aggrading part of the river. This composition was then added to the system, so no dredging was modelled. When using the dredging module, actual dredging can be implemented. Furthermore, this can be combined with dredging the additional sedimentation that occurs in the Beneden-Waal due to the implementations of nourishments upstream.

The behaviour of a nourishment is affected by the applied boundary conditions. In this model, this includes the upstream hydrograph and the downstream Qh-relations. The hydrograph from this research is based on historic hydrological years. As the climate changes, summers get dryer and winters get wetter. Furthermore, the sea level rises. This can be included in the model by adjusting the boundary conditions accordingly. It is recommended to use an approach similar to the one applied by Ylla Arbós et al. (2023) as a starting point. Furthermore, the influence of the upstream sediment influx can be investigated by adjusting the influx. A recommended approach is to use the upper and lower bounds of the uncertainty range of Frings et al. (2014) in scenarios for the upstream sediment influx. This approach is also applied by Ylla Arbós et al. (2023).

The IRM programme focusses on two policy options regarding the current bed level: fixating the current bed level and to prevent further skewing of the low water discharge distribution. As the model used in this study has not been calibrated for hydrodynamic calculations, it contains uncertainties in determining the effect of sediment nourishments on the discharge distribution. It is recommended to investigate these hydrodynamic properties in a suitable model, such as SOBEK.

Nourishments alone will not solve the erosion problem in the Waal. For this, infrastructural changes are needed. Research has already been done on the effects on training dams and side channels. However, there is still much to learn about the combined effects of infrastructural changes and sediment nourishments. As infrastructural changes tackle the cause of erosion, they decrease the amount of sediment needed in the form of nourishments. Therefore, it is recommended to research the combined effects of these river interventions.

Finally, using a 1D model oversimplifies the morphological behaviour of a river system. In reality, there are differences in bed level along the width of a river cross section. For example, this can be an eroded bend or the presence of an erosion hole. Furthermore, effects such as spiral flow and sorting are very important in the development of a river. As the Boven-Waal is characterised by four successive bends, these effects do influence the morphological behaviour here. To get a better representation of reality, nourishments can be modelled using a 2D model when going to an actual design phase.

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A Model Definition and Input

A.1 Model Equations

A.1.1 1D Shallow Water Equations

The water flow is determined by solving the one-dimensional shallow water equations, which include the continuity equation (Eq. 2) and the momentum equation (Eq. 3).

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

Here, 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).

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

A.1.2 Sediment Transport Formulas

The sediment transport of the sand fractions is modelled based on the relation by Engelund and Hansen (1967), which is presented in Eq. 4. This information was taken from Chavarrías et al. (2020).

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

Here, $q^*_{\mathrm{b}k}$ is the nondimensional sediment transport rate (-) as determined by Eq. 5; α is a calibration parameter (-), of which the values are shown in Table A.1; C_f is the non-dimensional friction coefficient (-) determined by Eq. 6; and θ_k is the Shield stress on size fraction k (-) as determined by Eq. 7.

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

Here, $q_{\mathrm{b}k}$ 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); Δ is the submerged specific density (= 1.65) (-); and d_k is the characteristic grain size of size fraction k (m).

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

Here, n is the Manning friction coefficient (s/m$^{1/3}$) and R_h is the hydraulic radius (m).

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

Here, τ_b is the bed shear stress (N/m^2) as defined by Eq. 8.

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

Here, S_f is the friction slope (-) defined by Eq. 9.

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

Here, u is the main channel velocity (m/s).

---

*Note that this h is not the same as the one in the Qh relations defined by Paarlberg and Van Lente (2021).

Table A.1 Values of calibration parameter α (-) of the sediment transport relation by Engelund and Hansen (1967) (Eq. 4) for each branch and sediment type (Chavarrías et al., 2020).

Branch	α_{sand}	α_{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 of Meyer-Peter and Müller (1948), given in Eq. 10.

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

Here, $q^*_{\mathrm{b}k}$ is the nondimensional sediment transport rate (-) as determined by Eq. 5; α is a calibration parameter (-); A is an equation specific parameter (= 8) (-); θ_k is the Shield stress on size fraction k (-) as determined by Eq. 7; ξ_k is the hiding-exposure relation (-) by Ashida and Michiue (1971) as defined in Eq. 11; θ_c is the critical bed shear stress (= 0.025) (-); and B is another equation specific parameter (= 3/2) (-).

