Delft University of Technology

The morphological response to peak flows at the Pannerdense Kop

Master Thesis

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TU Delft

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The morphological response to peak flows at the Pannerdense Kop

by

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Preface

This thesis marks the end of my period as masters student Civil Engineering at the TU Delft. Ever since I entered the faculty as a bachelors student, I have felt in place in a field where mathematics come together with things that can be observed in the everyday life. Capturing the flow of water has especially fascinated me, which led me to the choice of Hydraulic Engineering and the specialisation of River Engineering. I have really enjoyed the research in the last few months on a topic with interesting river engineering complexities that is currently widely discussed among Dutch river engineers.

I would like to thank all people who were involved in this project. Gijs Nannenberg, thank you for all your time, your thinking along, and your help to keep me headed in the right direction. Thank you Astrid Blom for limiting me in my sometimes too ambitious plans and for providing good feedback that sharpened my mind. Thank you Wiebe de Jong for providing the opportunity to do this thesis as an intern at Haskoning. Thank you to all the Haskoning colleagues for your open attitude which made me feel welcome and part of the team. Thank you Jaime Arriaga Garcia for always adding a cheerful note in the meetings. Thank you Kifayath Chowdhury, Kees Sloff and Spyros Handrinos for providing the models and for the help to get them working. Thank you Ralph Schielen, Michiel Reneerkens en Merel Verbeek from Rijkswaterstaat for thinking along and providing the field data.

Finally, I want to thank my parents, housemates, friends, and other family for all their support during the past months. I am deeply grateful for your presence in my life and the support you have given me during the past months.

Debora van Dieren
Delft, July 2025

Summary

The Pannerdense Kop is a bifurcation point where the Bovenrijn splits into the Waal and the Pannerden Canal. In recent decades, the discharge partitioning changed to more discharge towards Waal at the expense of the Pannerden Canal, which negatively impacts navigation, flood safety, and freshwater availability in the downstream river area. This recent change of the river system is linked to deposition in the Pannerden Canal during three large peak flows in the 1990s. However, an overview of peak flow impacts on the river bed at the Pannerdense Kop is missing, whereas peak flows will occur more frequently and increase in magnitude in the future due to climate change.

This thesis investigates the morphological response of peak flows on the river bed at the Pannerdense Kop, using field measurements and numerical models. First, the peak flow response is determined using several datasets of bed level measurements. Second, a 1D and a 2D morphological model are applied and their outcomes are analysed to determine the impact of peak flows on the river bed around the Pannerdense Kop. In the last step, the peak flow response in the model results and the field data are compared.

Two numerical models are used in this report: a 1D Sobek model developed for the paper of Chowdhury et al. (2025) and a 2D Delft3D model '*delft3d_4-rijn-j18*' version April 2025. Fundamental differences between a 1D and a 2D model are (a) a nodal point relationship is required in a 1D morphological model to determine the sediment distribution at a bifurcation, (b) differences over the width are in the 2D model while a 1D model is width-averaged, and (c) secondary flow is parametrized in the 2D model and secondary flow is generally not accounted for in 1D models. The goal of the 1D model is to determine the impact of climate change on the flow partitioning in the Dutch Rhine system over the next 150 years and the 2D model is developed to determine the morphological effect of river interventions such as the application of longitudinal training walls. The morphology in both models is calibrated such that the aggradation rate per branch has the correct sign and order of magnitude. An important notion regarding both models is that they are still under development and will differ from the final published versions.

The morphological peak flow response is divided into three categories: small-scale changes with a length less than 100 m, intermediate-scale changes with lengths of several hundred meters, and large-scale changes with a length of several kilometers.

Small-scale changes appear in the form of dunes during the rise of the peak flow, grow to their maximum size at or a few days after the peak flow, and the dunes diminish in the weeks afterward. These dunes increase the bed roughness during the peak flow. This information on dune growth is mainly based on previous research using the bed level measurements during the peak flow of November 1998. Bed level measurements during a peak flow in 2021 underline the dune growth during the rising stage, and the presence of dunes during peak flows is also indicated in biweekly field data. Dunes do not appear in the model results as dunes are shorter than the model grid sizes and also the effect of dunes on the bed roughness is not explicitly accounted for in the models.

Intermediate-scale peak flow responses are visible in multiple sources. The field measurements around the peak flow of December 2023 and the 2D model results show a similar spatial distribution of these changes: (i) deposition at the upstream end of the Waal and a slight deposition at the Pannerden Canal upstream end, (ii) erosion at the locations where floodplains narrow and enter the river again, (iii) patterns of erosion and deposition possibly linked to the presence of groynes, and (iv) deposition at the inner bends of the Waal. Comparison of the intermediate-scale responses in the biweekly field measurements and the 2D results show different locations and durations of these changes, which may indicate the limitations of the 2D model although differences in width, discharge, and river interventions may also explain these differences. In the 1D model, the only intermediate-scale peak flow responses are deposition at the upstream end of the Waal and erosion at the upstream end of the Pannerden Canal, as the effect of bends and groynes is not in a 1D model and smoothing of the width over river

reaches prevents local floodplain effects. The 1D model shows erosion at the upstream end of the Pannerden Canal, whilst deposition is observed in that area in several sources of field data and in the 2D model.

A description of the large-scale peak flow response at the Pannerdense Kop remains limited. Chowdhury et al. (2023) shows that an erosion adjustment wave is initiated during peak flows with a maximum discharge at Lobith of more than 9000 m^3/s in the Waal and similar waves are not visible after the lower peak flows in the biweekly field dataset. Still, the visualisation of these erosion waves may be sensitive to choices of visualisation and changes of the river system may also play a role. The current 1D and 2D model results also do not show erosion adjustment waves in the Waal, which may also be related to the visualisation method.

Ultimately, peak flows impact the bed level at the Pannerdense Kop on three scales: small-scale dunes grow, intermediate-scale changes are linked to local river characteristics, and observations of large-scale changes remain limited to one source of field data showing erosion adjustment waves. It is recommended to further study the large-scale peak flow impact and the sediment distribution during different discharge situations. In addition, suggestions are made to improve current models and to model the impact of peak flows.

Contents

1

Introduction

The Rhine river crosses the German border and enters The Netherlands, from where it is called the Bovenrijn. A few kilometers downstream, the Bovenrijn splits into the Waal and the Pannerden Canal at a bifurcation point called the Pannerdense Kop, see Figure 1.1. 11 kilometer downstream of the Pannerdense Kop, the Pannerden Canal splits into the Nederrijn and IJssel at a bifurcation called the IJsselkop.

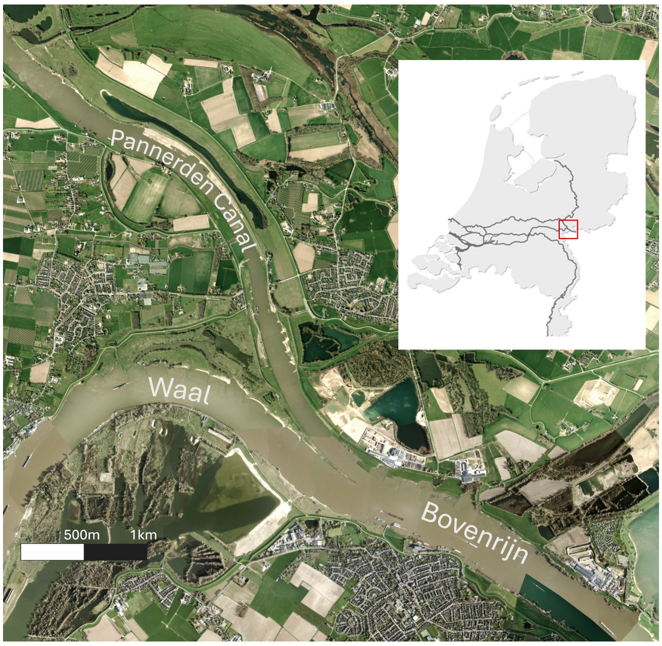


Figure 1.1: The Pannerdense Kop. The water flows from the Bovenrijn to the Waal and Pannerden Canal branches.

1.1. Research context

The bifurcation is part of the Rhine river system which is now under consideration in the Room for the River 2.0 programme (previously called IRM). The goal of the programme is to create a future-proof river system. This involves, on the one hand, counteracting trends caused by past interventions like main channel erosion. The other goal is to anticipate the effects of climate change with increasing droughts and peak flows (Klijn et al., 2022).

Concerns have risen regarding recent changes at the Pannerdense Kop. Since the 1990s, an increasing share of discharge flows towards the Waal (Becker, 2021; Blom et al., 2024; Chowdhury et al., 2023). Additionally, the Waal erodes faster than the Pannerden Canal since the 1990s (Chowdhury et al., 2023; Sloff, 2019). These changes in discharge partitioning and erosion rate mutually reinforce each other, further increasing the dominance of the Waal. This change of discharge partitioning impacts the flood safety, navigability and freshwater availability in the downstream area and understanding of the bifurcation point is therefore of great importance for the future of the Rhine river system.

Chowdhury et al. (2023) and Blom et al. (2024) link the changing discharge partitioning to the morphological impact of three large peak flows in the 1990s in the following manner: the sediment flux increases during peak flows, and the increased sediment flux that entered the Pannerden Canal exceeded the local sediment transport capacity, leading to deposition. This deposition at the upstream end of the Pannerden Canal emerged during the peak flow of 1993 and could not disperse before the next peak flows of 1995 and 1998 arrived, and more deposition was added during those peak flows. The bed level thus increased at the upstream end of the Pannerden Canal, which has led to less discharge entering the Pannerden Canal and more discharge entering the Waal.

From the last paragraph follows that peak flows may play an important role in the morphological development of the Pannerdense Kop. However, the link between the observed deposition and the peak flows is based on a bed level difference between 1992 and 2002 and leaves the possibility open that other factors, such as human interventions, may have caused the system changes in that period.

In addition, climate change will increase the peak flow magnitudes and intensities (Sperna Weiland et al., 2015). The morphological impact of peak flows will therefore play a more important role into the future, which further stresses the importance of understanding morphological effects to peak flows.

Morphological impact of peak flows
Whether erosion, deposition or an equilibrium of the river bed level occurs depends on the match or mismatch between the sediment supply and the sediment transport capacity. If the sediment flux is lower than the sediment transport capacity, erosion occurs. If the sediment flux is higher than the sediment transport capacity, deposition occurs (Chowdhury et al., 2023; Kleinhans et al., 2012; Le et al., 2018).

In single channels, peak flows impact the river bed in several ways: (a) narrow reaches deepen and deposition occurs in wider reaches (Cenderelli & Wohl, 2003; Hauer & Habersack, 2009; Sholtes et al., 2018), (b) a more pronounced M1 backwater curve during peak flows leads to erosion in the backwater reach (Arkesteijn et al., 2019; Chatanantavet & Lamb, 2014; Chatanantavet et al., 2012), (c) overbank flows cause deposition in floodplains (McKee et al., 1967; Ten Brinke et al., 1998; Ten Brinke, 2002), (d) patterns of erosion and deposition occur at in- and outflows of floodplains (Ahrendt et al., 2022), (e) inner bends aggrade and outer banks erode (Parker et al., 2011; Pizzuto, 1994)and (f) sediment is supplied to groyne fields (Ten Brinke, 2002).

In river systems, peak flows can also cause significant changes. In natural rivers, the planform and width can change (Bertoldi, 2012) and peak flows can initiate new branches (Kleinhans et al., 2013; Syvitski & Brakenridge, 2013). These morphological adjustments to peak flows are generally not expected in engineered river systems, where the morphological response is limited to bed level and bed surface texture (Arkesteijn et al., 2019; Chowdhury et al., 2023). In engineered river systems, sediment supply increases during peak flows and sediment waves migrate into the bifurcation area (Frings & Kleinhans, 2008).

Bed level observations at the Pannerdense Kop during the 1998 peak flow showed migrating dunes on the river bed. These bed forms grow during peak flows and increase the bed roughness (Julien et al., 2002; Ten Brinke, 2002). For cases with very high flow velocities and Shields stresses, the dunes will flatten (van Rijn, 1993; Van Den Berg & Van Gelder, 1993), but experiments show that the plane bed stage is not reached in the Dutch Rhine system during peak flow events with Q_{max} = 11,000 m^3/s (Julien & Klaassen, 1995).

Despite the knowledge on these factors, the combined morphological impact of these factors and the long-term impact of peak flows on the bed around the Pannerdense Kop is still unknown.

1.2. Problem statement

Despite the important role of peak flows on the morphology at the Pannerdense Kop, current knowledge of peak flow responses primarily focuses on the individual processes involved, while the integrated morphological changes resulting from these peak flows remain poorly understood.

Furthermore, current morphological models are used to predict the future morphology of the river system and decisions for river interventions are based on these models. However, the morphological impact of peak flows in these models has not been examined yet. A better understanding of the model response to peak flows will help to further understand the model behaviour, advantages and limitations.

Research question

This research aims to study the morphological response of peak flows at the Pannerdense Kop bifurcation, answering the research question:

> *What is the influence of peak flows on the bed level at the Pannerdense Kop and to what extent can we model this response?*

With the following subquestions:

1. What is the morphological response to peak flows at the Pannerdense Kop according to field measurements?
2. What is the morphological response to peak flows according to existing 1D and 2D models?
3. What differences and similarities are observed when comparing the peak flow responses of the field data and model results?

1.3. Description of methods

As a first step, existing field data of the bed level around the Pannerdense Kop are gathered and analysed. This is done first, as field measurements are not impacted by model choices and therefore later provide a trustworthy reference to assess the model outcomes. This research limits itself to existing field data, as many data sources are available for this area and peak flows may not occur during the thesis period. In the analysis, the main focus will be on the combined effect of all factors and the long-term bed level changes.

In a second step, morphological models are used to show their morphological response to peak flows. The 1D Sobek model developed for the papers of Chowdhury et al. (2025) focuses on the impact of climate change on the discharge partitioning at the Pannerdense Kop and IJsselkop towards 2150 and is used in this report to see what changes occur in a 1D model due to peak flows. The 2D model *delft3d_4-rijn-j18* (version April 2025) is used to determine the morphological impact of river interventions such as longitudinal training walls and is used in this report to see what changes occur in a 2D model due to peak flows. These models are the most recent models that predict the future morphology of the Pannerdense Kop and are now used to describe how the system will develop into the future. Regarding their important role in the analysis of the river system, understanding of their morphological response to peak flows will help to further understand current limitations and possibilities of model predictions.

The third step is to assess the model outcomes by comparing the model outcomes to the field data from the first step. This will help to understand limitations and advantages of field data, the 1D model, and the 2D model.

1.4. Research structure

The research will begin with a description of the Pannerdense Kop in Chapter 2. Chapter 3 uses field data to describe the response to peak flows. Chapter 4 explains how existing models are used to model the response to peak flows and shows the results. The field data is compared to the modelling results in Chapter 5. The discussion can be found in Chapter 6 and the Conclusion and Recommendations follow in Chapter 7.

2

Study area

This chapter provides more information on the Pannerdense Kop. Section 2.1 explains the river interventions that have led to the current bifurcation. The discharge and discharge distribution is treated in Section 2.2 and the river bed characteristics are described in Section 2.3.

2.1. River interventions

The Pannerden Canal was opened in 1707 and replaced the original bifurcation point 10 kilometer upstream. The initial design of the Pannerdense Kop led to sedimentation which hindered navigation and therefore the IJsselkop and Pannerdense Kop were modified in 1773-1782 (Chowdhury et al., 2023; Schielen et al., 2007; Van de Ven, 1976).

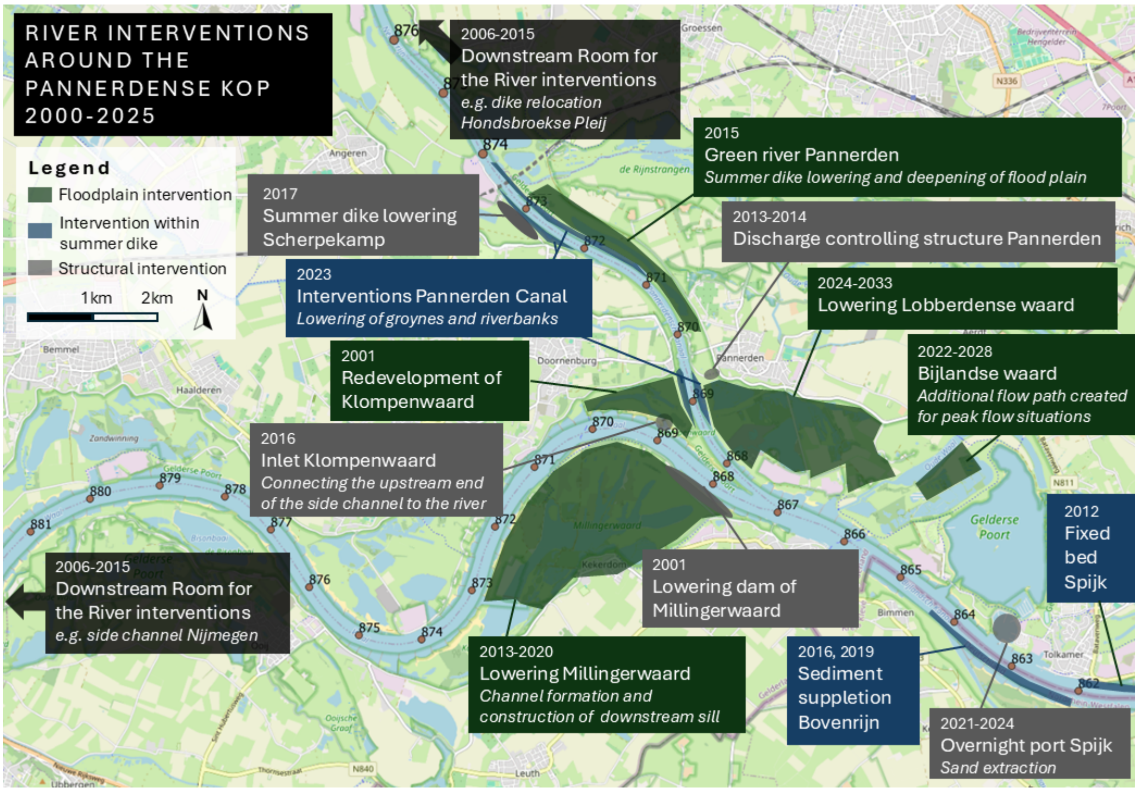


Figure 2.1: Overview of river interventions around the Pannerdense Kop in the years 2000-2025 (ARK Rewilding Nederland, n.d.; Commissie MER, 2013; Coördinatie Rijnwaardense Uiterwaarde, 2022; Google Earth, 2025; Jansen et al., 2023; Programmabureau Ruimte voor de Rivier, 2018; radiomozaiek, 2022; Reneerkens, 2025; Rijkswaterstaat, n.d.; Ylla Arbós et al., 2024).

Ever since, many river interventions such as narrowing, dredging, bend cut-offs, weir constructions and fixed layers have altered the river system (Chowdhury et al., 2023). For example, the river narrowing led to a deeper main channel (Ylla Arbos et al., 2021). Even in recent decades, many river interventions adjust the river system around the Pannerdense Kop, see Figure 2.1. All these changes have made the Rhine river system a highly engineered river system with a set planform. Morphodynamic changes are therefore limited to the bed level and the bed texture (Ahrendt et al., 2025; Arkesteijn et al., 2019; Chowdhury et al., 2023).

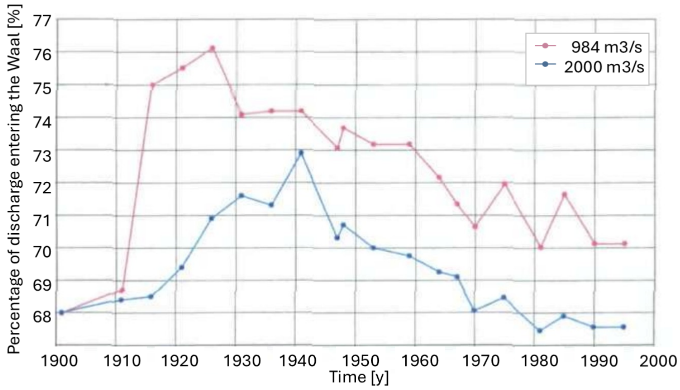
2.2. Discharge and discharge changes

The discharge in the Bovenrijn is measured at Lobith. In the later stages of this research, the discharge per peak flow is frequently provided and these discharges refer to the discharge in the Bovenrijn rather than the Pannerden Canal or the Waal. In the Bovenrijn at Lobith, the mean annual water discharge is 2210 m^3/s and the highest discharge ever recorded was 12,600 m^3/s in 1926 (Chowdhury et al., 2023). The design discharge is currently 16,000 m^3/s. Discharges exceeding 18,000 m^3/s are not expected, as the upstream levees in Germany will overflow in those cases (Klijn et al., 2022).

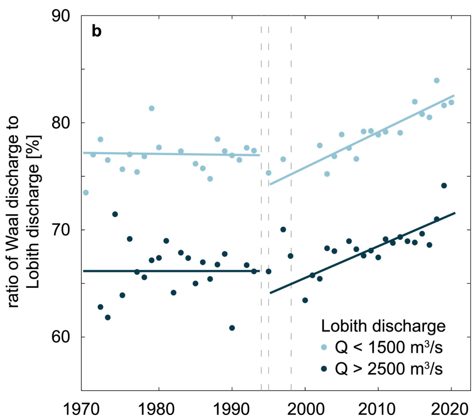
Climate scenarios by the KNMI show that the discharges in the Rhine will increase during the winter and will decrease during summer and all KNMI'14 scenarios show an increase of the extreme discharges compared to the reference situation (Sperna Weiland et al., 2015).

The discharge distribution was set in a treaty in the 18th century: the Waal should receive $2/3^{rd}$ of the discharge in the Bovenrijn, the Pannerden Canal $1/3^{rd}$. The Pannerden Canal splits to the IJssel receiving $1/9^{rd}$ and the Nederrijn receiving $2/9^{rd}$ (Chowdhury et al., 2023).

That discharge distribution has changed at some points in time. During the last century, the Waal discharge increased at the start of the 1900s and decreased in the second half of the century, see Figure 2.2a. Installation of weirs in the Nederrijn in 1954-1970 changed the discharge distribution during low discharges to ensure navigability of the IJssel (Chowdhury et al., 2023). The Waal share of discharge increased again after the 1990s, see Figure 2.2b.



(a) Percentage of discharge from the Bovenrijn entering the Waal during the last century. The lines are corrected for the impact of the weirs (Schropp, 2000).



(b) The discharge partitioning before and after the 1990s. During low flow conditions (< 1500 m^3/s) the weir in the Nederrijn is fully closed, for discharges >2600 m^3/s the weir is fully open (Klijn et al., 2022). Obtained from Blom et al. (2024).

Figure 2.2: Changes in discharge partitioning at the Pannerdense Kop.

2.3. River bed characteristics

The lower Rhine river has been eroding as a result of river interventions (Ylla Arbos et al., 2021). Around the Pannerdense Kop, the Waal and Bovenrijn have eroded with more than 2 m since 1950 (Klijn et al., 2022). In the period 1999-2018, the Waal eroded -1.9 cm/y, the Pannerden Canal eroded -1.0 cm/y and the Bovenrijn remained stable with 0.0 cm/y (Sloff, 2019).

The river bed around the Pannerdense Kop is a mixed sand-gravel bed. The sediment is bimodal, meaning that the bed surface consists of two separate groups of grain sizes -gravel and sand- with only little sediment in the fractions in between (1-2 mm) (Frings et al., 2019; Sloff et al., 2024). An example of the bimodal sediment distribution is shown in Figure 2.3. The subsurface below the morphologically active layer consists predominantly of sand (Schielen et al., 2007; Sloff, 2022).

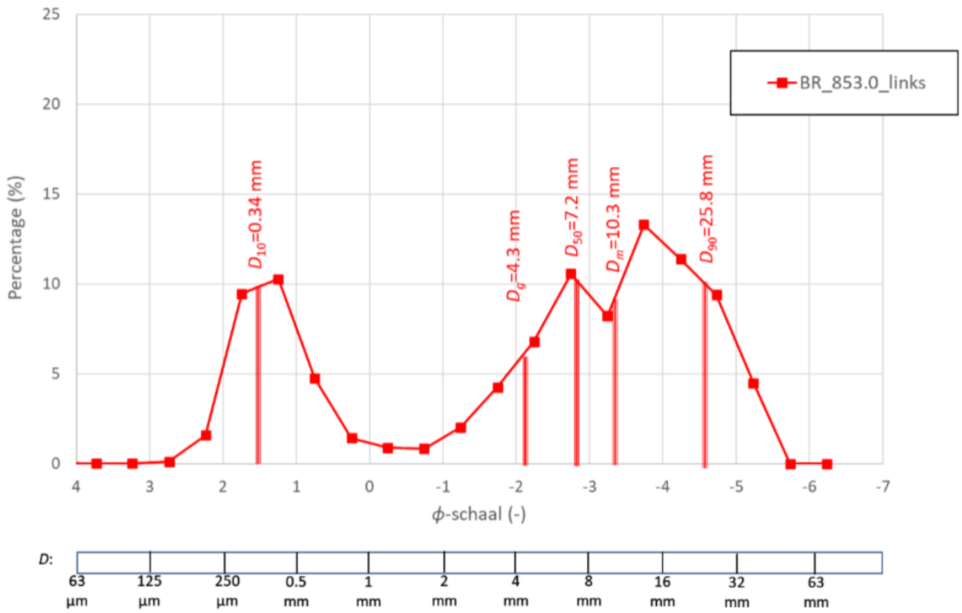


Figure 2.3: An example of a bimodal grain size distribution as presented by Sloff (2022). This grain size distribution follows from measurements in 2020 in the Bovenrijn at river kilometer 853, left of the river axis. Characteristic percentiles and mean values are shown, and the square markers correspond with the mean D_i of each sieve.