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

Here, d_k is the characteristic grain size of size fraction k (m); and D_m is the arithmetic mean grain size (m).

A.1.3 Nodal-Point Relation

The sediment discharge distribution at the bifurcation points is determined by the nodal-point relationship defined by Sloff (2006), which is expressed in Eq. 12 (Chavarrías et al., 2020). The calibration parameter is distinct for each bifurcation point and sediment type (Chavarrías et al., 2020), and is determined using measurements by Frings et al. (2019).

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

Here, $Q_{\mathrm{b}kj}$ is the sediment transport rate of the 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 β_k is a calibration parameter (-), as defined in Table A.2.

Table A.2 Calibration parameter β (-) of the nodal-point relation by Sloff (2006) (Eq. 12) (Chavarrías et al., 2020).

Bifurcation	**Outgoing Branch 1**	**Outgoing Branch 2**	β_{sand}	β_{gravel}
Pannerdensche Kop	Waal	Pannerdensch Kanaal	1.79	1.79
IJsselkop	Neder-Rijn	IJssel	1.35	0.99

B Schematisation of Nourishments

B.1 Sediment Properties Mooring Facility Spijk

Wezendonk constructed seven different products from the sediment extracted at the mooring facility Spijk. Fig. B.1 displays the grain size distribution of the products. The numbers behind the product names refer to the grain size range of the mixture. Fig. B.2 shows the volumes of the products. Approximately 2.3 Mm^3 was extracted in Spijk. Of this volume, information is available from 750,000 m^3. The three finest products, *kwartszand (0-4)*, *terugloopzand* and *drainzand*, make up almost 85% of the total volume.

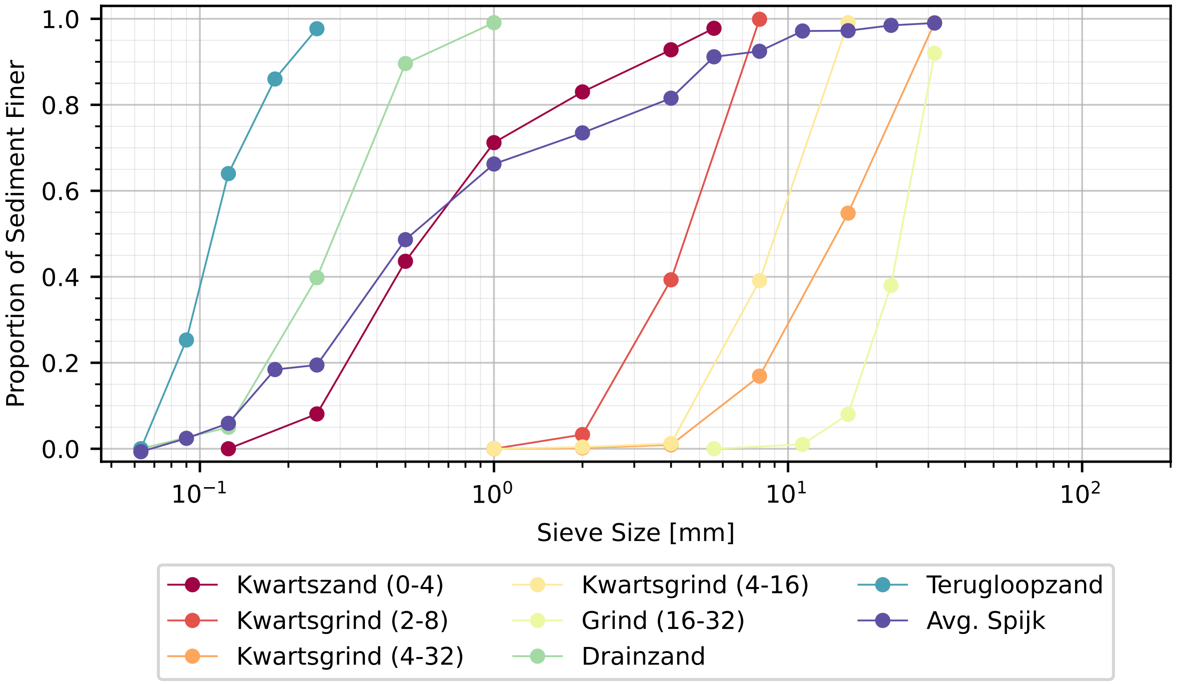

Fig. B.1 Grain size distribution of the different products made from the sediment at Spijk.

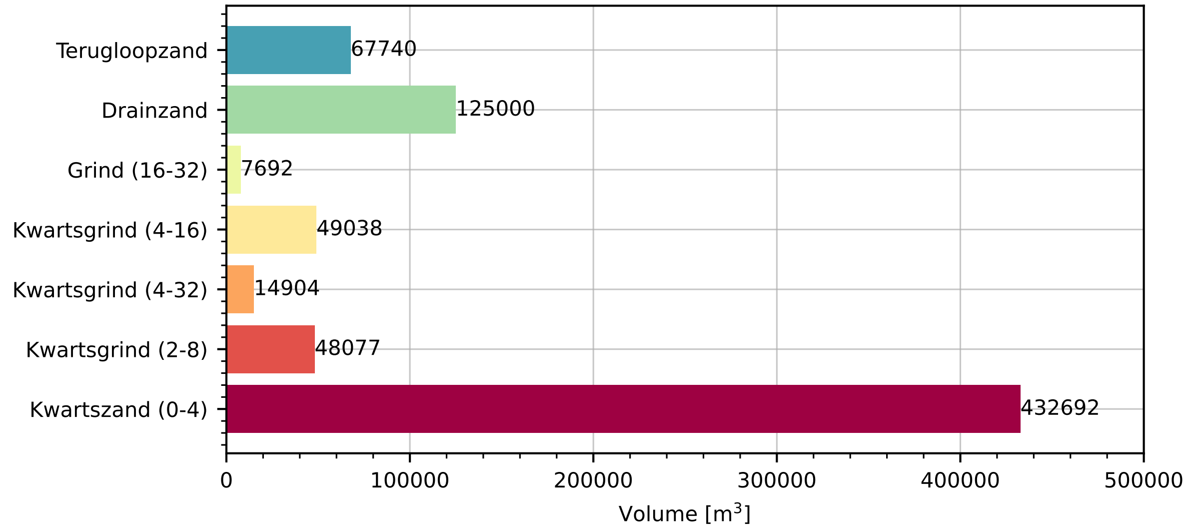

Fig. B.2 Extracted volumes of the different products made from the sediment at Spijk.

B.2 Sediment Properties Area Vision Midden-Waal

Dekker Groep is able to create three different products with different grain size distributions: *fijnzand* (0-0.5 mm), *grofzand* (0.5-2 mm), and *kif* (2-8 mm). Based on information from a previous project close to Area Vision Midden-Waal, Dekker Groep estimates that the sediment composition has a 64-28-8 ratio of these products. The individual grain size distributions are presented in Fig. B.3.