The gravel-sand transition (GST) marks the transition between the upstream bed with gravel and the downstream sand bed. In the upstream area with less than 30% sand, the bed is dominated by gravel and has a so-called 'clast-supported' bed, where the gravel particles form a frame. In the downstream area with more than 30% sand, the bed is dominated by sand in a so-called 'matrix-supported' bed, where the gravel particles do not form a frame (Sloff, 2022). The GST moves downstream and the GST spans over the area from about rkm 840 in the German Niederrhein, to rkm 915 in the Waal (Ylla Arbos et al., 2021). An analysis of surface grain size measurements shows a clear coarsening of the Bovenrijn and Waal, although the coarsening in the Waal may also be caused by river interventions according to Sloff (2022).

The design of the bifurcation is such that the Pannerden Canal takes of the outer bend and the Waal from the inner bend. This is important for the type of sediment that enters each of these branches. Due to bend sorting, coarser sediment can be found in the outer bend and finer sediment in the inner bend (Parker & Andrews, 1985). The bend effect leads to finer sediment entering the Waal and coarser sediment entering the Pannerden Canal (Gruijters et al., 2001; Sloff, 2022). Comparison of grain size measurements indeed show this effect: measurements show a width-averaged median grain size of 3.7 mm in the Bovenrijn, 1.6 mm in the Waal, and 7.2 mm in the Pannerden Canal (Frings & Kleinhans, 2008).

Whether deposition or erosion occurs depends on the sediment supply versus the sediment transport capacity (Chowdhury et al., 2023; Kleinhans et al., 2012; Le et al., 2018). Few studies are available on the topic of sediment supply and distribution at the Pannerdense Kop. The annual sediment budget is estimated by Frings et al. (2019). Although mainly clay and slib are transported (2.0 Mt/y), this barely influences the main channel bed as this sediment is too small to settle in main channel. Frings et al. (2019) estimates a yearly sand transport of 0.63 Mt/y in the Bovenrijn, of which 0.08 Mt/y enters the Pannerden Canal and 0.55 Mt/y enters the Waal, and a yearly gravel transport of 0.1 Mt/y of which 0.03 Mt/y enters the Pannerden Canal and 0.07 Mt/y enters the Waal. Estimations of the sediment transport per peak flow in the 1990s are available for the Waal and Bovenrijn (Ten Brinke et al., 2001), showing a sediment transport in the order of 250.000 m^3 during the peak flows of 1993 and 1995 and less during later peaks. Wilbers (1999) calculates the bed load transport based on dune migration and shows 88 $\pm$5% of the sediment entered the Waal and 12 $\pm$5% entered the Pannerden Canal during the 1998 peak flow.

3

Response to peak flows - field data

In this chapter, field data are analysed to understand the morphological response to peak flows. An overview of the data sources can be found in Appendix A. The five data sources are: width-averaged biweekly measurements of the navigation channel in the period 2005-2021, bed level measurements before and after the peak flow of December 2023, bed level measurements at the Pannerdense Kop during the peak flow of February 2021, yearly bed level measurements as presented by Chowdhury et al. (2023), and bed level measurements during the 1998 peak flow as presented by (Ten Brinke, 2002).

In this chapter, the small-scale bed forms that occur during peak flows are described first in Section 3.1. Secondly, intermediate-scale bed level changes are linked to local river geometry in Section 3.2. Third, the large-scale impact of peak flows over multiple years is examined in Section 3.3.

3.1. Small-scale bedforms

Dunes are examined in this section because these bedforms impact the roughness of the bed. The evolution of dunes is well described based on measurements during a peak flow in November 1998 by Frings and Kleinhans (2008), Julien et al. (2002), Kleinhans et al. (2007), and Ten Brinke (2002) and also appear in bed level measurements during the peak flow in February 2021.

In November 1998, a peak flow occured with a maximum discharge of 9500 m^3/s (Rijkswaterstaat, 2025). The bed level around the Pannerdense Kop was measured daily during this peak flow. Figure 3.1 shows the bed level at four moments during the peak flow. Ten Brinke (2002) uses this to describe the evolution of dunes: the bed is relatively smooth before the peak flow and dunes form and grow in height and length until the day of the peak flow or a few days after. These primary dunes diminish after the peak flow and smaller secondary dunes appear during the falling stage. The same behaviour is described in using bed level measurements during the peak flow of 1988 with $Q_{max} = 10,274\ m^3/s$ Julien and Klaassen (1995).

Dunes increase the bed roughness and as the dune geometry differs per branch, the bedform roughness also differs per branch. The dune geometry in this dataset is determined by Julien et al. (2002): the highest dunes during the 1998 peak flow occured in the Bovenrijn (up to 1.2 m, length up to 40 m) and lower dunes were found in the Waal (up to 0.4 m, length up to 18 m). The dunes in the Pannerden Canal mainly occur at the outer bend bank and have a maximum height of 0.7 m (Frings & Kleinhans, 2008). Julien et al. (2002) shows that the bedforms increase the bed resistance in the Bovenrijn, and shows a weaker relationship between discharge and increased roughness in the Waal. The bedform roughness is not determined for the Pannerden Canal. All dunes lowered during the falling stage of the peak flow, although the dune length decreased in the Waal which led to steeper dunes whilst the dunes in the two other branches flattened (Frings & Kleinhans, 2008). These differences may also lead do differences in bed roughness in the different branches. de Lange et al. (2021) indicate the impact of dunes on the bed roughness: roughness inferred from dune geometry explains at best 31% of the roughness variance. However, this is based on measurements during low flow conditions with

$Q_{Lobith,mean}$ = 1030 m^3/s and $Q_{Lobith,max}$ = 1664 m^3/s whilst the dunes are higher during peak flows and may thus lead to higher bedform roughnesses (Frings & Kleinhans, 2008; Lokin, 2024; Ten Brinke, 2002).

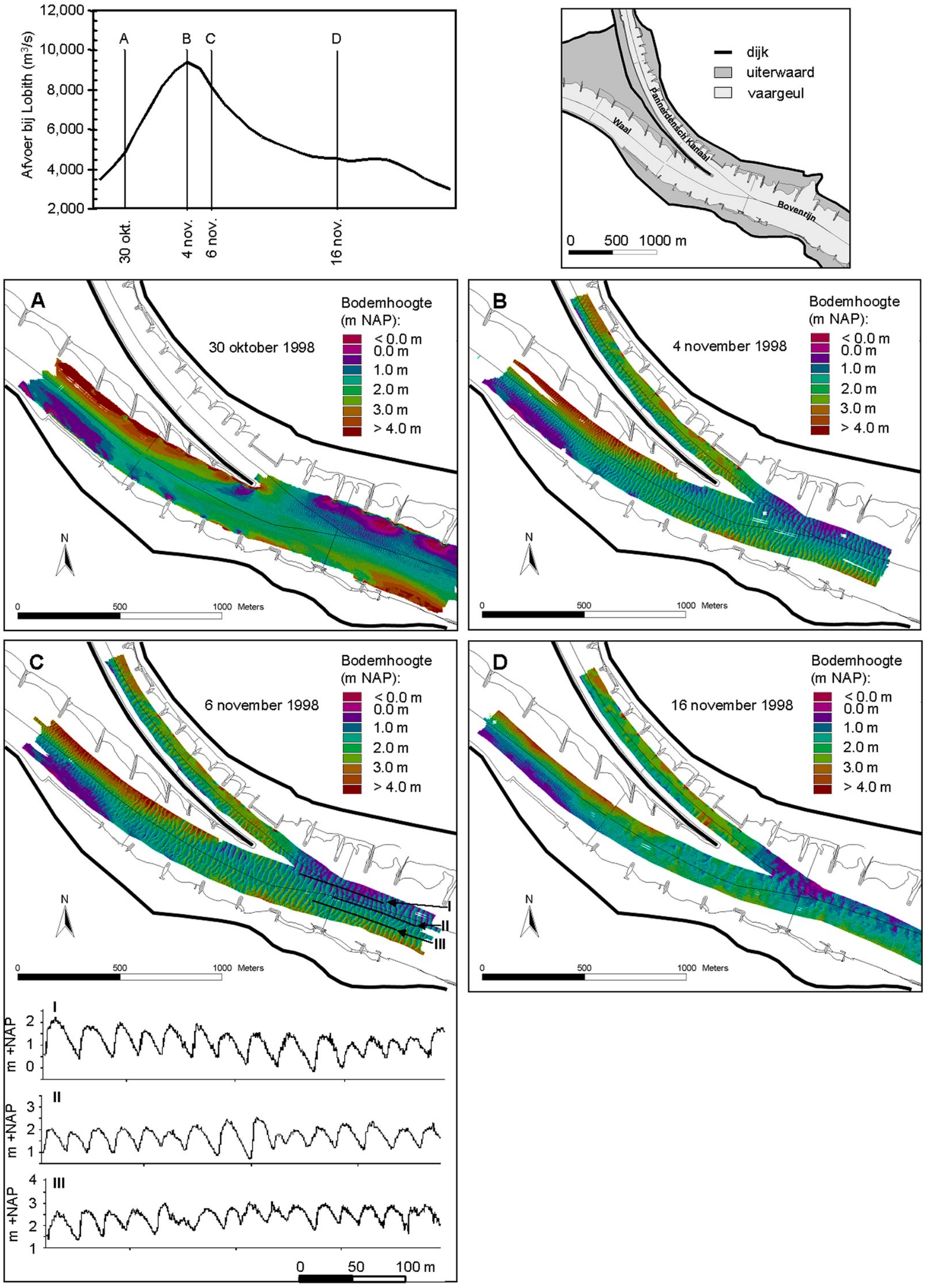


Figure 3.1: Bed level around the Pannerdense Kop measured during the peak flow of 1998, obtained from Ten Brinke (2002). Subfigure A shows the bed level just before the peak, B at the peak, C a few days after the peak and D just after the peak wave. The ripples in the bed are river dunes. Cross sections of subfigure C are shown, when the dunes reached their maximum size.

Bed level measurements during the peak flow of February 2021 also show growing dunes. Figure 3.2 shows multibeam measurements during the peak flow, the bed level difference, and the discharge during that period. The maximum discharge of this peak was Q_{max} = 7400 m^3/s. The measured area of the data is limited to an 800 m reach around the Pannerdense Kop. Despite the small area, dunes are clearly visible. The dune height and length has increased between 4 and 9 February, which is in line with the explanation of Ten Brinke (2002) that dunes grow as the discharge increases. Similar to the dunes during the 1998 peak flow, the dunes in the Pannerden Canal are also located at the left bank. Any statements on the dune height and length would not provide a reliable estimation for the roughness of these branches, as they would be based on very short reaches only.

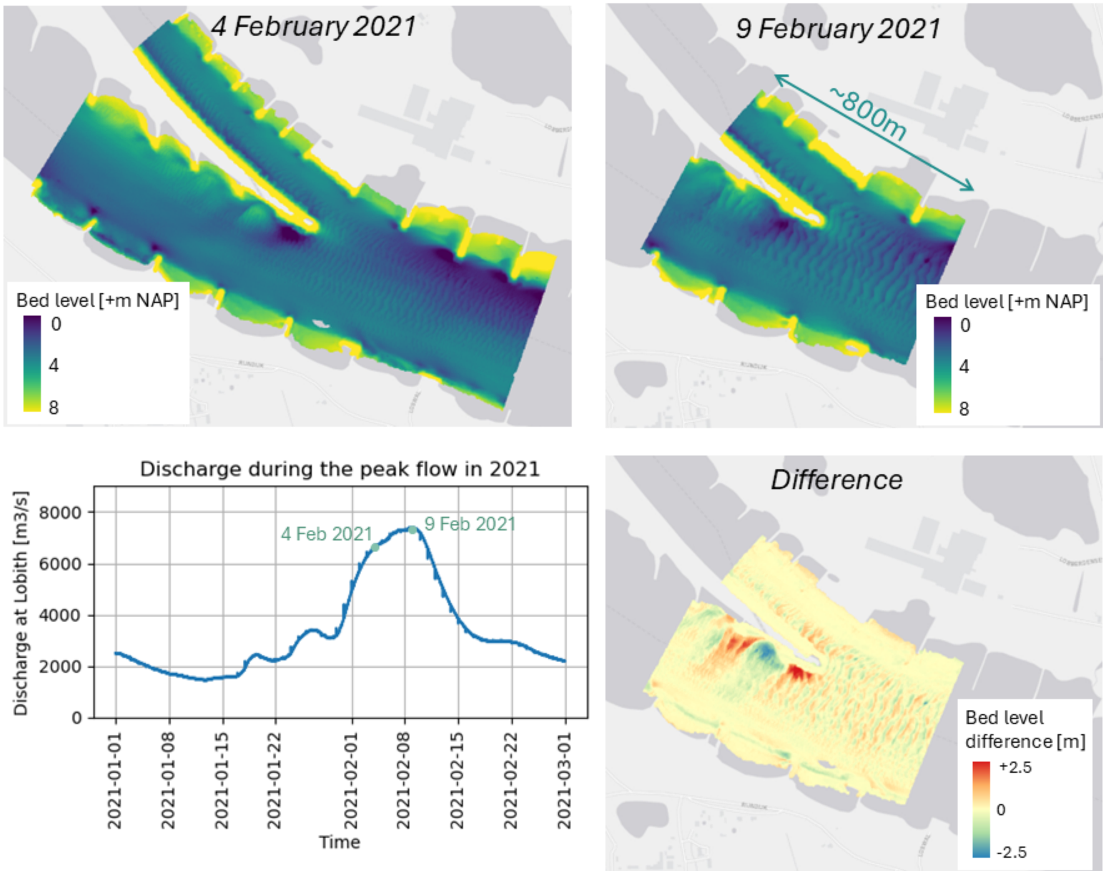


Figure 3.2: Bed level around the Pannerdense Kop measured during the 2021 peak flow.

The behaviour of dunes as described above can also be used to interpret the biweekly, width-averaged field data. Figure 3.7 and 3.8 show the bed level during the 2011 and 2018 peak flows. Many very narrow stripes of erosion and deposition are visible during the peak flow and these stripes smoothen out in the weeks after the peak flow. Using the knowledge on dunes as described in this section, these changes can be interpreted as dunes.

Dunes are not clearly visible in Figure 3.4, which shows a map of the bed level changes over the peak flow in December 2023. This is not surprising taking into account the dune evolution described by Ten Brinke (2002): dunes appear and grow during the rise of peak flows and diminish in the weeks after the peak passed. The 23/24 data shows the bed level change over months during which a peak flow passed, and the dunes will have appeared and disappeared within that period.

3.2. Intermediate-scale changes linked to local river geometry

From the field data appeared that patches of erosion and deposition with a length in the order of several hundred meters and a height in the order of decimeters appear after peak flows. Observations at this intermediate scale are treated in this section using two data sources: the bed level difference over the 2023 peak flow and the biweekly dataset.

Bed level difference over the peak flow of December 2023

The intermediate-scale changes are clearly visible in a bed level difference map over a peak flow that occurred in December 2023. The bed level was measured before the peak flow in October 2023 and after the peak flow in January 2024. Figure 3.4 shows these bed levels and the bed level difference from October 2023 to January 2024. The maximum discharge at Lobith during this peak was 7550 m^3/s. The hydrograph during this period is presented in Figure 3.3.

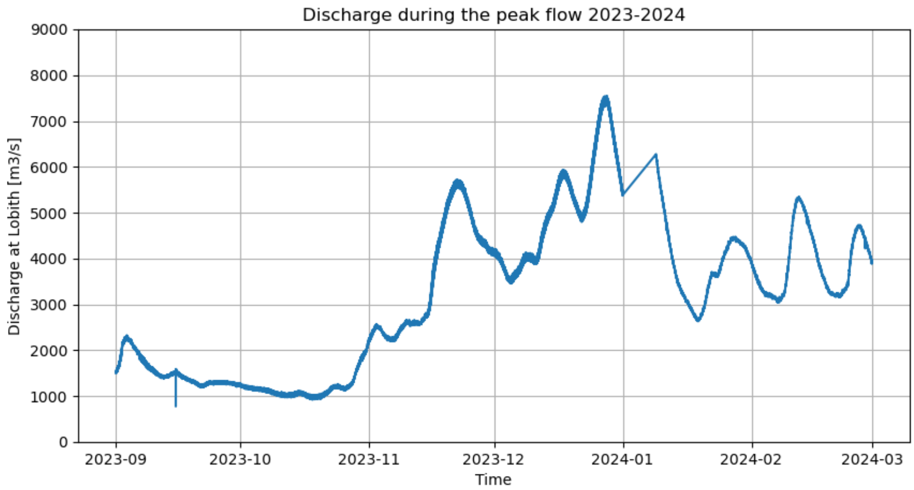


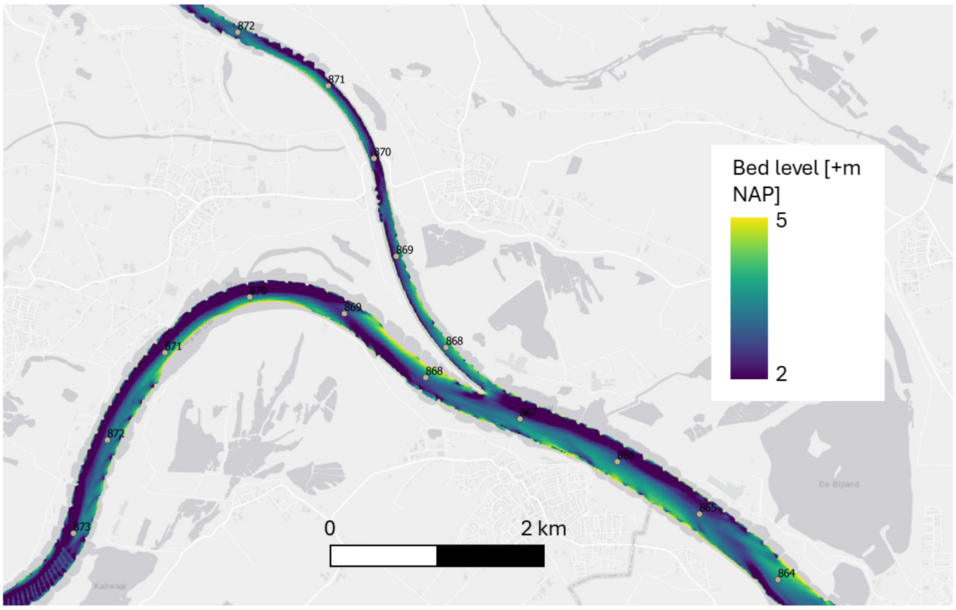
Figure 3.3: Discharge during the peak flow December 2023. The bed level was measured in October 2023 and in January 2024.

The bed level differences in Figure 3.4c can not be directly linked to peak flows for several reasons. First, the morphological response is not only a result of the peak flow and river interventions may also impact the bed. This case may especially be impacted by the river bank and groyne lowering in the Pannerden Canal during 2023. The exact location of these interventions can be found in Appendix B. Second, Figure 3.4c is based on only two maps of bed level data, which makes the image sensitive to measurement errors. Third, the changes observed during this peak flow may not be representative for other peak flows. Thus, interpretation of Figure 3.4c must be done carefully.

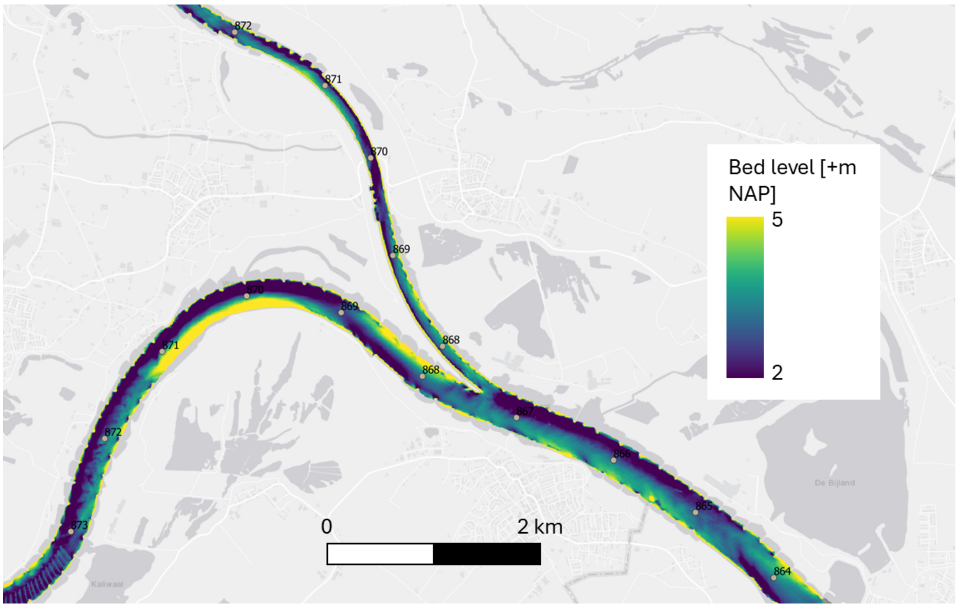
The Waal and Bovenrijn data of October 2023 are not of sufficient quality to use for bed level trends as there may be an offset of a few centimeters. Rijkswaterstaat highlighted this concern when sharing the data. However, the erosion and deposition patterns observed in Figure 3.4c are in the order of 70 centimeters and a few centimeters offset will therefore lead to negligible changes in the difference map, so the offset is not regarded problematic for this use of the data.

The patches of erosion and deposition in Figure 3.4c have magnitudes in the order of decimeters and length scales in the order of a few hundred meters. The patches seem randomly distributed over space, but a closer look shows how these changes may be related to local river characteristics:

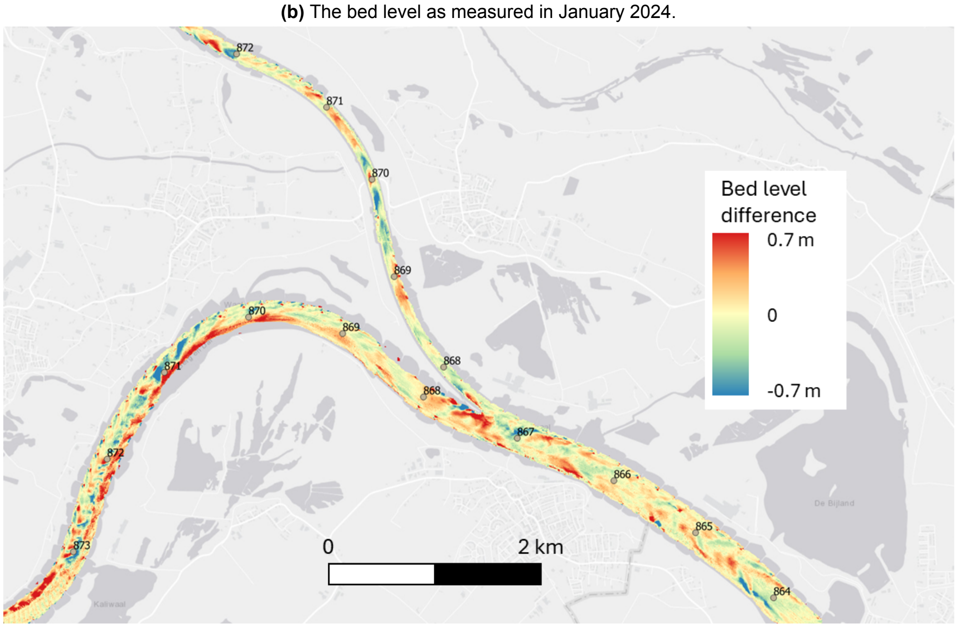
- Deposition is observed at the upstream end of the Waal. Deposition is also present at the upstream end of the Pannerden Canal, although this deposition is less and is followed by erosion downstream. Looking back at the bed level changes during the peak flow of 2021 in Figure 3.2, the upstream end of the Waal also shows a net deposition at the right bank, and a slight net deposition at the left bank of the Pannerden Canal upstream end. Thus, a net deposition at the upstream ends of the Waal and Pannerden Canal is observed both during the 2021 and over the 2023 peak flow.
- The bed has eroded at the downstream ends of floodplains, where the water enters the main channel again. This is observed at rkm 864 at the Schenkenschanz floodplain outflow, at rkm 871 in the Waal at the Klompenwaard outflow, and at rkm 869.8 and 872 in the Pannerden Canal. This is in line with Cenderelli and Wohl (2003), Hauer and Habersack (2009), and Sholtes et al. (2018) who show erosion occurs in narrow reaches during peak flows. However, these sources also indicate deposition in wider reaches during peak flows which is not clearly visible in Figure 3.4c.