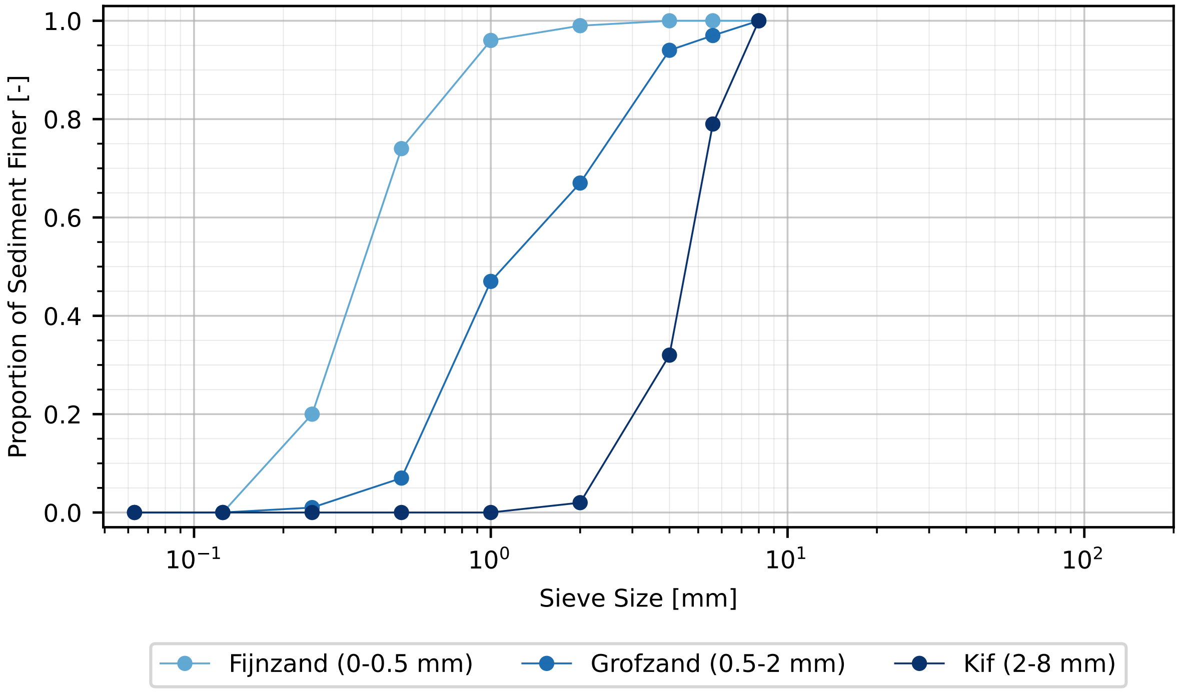

Fig. B.3 Grain size distribution of the different products made from the sediment at Area Vision Midden-Waal.

B.3 Modelled Sediment Fractions

Table B.1 contains the percentages belonging to the sediment fractions incorporated in the model for the different nourishment sources. For every source, the total is equal to exactly 100.0 percent.

Table B.1 Modelled sediment fractions of the different sources.

MWC				**AVMW**				**DA**				**Spijk**			
#	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%
1	0	**9**	4.92	**1**	0	**9**	6.49	**1**	0	**9**	9.94	**1**	0	**9**	6.71
2	4.2	**10**	2.97	**2**	0	**10**	5.19	**2**	0.04	**10**	6.47	**2**	9.43	**10**	4.83
3	5.82	**11**	4.95	**3**	2.62	**11**	8.11	**3**	0.25	**11**	7.39	**3**	7.45	**11**	4.64
4	9.83	**12**	7.68	**4**	6.49	**12**	2.46	**4**	2.43	**12**	4.26	**4**	14.25	**12**	4.81
5	11.52	**13**	6.14	**5**	10.93	**13**	0	**5**	8.34	**13**	0	**5**	19.68	**13**	1.83
6	14.09	**14**	1.6	**6**	17.83	**14**	0	**6**	16.13	**14**	0	**6**	8.88	**14**	0.98
7	15.09	**15**	0	**7**	21.92	**15**	0	**7**	25.26	**15**	0	**7**	8.77	**15**	0
8	11.19	**16**	0	**8**	17.96	**16**	0	**8**	19.49	**16**	0	**8**	7.74	**16**	0

C Changes in Discharge Distribution

C.1 Area Vision Midden-Waal

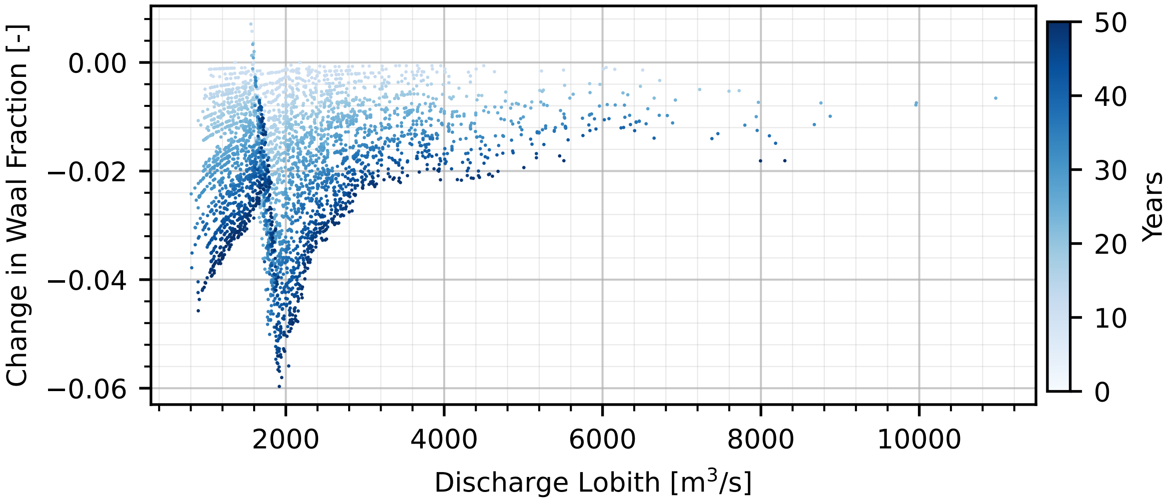

Fig. C.1 Change in discharge distribution due to the yearly nourishment from Area Vision Midden-Waal relative to the reference scenario.

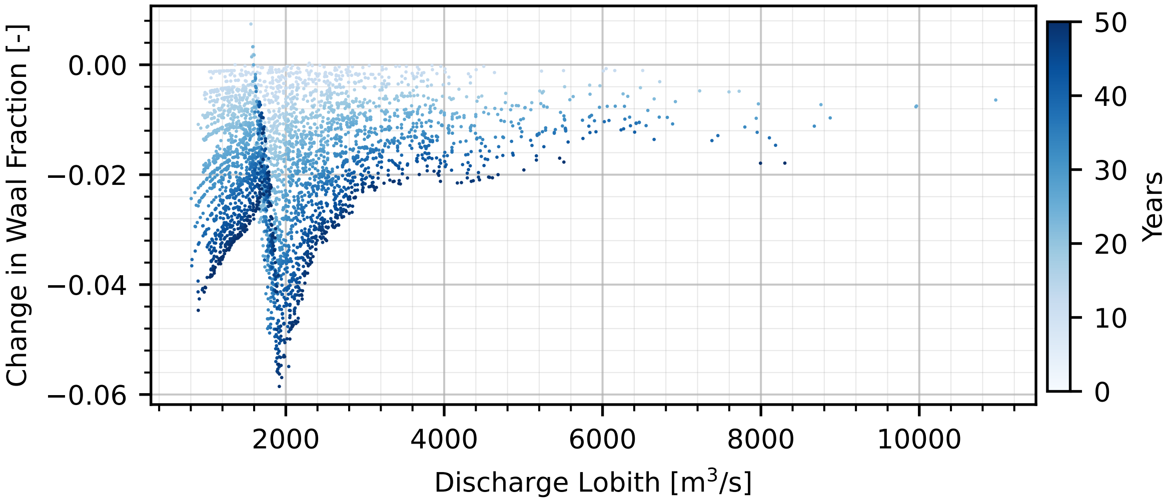

Fig. C.2 Change in discharge distribution due to the quarterly nourishment from Area Vision Midden-Waal relative to the reference scenario.

C.2 Downstream Aggradation

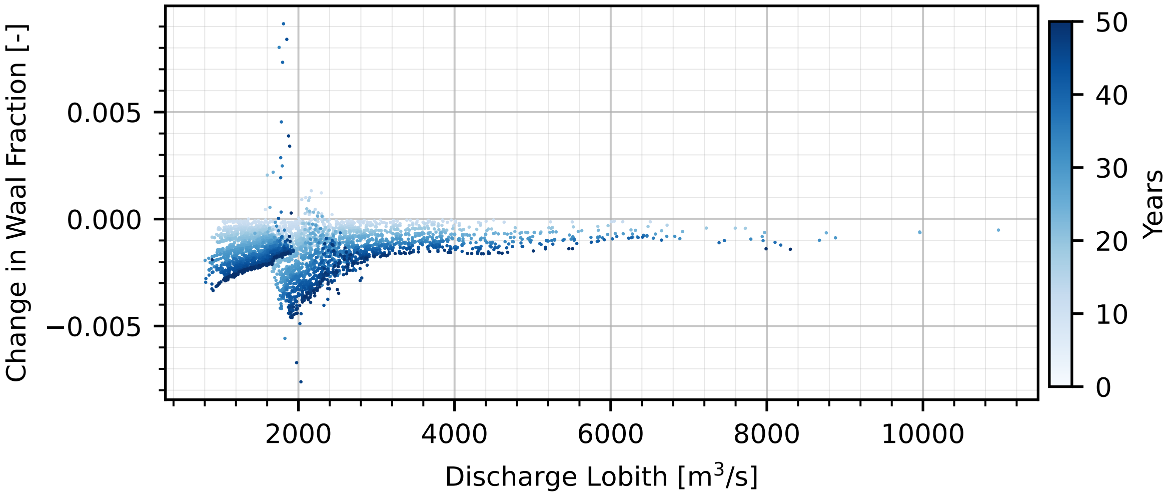

Fig. C.3 Change in discharge distribution due to the yearly, narrow nourishment from downstream aggradation relative to the reference scenario.