(a) The bed level as measured in October 2023.



(b) The bed level as measured in January 2024.



(c) Bed level difference over the period October 2023 and January 2024

Figure 3.4: The bed level measured in October 2023 and January 2024 and the bed level difference over this period.

- The patterns in the Bovenrijn resemble groyne flames and a close look shows that these 'flames' of deposition start at the groyne tips and stretch out into the main channel in downstream direction. Similar patterns are observed in the Waal at rkm 871-873 and in the Pannerden Canal at rkm 871-872.
- In the Waal, deposition is observed at the inner bends. A similar pattern is not clearly visible in the milder bends of the Pannerden Canal and Bovenrijn. Natural rivers show outer bank erosion and inner bank aggradation during peak flows (Parker et al., 2011; Pizzuto, 1994). Inner bend aggradation is observed in Figure 3.4c, but outer bend erosion is not observed in Figure 3.4c. This expected erosion in the outer bend may not be visible for two reasons: it does not occur or the erosion occurs in the area that is not measured.

Bed level changes during peak flows in biweekly data
The bed level in the navigation channel was measured biweekly during 2005-2021 (van Denderen & van Hoek, 2022) and this dataset also shows changes on the intermediate timescale.

For the interpretation of the biweekly dataset, it is important to realise several limitations and advantages of the dataset. An overview of the advantages and limitations of the biweekly dataset is given in Table 3.1.

Table 3.1: Advantages and limitations of the biweekly dataset.

	Advantages		Limitations
✓	High measurement frequency: biweekly	✗	Does not contain Pannerden Canal
✓	Multiple years of data: 2005-2021	✗	Width averaged so only longitudinal variations visible
✓	High spatial resolution: bed level given every 5 m	✗	Measured only over the navigation channel width, not the full main channel
✓	Long river reach: rkm 857.7-965.5	✗	Maximum peaks in this period are relatively low (max discharge of 8400 m^3/s at Lobith)

Figure 3.5 shows the bed level around the Pannerdense Kop over time as measured in the biweekly field measurements. Figure 3.6 shows the bed level relative to the mean bed of 2005.

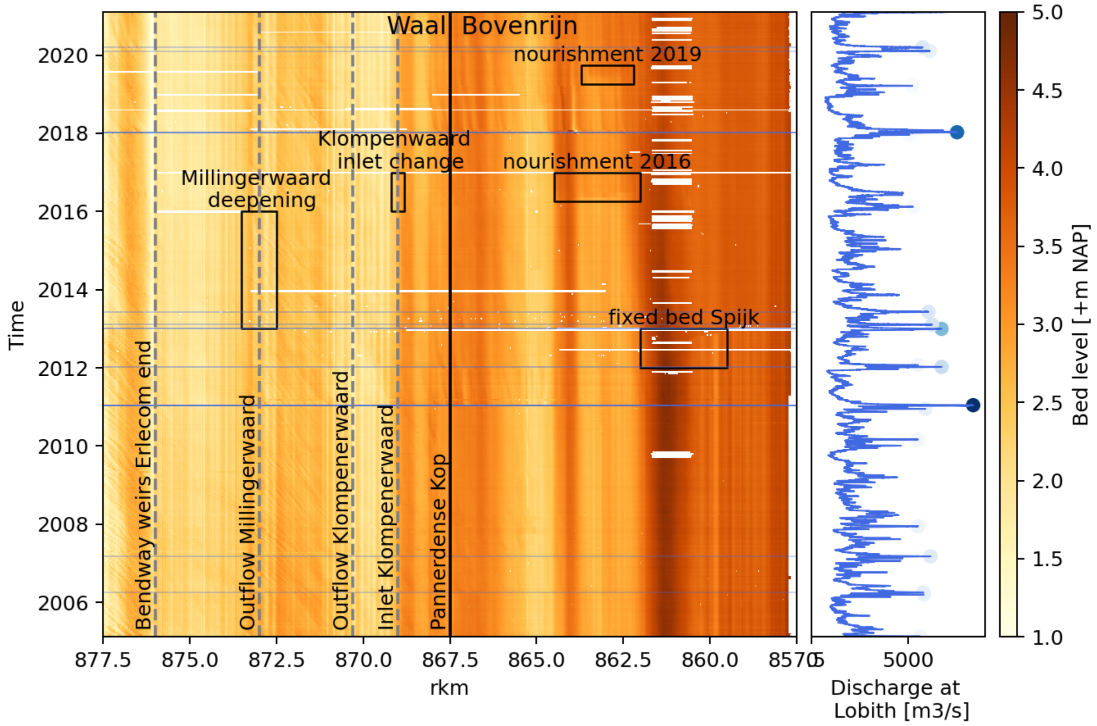


Figure 3.5: The bed elevation [+m NAP] in the biweekly measurements of the navigation channel during the period 2005-2021. The vertical lines represent in- or outflows of floodplains. The black boxes show interventions based on Figure 2.1.

Interpreting the figures showing the bed level evolution over time

Images similar to Figure 3.6 appear many times throughout this report. An initial guide to these images may help. The x-axis shows the Rhine river kilometers and the water flows from right to left. On the y-axis is the time. The width-averaged bed level is used. The bed level change is plotted over time: blue means that the area eroded relative to the initial bed level and red means aggradation relative to the initial bed level. The definition of the initial bed level is presented in the text next to the colorbar. The discharge in the Bovenrijn is also plotted and peak flows are indicated using a dot in the discharge plots. The thin blue horizontal lines in the bed level change plot also indicate the peak flow moment.

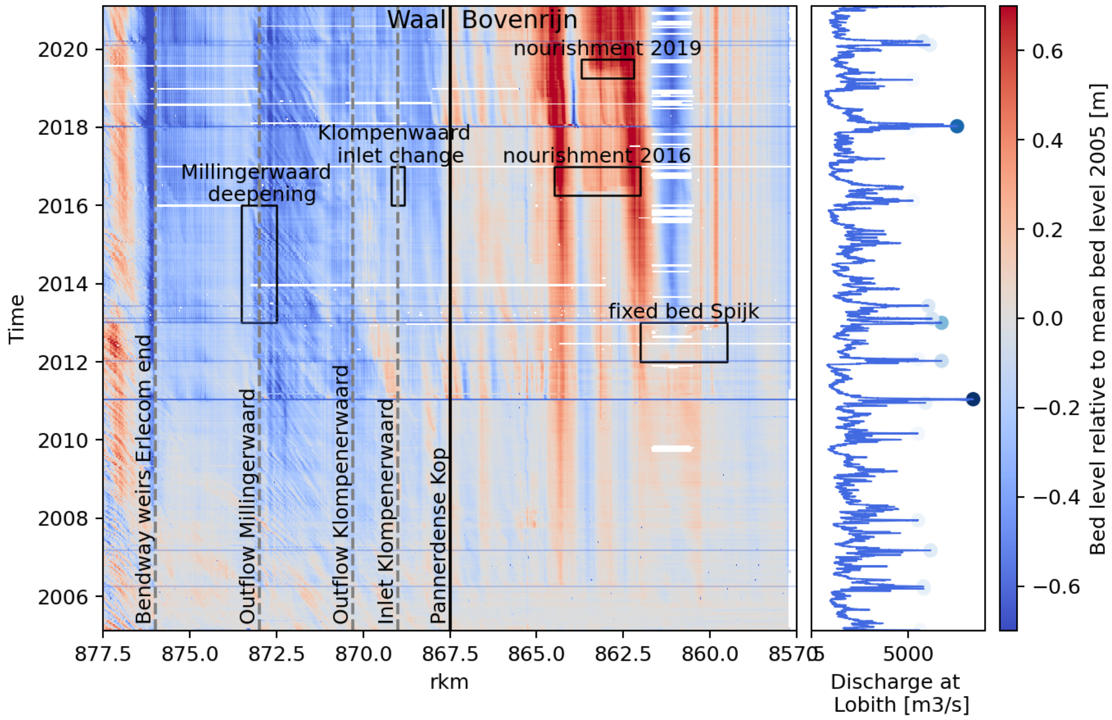


Figure 3.6: The biweekly measured bed level relative to the mean bed of 2005. The vertical lines represent in- or outflows of floodplains. The black boxes show interventions based on Figure 2.1.

Several changes in Figure 3.6 may be related to river interventions:

- After construction of the *fixed bed at Spijk*, the bed level has changed there. Figure 3.5 shows that the fixed layer effectively lowered the river bed. Figure 3.6 shows the impact of the fixed layer from 2013 onwards, where the bed level changed at rkm 859-863 in a certain pattern. Erosion is visible at rkm 860.5-861.5, deposition at rkm 861.5-862.5, and an alternating pattern occurs between rkm 859 and 860.5. The pattern does not show a clear migration up- or downstream. The most obvious cause of these changes is the construction of the fixed bed at Spijk.
- *Bendway weirs* are located at rkm 873.2–876 in a bend near Erlecom since 1994–1996 (Ylla Arbós et al., 2024). Downstream of these bendway weirs, erosion is visible over the years.
- At rkm 862-865, the bed level increased in 2016 and 2019, which coincides with the *nourishment* area and construction periods (Jansen et al., 2023). The peak flows clearly fasten the downstream migration of the nourished sediment, which can be observed during the peak flow of 2018 and -to a lesser extent- the peak flow of 2020.
- At the *inlet of the Klompenwaard*, a sedimentation wave starts at the peak flow of 2011. The sedimentation wave moves downstream during the next peak flow in 2012 and ceases to exist in 2013. However, a similar erosional wave is not visible after the peak flow of 2018. The changed response may be related to the inlet change in 2016.
- The *deepening of the Millingerwaard* does not show a clear response.

Figure 3.6 also shows discontinuities after peak flows. In the graph, the peak moments show a different pattern before and after the peak:

- As observed in the part on the river interventions, the sediment nourishments migrate faster during peak flows. Additionally, at the inlet of the Klompenwaard, erosion was observed after the 2011 peak flow but not after the peak flow of 2018, which may be related to the changes to the Klompenwaard inlet in 2016.

- In the area of the Pannerdense Kop and a few kilometers upstream (rkm 864-868), an alternating pattern of deposition and erosion waves is visible after the peak flows. These changes remain in the system until they disperse during subsequent peak flows a few years later. The location of these changes matches with the location where groyne flames were observed in Figure 3.4c.
- In the reaches rkm 871-873 and 874-876 erode during peak flows. This erosion moves downstream and starts disappearing at the upstream end, and the bed level of before the peak flows is reached again after several months to a few years. Erosion in these reaches is not clearly observed in Figure 3.4c.

For a more detailed view of the peak flow impact, a zoomed-in plot is made for the two largest peak flows during 2005-2021, which occurred in January 2011 and February 2018. Figures 3.7 and 3.8 show how the width-averaged bed level changed over time around these peak flows.

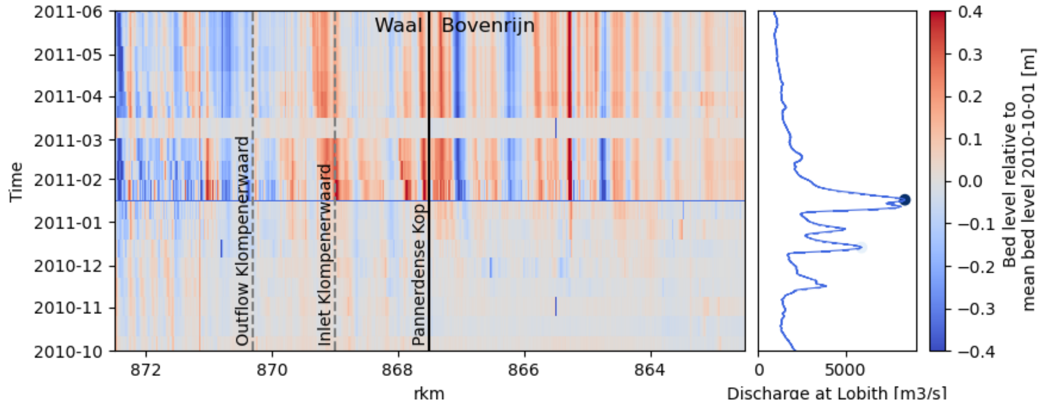


Figure 3.7: Bed level relative to the bed level in October 2010, showing the bed level change during the peak flow of 2011 with a maximum discharge of 8400 m^3/s.