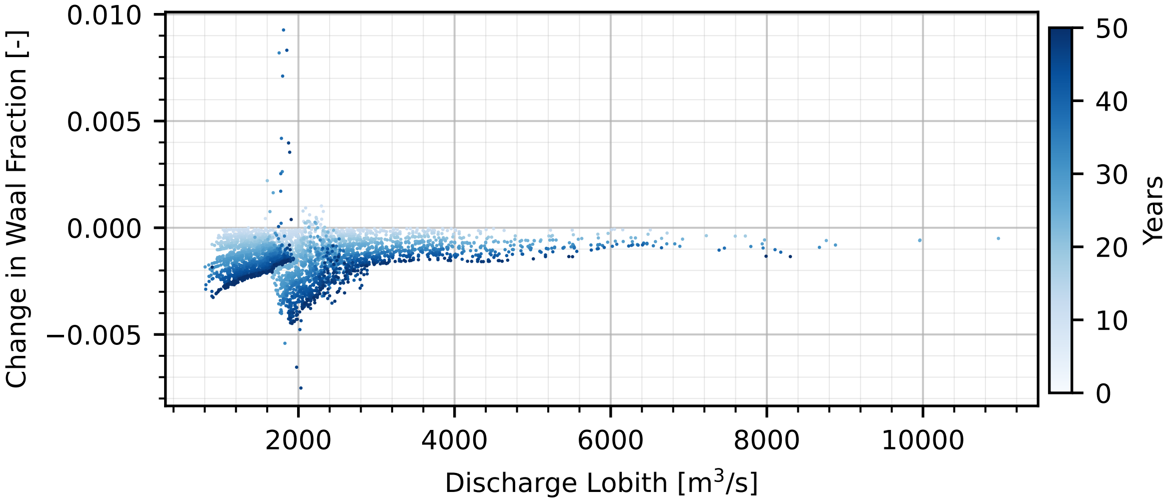

Fig. C.4 Change in discharge distribution due to the yearly nourishment from downstream aggradation relative to the reference scenario.

C.3 Spijk

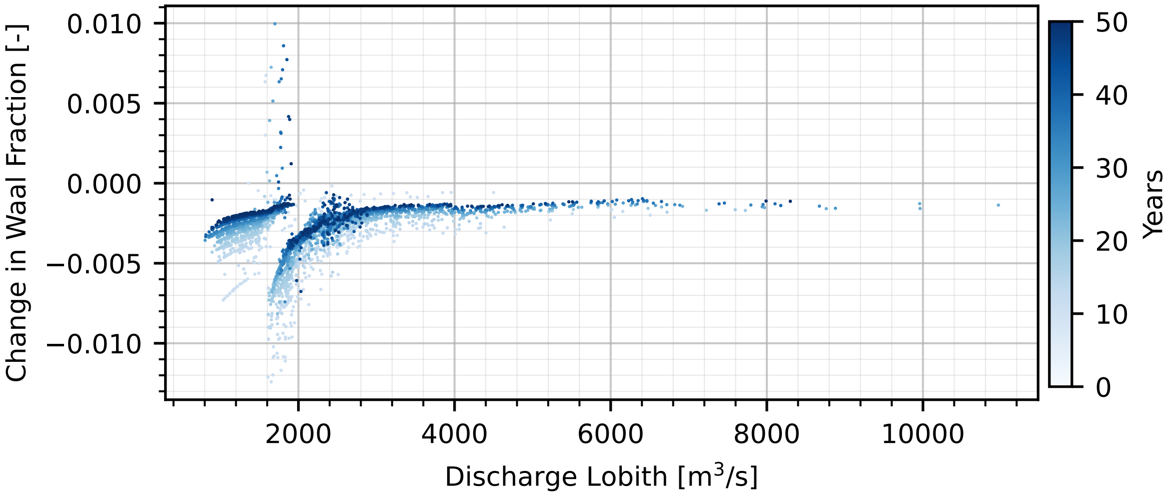

Fig. C.5 Change in discharge distribution due to the repeated nourishment from Spijk relative to the reference scenario.