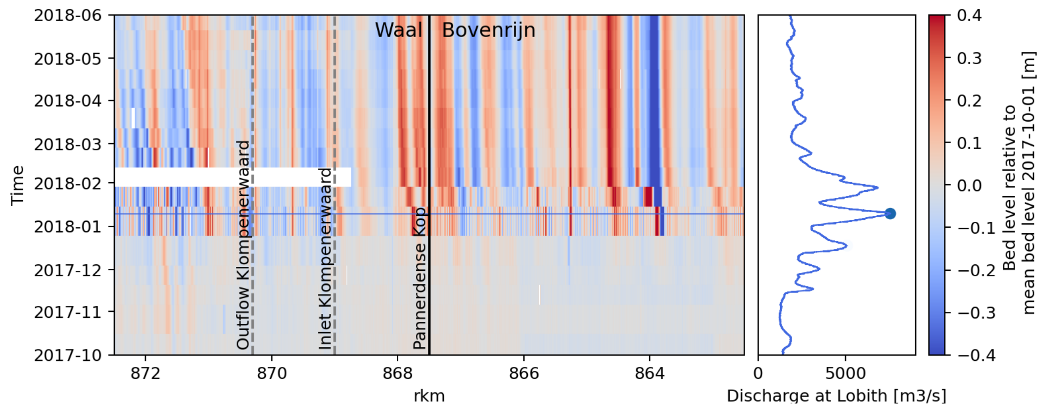


Figure 3.8: Bed level relative to the bed level in October 2017, showing the bed level change during the peak flow of 2018 with a maximum discharge of 7550 m^3/s.

Figure 3.7 and 3.8 show that the bed level seems relatively stable before the peak flow and show clear discontinuities during and after the peak flow. At the peak flow, the bed level shows many very narrow stripes. These very narrow stripes are mainly observed during the peak of the flow and smoothen out in the weeks after the peak. These changes may be related to the dunes that occur during peak flows and smooth out in the weeks after, see Section 3.1. Wider stripes of erosion and sedimentation patterns are observed after the peak. These erosion and deposition reaches are in the order of 100-500 m arise and remain in the months after the peak flow. In 2018, erosion is observed at rkm 864 and deposition downstream at rkm 864.7. This change is not visible in the 2011 peak flow and Figure 3.6 shows that at these changes can be linked to the downstream migration of the sediment nourishment of 2016 during the 2018 peak flow.

One measurement in March of 2011 strongly deviates from the measurements before and after. This behaviour is possibly the result of measurement errors. The white bar in February 2018 is the result of no data (van Denderen et al., 2022).

3.3. Large-scale changes over multiple years

This section focuses the impact of peak flows over multiple years. First, the bed level changes over the 1990s as described by Chowdhury et al. (2023) are repeated. Secondly, the biweekly dataset is utilized in an attempt to identify a long-term trend and to evaluate the influence of peak flow events on this trend. Third, the presence of an erosion adjustment wave as indicated by Chowdhury et al. (2023) is presented and compared with the biweekly field data.

Yearly bed level measurements around the Pannerdense Kop

Chowdhury et al. (2023) uses yearly bed level data averaged over the river width to examine bed level changes. Figure 3.9 shows the results of the analysis around the Pannerdense Kop. One obvious general trend is that the Bovenrijn, Waal and Pannerden Canal are all eroding around the Pannerdense Kop. However, the upstream end of the Pannerden Canal deviates from this eroding trend around the 1990s. In those years, the bed level in this area increases and the erosion rate slowed down significantly after. The deposition at the most upstream kilometers of the Pannerden Canal decreases in downstream direction. Further downstream the Pannerden Canal (rkm 871-877), erosion is observed over the 1990s.

Chowdhury et al. (2023) links the bed level changes during the 1990s to the peak flows in 1993, 1995 and 1998 in the following way: the sediment supply increased as a result of peak flows and the sediment transport capacity in the Pannerden Canal was insufficient, so the peak flows resulted in deposition at the upstream end of the Pannerden Canal. The sediment hump formed during the first peak could not disperse before the other peak flows arrived and those peaks added to the deposition. This deposition in the Pannerden Canal led to less discharge entering the Pannerden Canal and increased the discharge share in the Waal.

The peak flows of 1993, 1995 and 1998 had a maximum discharge of 10.940, 11.885 and 9.413 m^3/s respectively. The peak flows in the period 2005-2024 were significantly lower and shorter, with a maximum peak flow of 8400 m^3/s, see the peak flow overview in Appendix C.

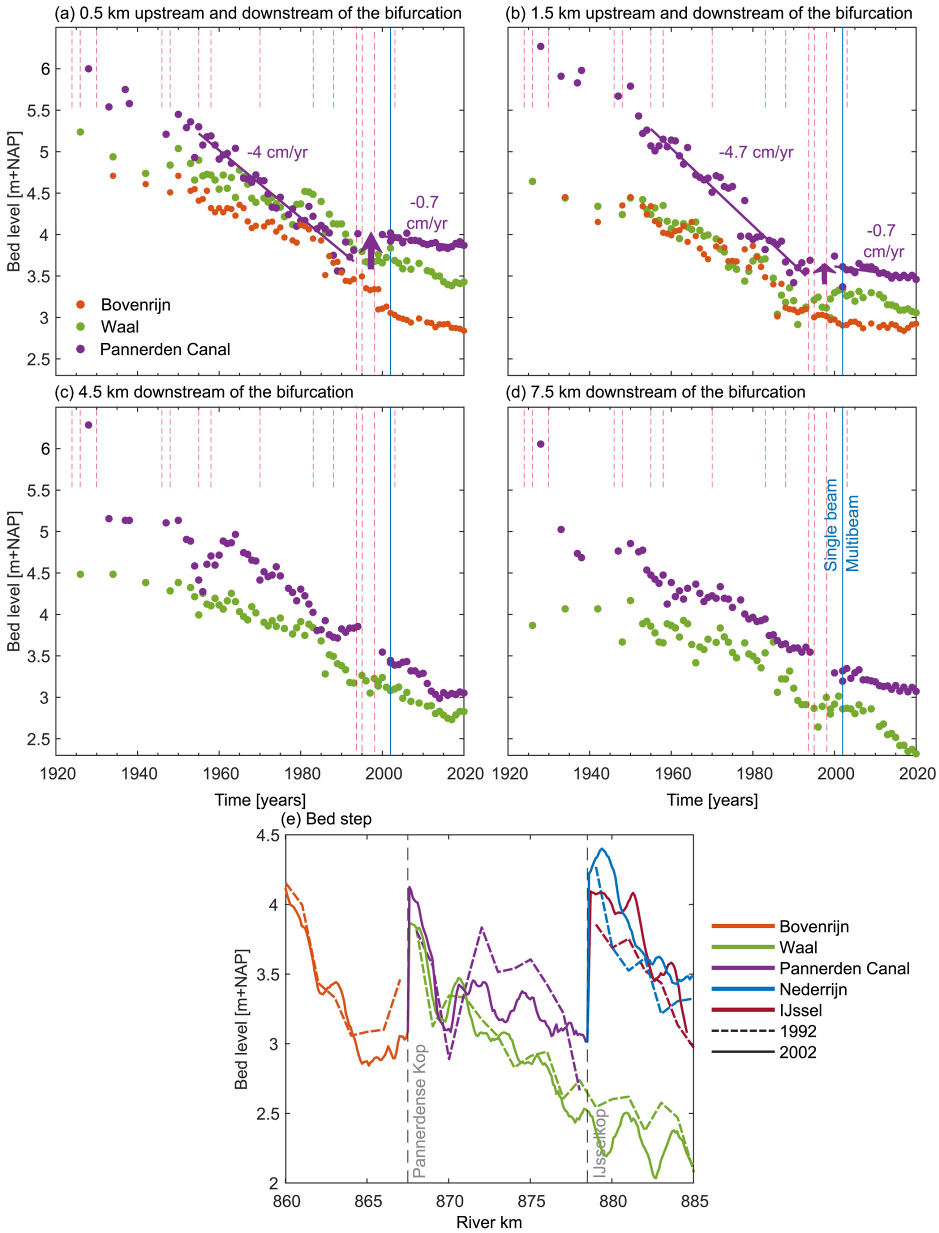


Figure 3.9: Evolution of cross-section averaged bed levels at the Pannerdense Kop. Linear regression shows a change erosional trend at the upstream end of the Pannerden Canal since the 1990s (Chowdhury et al., 2023).

Bed level trend in the biweekly dataset

The biweekly dataset from the main channel is analysed to identify long-term trends and to assess the impact of peak flows on these trends. For a first understanding of the bed level evolution, the bed level is plotted over the river reach around the Pannerdense Kop, see Figure 3.10. The bed level decreases in the Waal and increased in several parts of the Bovenrijn.

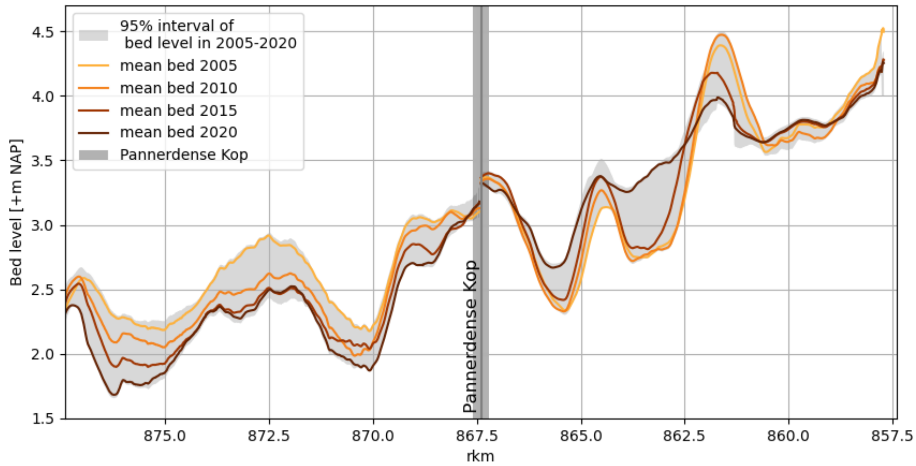


Figure 3.10: Bed level around the Pannerdense Kop using a moving average of 1 km. Upstream of the Pannerdense Kop is the Bovenrijn, downstream of the Pannerdense Kop is the Waal. The bed level is width-averaged over the navigation channel. The 95% interval is calculated per location, based on all measurement of the measurement period 2005-2021.

Figure 3.6 shows an overall trend to blue over the years in the Waal, meaning an erosional trend. The same erosional trend is visible in Figure 3.10 as the bed level drops over the years. A similar trend is hard to determine for the Bovenrijn, as the sediment nourishments and fixed layer at Spijk have a major impact on the bed level. An estimate of the erosion trends is made using the mean bed level of 2005 and 2020 over the 2 km reach from the Pannerdense Kop. 2 km is chosen as a longer distance would mean that the nourishment in the Bovenrijn gives a false image of aggradation. This leads to an aggradation rate of -1.7 cm/y for the Waal and 0.1 cm/y for the Bovenrijn. These values match well with trends observed in 1999-2018: the Waal then eroded with -1.9 cm/y and the Bovenrijn remained stable with 0.0 cm/y (Sloff, 2019). However, if the aggradation is calculated over a 1 or 10 km reach starting at the bifurcation, the values range significantly from respectively -1.3 cm/y to -2.2 cm/y in the Waal, and -0.32 cm/y to 1.0 cm/y, the latter being impacted by nourishments in the Bovenrijn. The erosion rates are thus quite sensitive to the distance over which the average was taken.

Disentangling the large-scale impact of a peak flow is challenging based on Figure 3.6. Although discontinuities are clearly visible after peak flows, it is hard to determine the peak flow impact over multiple kilometers that remain multiple years, as many smaller changes interfere resulting from both river interventions and peak flows. Additionally, the peak flows in this 15-year time series are limited to 8400 m^3/s, whilst peak flows up to 12,600 m^3/s were observed during the past century and therefore the peak flow impact may also not be as pronounced as it would be during more extreme peak flows.

Erosion adjustment wave in the Waal

Chowdhury et al. (2023) also studies downstream migrating adjustment waves. The aim of this analysis was to determine whether the sediment supply and the sediment transport capacity are in balance. During a peak flow, a sudden imbalance between the upstream sediment supply and the sediment transport capacity can trigger the formation of adjustment waves that migrate downstream, influencing the bed level (Chowdhury et al., 2023). The aggradation rates can indicate whether such adjustment waves are observed. Figure 3.11 shows the aggradation rates of the Niederrhein, Bovenrijn, and Waal. At a peak flow, a blue area starts at the Pannerdense Kop and travels downstream into the Waal, as indicated by the white lines. These observations indicate the presence of erosion adjustment waves triggered by peak flows.