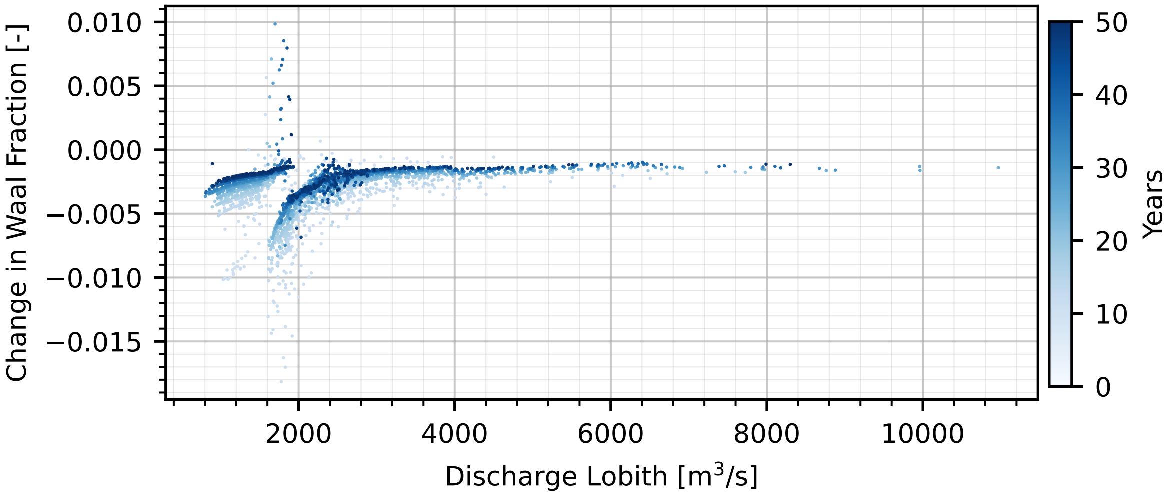

Fig. C.6 Change in discharge distribution due to the repeated, narrow nourishment from Spijk relative to the reference scenario.

C.4 Maas-Waal Canal

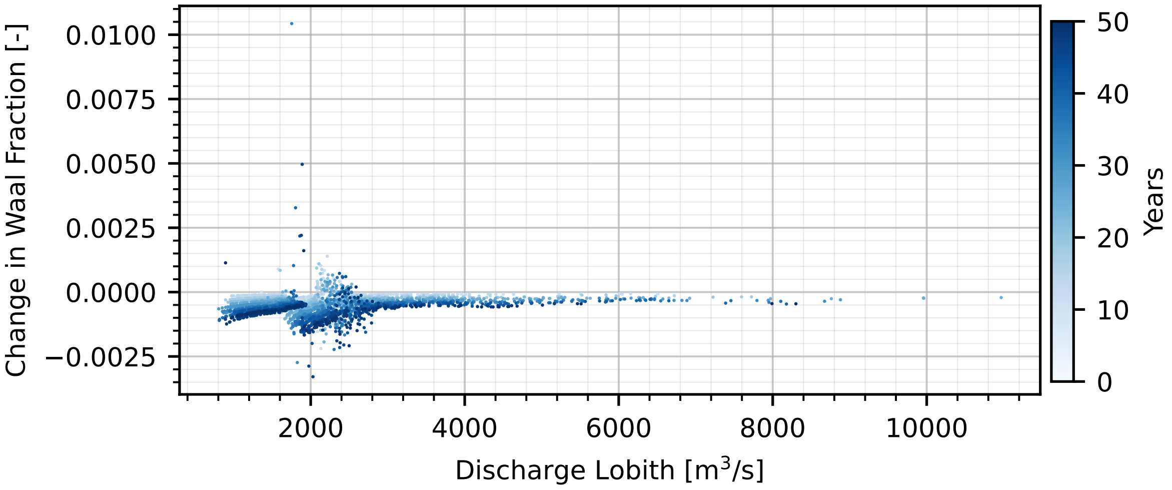

Fig. C.7 Change in discharge distribution due to the five-yearly nourishment from the Maas-Waal Canal relative to the reference scenario.