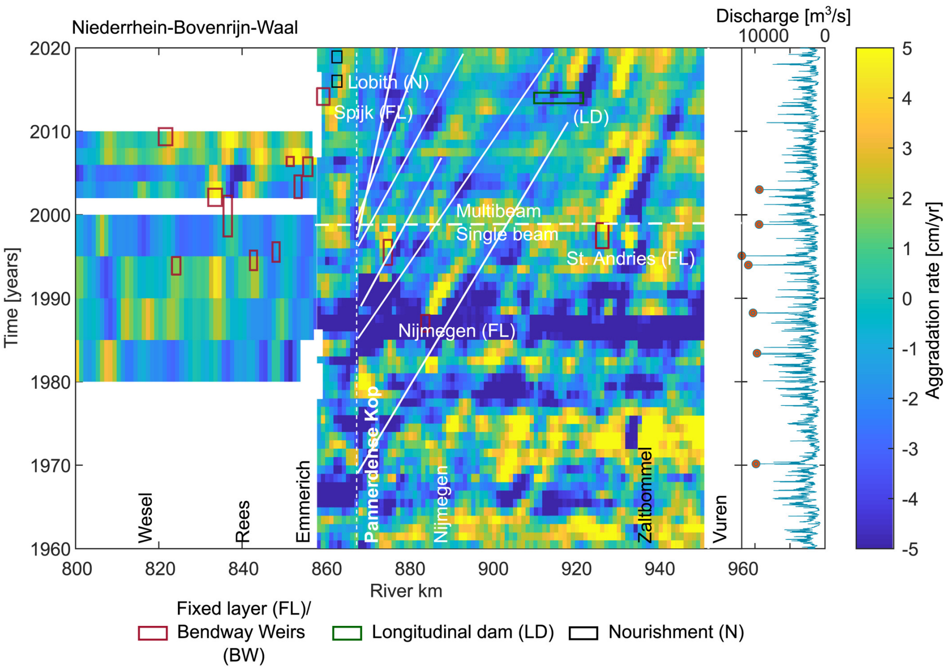


Figure 3.11: Five-year averaged aggradation rates for Niederrhein-Bovenrijn-Waal as presented by Chowdhury et al. (2023). The aggradation rate is determined based on yearly measurements using a 2-km moving average window. The values are averaged over 5 years to smoothen out temporal changes. The white lines indicate downstream migrating erosion waves initiated at the Pannerden bifurcation during peak flows. Please note that Chowdhury et al. (2023) presents the Bovenrijn is on the left of this figure and the Waal on the right, unlike the other images in this report where the Bovenrijn is presented at the right and the downstream branches on the left.

A figure similar to 3.11 is made using the biweekly dataset, see Figure 3.12.

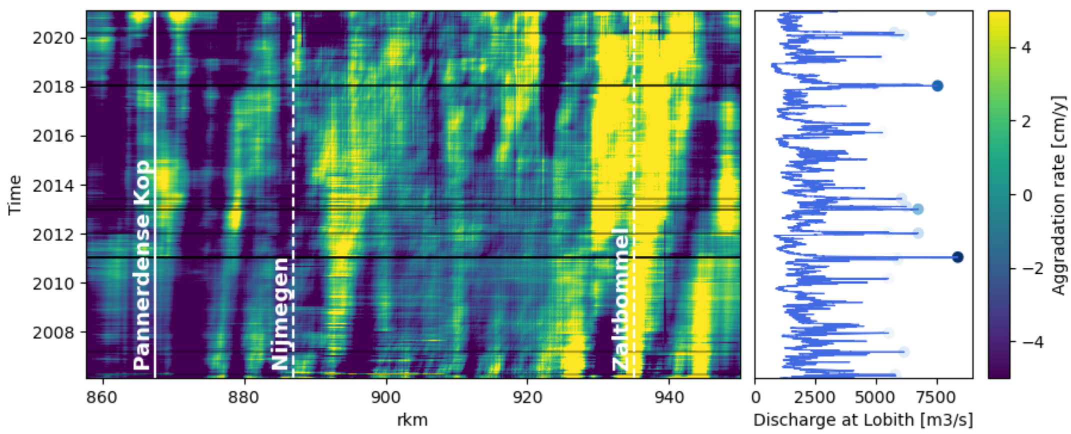


Figure 3.12: Aggradation rates in the biweekly dataset. Similar to Figure 3.11, a 2 km moving average and a 5 year averaging is used. Please note that the Bovenrijn is on the left and the Waal on the right in this figure unlike the other images in this report. This is done to create an image similar to Figure 3.11.

After the peak flows of 2011 and 2018, there is no clear sign of an erosion wave starting at the Pannerdensche Kop in Figure 3.12. After those 2 largest peaks in 2011 and 2018, there rather seems to occur some aggradation at the Pannerdense Kop until a few kilometers downstream. These aggradation waves disappear after a few years and do not travel far downstream. Thus, this dataset does not show erosion adjustment waves starting at peak flows as in Chowdhury et al. (2023). Possibly, this difference is linked to the fact that the peak flows in Figure 3.11 are larger (>9000 m^3/s) than the peak flows in Figure 3.12 (max. 8400 m^3/s). On the other hand, the presence of the erosion wave may also be indicated unjustly as the current analysis (Fig. 3.11) depends on several assumptions: (a) it is assumed that the erosion wave travels downstream and does not disperse and disappear, (b) the images are impacted by the choice of averaging over 2 km and 5 years and different choices may lead to different outcomes, (c) the erosion wave is assumed to have a constant velocity whilst this velocity may show variations based on discharge variations. A third reason why the erosion waves are visible in Figure 3.11 and not in Figure 3.12 is related to system changes. Many river interventions have changed the system and natural coarsening of the bed may also play a role.

In short, this chapter focused on the morphological response to peak flows at the Pannerdense Kop and distinguishes changes on three scales: small-scale dunes grow during peak flows and these dunes increase the roughness of the bed, intermediate-scale changes are observed at the upstream ends of the Waal and Pannerden Canal, at the outflows of floodplains, in river reaches with groynes, and in bends, and statements on the large-scale peak flow response follow from Chowdhury et al. (2023), who show an erosion adjustment wave in the Waal and deposition at the upstream end of the Pannerden Canal. Whereas this chapter focusses on the peak flow impact in field data, this research also focuses on the peak flow response in current models, which is treated in the next chapter.

4

Response to peak flows - 1D and 2D model

This chapter examines the morphological response to peak flows at the Pannerdense Kop as predicted by existing 1D and 2D morphological models. Section 4.1 provides the model information. The model results follow in Section 4.2.

4.1. Setup of the models

The 1D model used in this research was originally developed by Ylla Arbos et al. (2021) and further extended by Chowdhury et al. (2025). The purpose of the model is to determine the impact of climate change on the flow partitioning at the Pannerdense Kop and IJsselkop over the next 150 years.

This research also uses the 2D morphological model named *delft3d_4-rijn-j18*. The model was developed by Deltares for the project Integrated River Management (IRM, now called Room for the River 2.0). The model is a further development of the DVR (Duurzame Vaardiepte Rijndelta) model. The model description can be found in Sloff et al. (2024), although a slightly newer version of April 2025 is used with adjusted roughness and ripple factor values to improve the large-scale morphological behaviour. These values can be found in Table 4.2. The goal of the 2D model is to determine the morphological effect of river interventions such as the application of longitudinal training walls and is also used for decision-making for the overall river bed trends.

Both models are still in development. This is important to realise, because the model settings and results as presented in this report can deviate from the model settings and results of the final model versions.

1D versus 2D modelling

Modelling in 1D and 2D differs on several important points. A first difference is that variations over the width are in a 2D model and not in the width-averaged 1D model. A second difference between 1D and 2D modelling is strongly related to the first difference: the flow in lateral direction. 1D models generally do not take lateral flow into account, whilst 2D models can capture this 3D secondary flow effects, albeit in a parametrized manner. Secondary flow especially plays an important role in bends: the outer bend is deeper, has higher flow velocities and a larger bed surface grain size and transports coarser sediment than the inner bend (Chowdhury et al., 2023; Parker & Andrews, 1985). A third important difference is that morphological modelling of a bifurcation in 1D requires a nodal point relationship which determines the sediment distribution over the downstream branches. The sediment distribution can be expressed as a function of the discharge distribution (Wang et al., 1995), although other factors such as the transverse bed slope effect, helical flow, upstream asymmetry and bed topography effects can also be taken into account (Bolla Pittaluga et al., 2003; van der Mark & Mosselman, 2012). A nodal point relationship is not required in a 2D model. The advantage of 1D models is that they are less constrained by computational limits. For example, the 1D model used in this report took only 1 hour runtime to model 150 years, whilst the 2D model required 6 days to run with the current settings to model 32 years.

Model area

Both the 1D and the 2D model contain a large area of the Rhine river system. The 1D model area stretches from Bonn in Germany to the downstream boundaries of the Waal, Nederrijn and IJssel, see Figure 4.1a. The 2D area stretches from Xanten (rkm 825) in Germany to the downstream boundaries in the Waal, Nederrijn and IJssel, see Figure 4.1b.

(a) The 1D model domain (Chowdhury et al., 2025).

(b) The 2D model area. The model domains are indicated by the different colors (Sloff et al., 2024).

Figure 4.1: The modelled areas in the 1D and 2D models.

Schematization and initial conditions

The numerical grid cells are larger in the 1D model compared to the 2D model. In the 2D model, the main channel is subdivided into 6-20 cells over the width and the cells have a length in the order of 80 m. In the 1D model, the space step is 500 m and each cross section has only one cell.

Variations over the width are schematized differently in the models. In the 2D model, the geometry of floodplains is used although only the main channel is morphologically active. In the 1D model, the cross sections are based on smoothed floodplain and main channel widths, see Figure 4.2. Discontinuities at the bifurcations are preserved. The sediment transporting width in the 1D model is equal to the main channel only (RIZA, 2005).

The initial bed level in the 1D model is derived from measurements taken earlier than those used for the 2D model. In the 1D model, the initial bed level is the mean bed level of measured data over the period 1998-2002. In the 2D model, the bed elevation is determined for both the cell centers and the cell corners using the initial bed level from 2018 (Baseline j18).

The initial surface grain size is based on grain size measurements from 2020 in both models, yet the way of modelling the sediment differs in the models. Five sediment fractions are used in the 1D model, see Table 4.3. Similar to the widths, the volume fraction content of each sediment class is smoothened over the river reach in the 1D model. In the 2D model, the initial grain sizes are also based on the field data from 2020 and the sediment is divided into 11 sediment classes in the 2D model. The initial surface grain size distribution is kept similar over the width and a 10 kilometer moving average is used along the river to smooth out the high spatial and temporal variability.

The active layer thickness is constant over the whole model area in both models, being 0.8 m in the 1D model and 1 m in the 2D model.

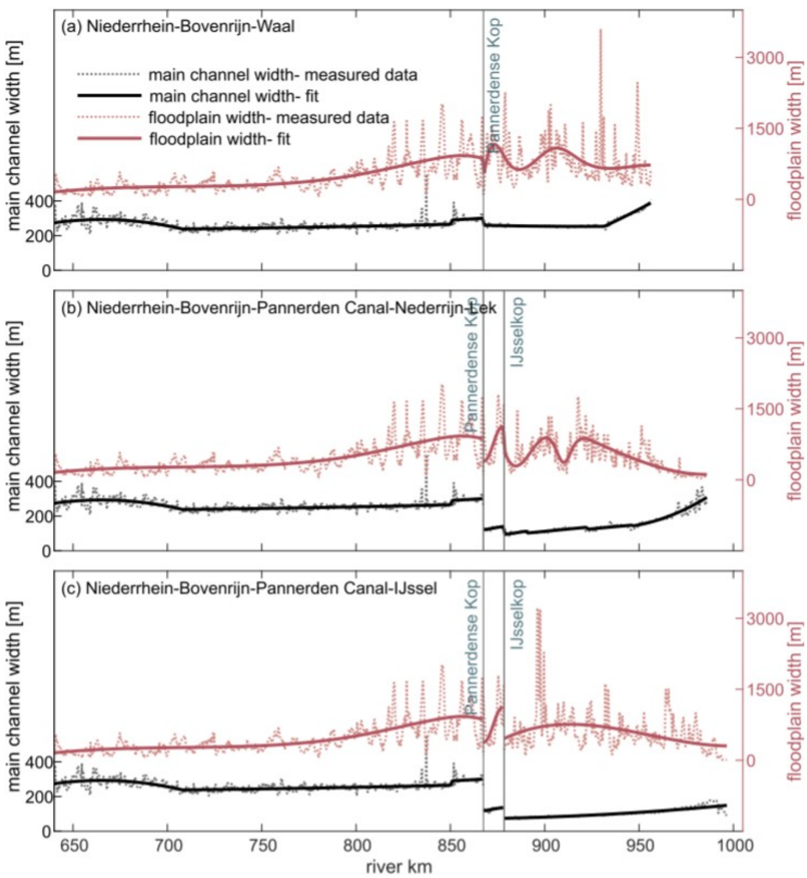


Figure 4.2: The main channel and floodplain widths are smoothened over the river reach using shape-preserving interpolation (Chowdhury et al., 2025)

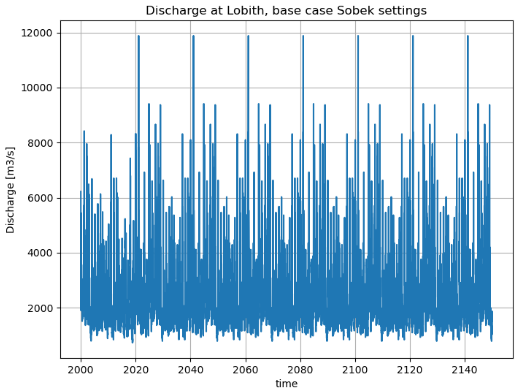
The nourishments of 2016 and 2019 in the Bovenrijn are modelled in the 1D model and not in the 2D model. In the 1D model, these nourishments are modelled as a total amount of 7000 m^3 sediment added to the reach 862-864 during 2016 and 2019, with 50% consisting of grain sizes between 2–8 mm and the remaining 50% comprising grain sizes between 8–31.5 mm.

The river bed is fixed at several locations. A very coarse layer prevents erosion of the river bed at Spijk (Bovenrijn, rkm 859-863) and in German reaches of the Rhine close to the Dutch border (Chowdhury et al., 2025). Additionally, bendway weirs are present in the bend near Erlecom (Waal, rkm 873-876) (Heitkönig, 2024). In the 1D model, the fixed layers are schematised as very coarse layers at 1.5 m below the initial bed surface over the full main channel. Around the Pannerdense Kop, such layers are in the model at rkm 850-862 and at rkm 874-876 in the Waal. In the 2D model, these fixed layers at Spijk and Erlecom are schematized as non-erodible cells and are located only at the part of the main channel where the fixed layer is present in reality.

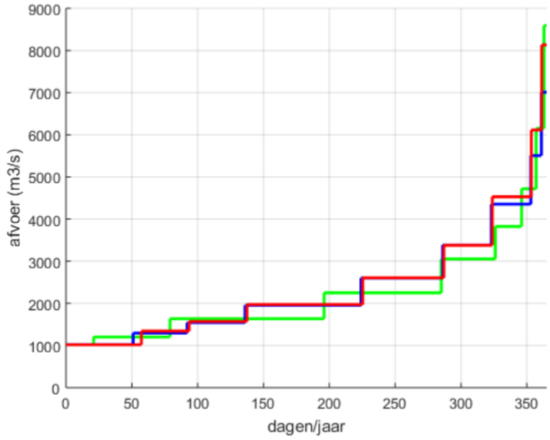
Groynes are modelled in a simplified manner in the 2D model and are not modelled in the 1D model. In the 2D model, areas around groynes are schematized as non-erodible layers. Groynes are thus in the 2D model but in a very simplified manner and the grid size is too large to reproduce exact flow patterns in the groyne fields. Based on this, a response near groynes can be expected in the 2D model, although this response is based on simplified behaviour. Groynes are not modelled in the 1D model.

Boundary conditions
Both models use discharges as upstream boundary condition and water levels as downstream boundary conditions.

In the 1D model, the model runs from 2000-2150 and the discharges are shown in Figure 4.3a. Discharges and water level measurements of 2000-2020 are used as boundary conditions for the model period 2000-2020. For the model years 2020-2150, the measured water levels and discharges of 1994-2013 are cycled, as that period represents current discharge statistics. Note that the 1994-2013 hydrograph also contains the peak discharge of 1995 with $Q_{max} = 11855 m^3/s$. Chowdhury et al. (2025) adopt hydrograph scenarios in the period of 2020-2150 to account for climate change. This research uses only the reference case, where the current rate of sea level rise is taken into account at the downstream boundaries.



(a) The discharges used in the 1D model run.



(b) Yearly discharge hydrograph levels and durations in the 2D model. Green is the previously used hydrograph and is the hydrograph used in this report, blue the hydrograph used for calibration and red the hydrograph used for IRM (Klijn et al., 2022).

Figure 4.3: The discharges imposed at the upstream boundaries for both the 1D and 2D model.

In the 2D model, the upstream boundary is a cycled yearly hydrograph. This simplification is required to limit the computational time. The yearly hydrograph consists of 9 discharge levels with different durations, see Figure 4.3b. These discharge levels and their durations are based on hydrograph statistics over 2011-2020 for the basic run. The highest discharge level used in calculations is 8400 m^3/s.

The highest peak discharges differ between the models. The 2D model has a yearly peak flow of 8400 m^3/s with a duration of three days. In the 1D model, the highest peak flow is the peak flow of 1995, with 11,885 m^3/s which occurred over a longer period and returns every 20 year as a result of the cycled hydrograph.

Sediment transport

Both models describe the sediment transport using a Meyer-Peter and Müller type of formulation. The sediment transport S [m^3/s] for grain size fraction i is determined by (Chowdhury et al., 2025; Deltares, 2018):

$$S_i = \Gamma F_i \sqrt{g \Delta D_i^3} (\mu \theta_i - \xi_i \theta_{cr})^{3/2} \tag{4.1}$$

where Γ is a calibration coefficient [-], F_i is the volume fraction content of grain size fraction i [-], g is the gravitational constant of 9.81 m/s^2, Δ is the relative density of sediment under water with a value of 1.65 [-], D_i is the characteristic diameter of grain size fraction i [m], μ is the ripple factor [-], θ_i is the Shields mobility parameter of grain size fraction i [-], θ_{cr} is the critical Shields' mobility parameter [-], and ξ_i is the hiding-and-exposure coefficient [-] which varies per grain size class according to hiding and exposure formulations. The hiding-and-exposure coefficient is based on the formulations of Ashida and Michiue (1972) and Egiazaroff (1965) in the 1D model and Parker et al. (1982) in the 2D model.

The Shields mobility parameter θ_i of grain size fraction i is defined by:

$$\theta_i = \left(\frac{u}{C}\right)^2 \frac{1}{D_i \Delta} \tag{4.2}$$

where u is the flow velocity [m/s] and C is the Chézy friction coefficient [$m^{1/2}/s$].

Spin-up, calibration and verification
In the 1D model, the period 2000-2010 is used as spin-up period and the period 2010-2020 is used for calibration. The critical Shields stress θ_{cr} and the calibration factor Γ are calibrated using bed level measurements over 2010-2020 such that (a) the sign and order of magnitude of the mean aggradation are optimised per branch, and (b) the discharge partitioning ratio at the bifurcations is optimised. The calibration values are presented in Table 4.1. Verification of the model is done by comparing measured water levels with water levels in the model at Lobith, Nijmegen, Arnhem and Doesburg in the period 2010-2020.

Table 4.1: Variables in the sediment transport formula of the 1D model per branch. *Increases from 32 $m^{1/2}/s$ at rkm 840 to 40 $m^{1/2}/s$ at the Pannerdense Kop. **35 $m^{1/2}/s$ at the Pannerdense Kop and increases further downstream.

Variable		Bovenrijn	Waal	Pannerden Canal
Γ	Calibration factor	10.4	3.2	8.0
μ	Ripple Factor	0.7	0.7	0.7
θ_{cr}	Critical Shields mobility parameter	0.043	0.028	0.030
C	Chézy friction coefficient	40*	35**	40

In the 2D model, a spin-up period of at least one hydrodynamic day is used for every discharge level. The morphological spin-up period of the 2D model is divided in two parts. First, a spin-up period of two years is used for local adjustments around fixed layers. Secondly, a spin-up period of two years is used for the whole model area with all branches.

Calibration of the 2D model is divided into hydrodynamic and morphological calibration. The hydrodynamic part of the model is calibrated first: the Chézy value is calibrated for each discharge level using water levels as measured in 2018, the discharge partitioning at the bifurcation in 2023, the discharge partitioning in the main channel in WAQUA model results, and hydrographs at certain specific locations. This calibration led to the Chézy values as presented in Table 4.2.

The calibration of most morphological parameters in the 2D model is done for previous model versions and additional calibration steps were done for the current model. For the model version *delft3d_4-rijn-j18* (Sloff et al., 2024), the morphological calibration focuses on: (a) reproducing changes in discharge distribution at the Pannerdensche Kop and IJsselkop due to the uneven erosion of both branches, (b) reproducing trends in sediment transport from Sloff (2019), (c) ensuring morphological displacement rates in the Bovenrijn–Waal are in the order of 1 km/year, (d) reproducing bed level trends per model domain by comparing it to values from Sloff (2019), (e) reproducing the 2D bed configuration (bend profiles), (f) ensuring that the model is suitable for evaluating the effect of measures on bed configuration. Several sediment transport formulations were tested with the aim to match the yearly sediment transport per branch of Frings et al. (2019) and bed level trends per model domain over 20 years of Sloff (2019). The resulting adjustments do not show large unrealistic bed level trends anymore, which was present in previous model versions. Still, the model overestimates trends for multiple trajectories and shows excessive sensitivity to changes in the discharge regime. Further adjustment is done after the official version was published to solve these problems, with the aim to better reproduce the large-scale morphological trends. This has led to lower Γ (also referred to as Acal) value in the Pannerden Canal, a reduced ripple factor, and slight variations of the Chezy friction coefficient which was previously set to a constant value of 50 $m^{1/2}/s$. The morphological factors per branch are presented in Table 4.2. Still, the erosional trends in the domains around the Pannerdense Kop differ from prognoses, up to -0.8 cm/y in the Bovenrijn whilst a stable Bovenrijn with 0.0 cm/y was expected (Sloff, 2025).

In summary, there are several similarities and differences in the calibration of the models. Both models calibrate using aggradation rates and the 2D model also considers the yearly sediment transport. Both models consider the discharge partitioning in the calibration. Besides this, the 2D model also focuses on bend profiles and the effect of interventions which is not considered in the calibration of the 1D model.

Table 4.2: Variables in the sediment transport formula of the 2D model per branch and domain. The domains are indicated by the colors in Figure 4.1b, where the bifurcation is at the transition of the pink coloured Bovenrijn (br2), the yellow coloured Pannerden Canal (pan), and the light grey coloured upper part of the Waal (wl2a). *This factor reduces in the downstream direction within this domain, so the bed becomes rougher in downstream direction. **The ripple factor in the Pannerden Canal is dependent on the discharge level.

Variable		Bovenrijn br2	Waal wl2a	Pannerden Canal pan
Γ	Calibration factor	2.4	2.0	3.2
μ	Ripple factor	0.9	1 to 0.89*	1 to 1.9**
θ_{cr}	Critical Shields mobility parameter	0.025	0.025	0.025
C	Chézy friction coefficient	50	50 to 48*	50 to 48*

The fact that the morphological calibration of both models is limited to the order of magnitude shows the uncertainty bandwidth of the morphological models: the morphology may still vary within an order of magnitude. Furthermore, the peak flow impact is not considered separately in the calibration and the role of peak flows in the morphological development may therefore be over- or underestimated. However, improvements to the calibration of the morphology in the models is often limited by a lack of calibration data and for improvements of the model it is important to keep the model purpose in mind: improvements are not really required when the relevant model model outcomes are insensitive to the changes.

Nodal point relationship
In the 1D model, a nodal point relationship is required at the bifurcation point to ensure solvability of the 1D equations. In this model, the nodal point relationship describes the sediment distribution at the bifurcation Q_{sPCi}/Q_{sWLi} for each grain size fraction i based on the discharge distribution at the bifurcation Q_{PC}/Q_{WL}:

$$\frac{Q_{sPCi}}{Q_{sWLi}} = \alpha_i \left(\frac{Q_{PC}}{Q_{WL}}\right)^{k_i} \tag{4.3}$$

Calibration of the α and k values is based on the sediment distribution in a 2D model by Becker (2021). That 2D model uses a yearly hydrograph upstream with 9 discharge levels, the highest being 8592 m^3/s. The α and k values resulting from the calibration are presented in Table 4.3.

Table 4.3: The grain size fractions used in the 1D model, and the nodal point relationship parameters for each grain size fraction at the Pannerdense Kop.

Grain size fractions	α	k
0.063-0.5 mm	10	3.9
0.5-2 mm	18	4.5
2-8 mm	44	5.3
8-31.5 mm	72	6.0
31.5-125 mm	80	6.2

4.2. Model results

This section provides the model results. The 1D model results are presented first, followed by the 2D model results.

1D model results
The main channel bed level change in the 1D model is shown in Figures 4.4 and 4.5. The spin-up period 2000-2010 is left out, and a period of 20 years is shown as this contains both the period 2010-2020

which can later be compared to the biweekly field dataset and 2020-2030 which contains a peak flow of almost 12.000 m^3/s.

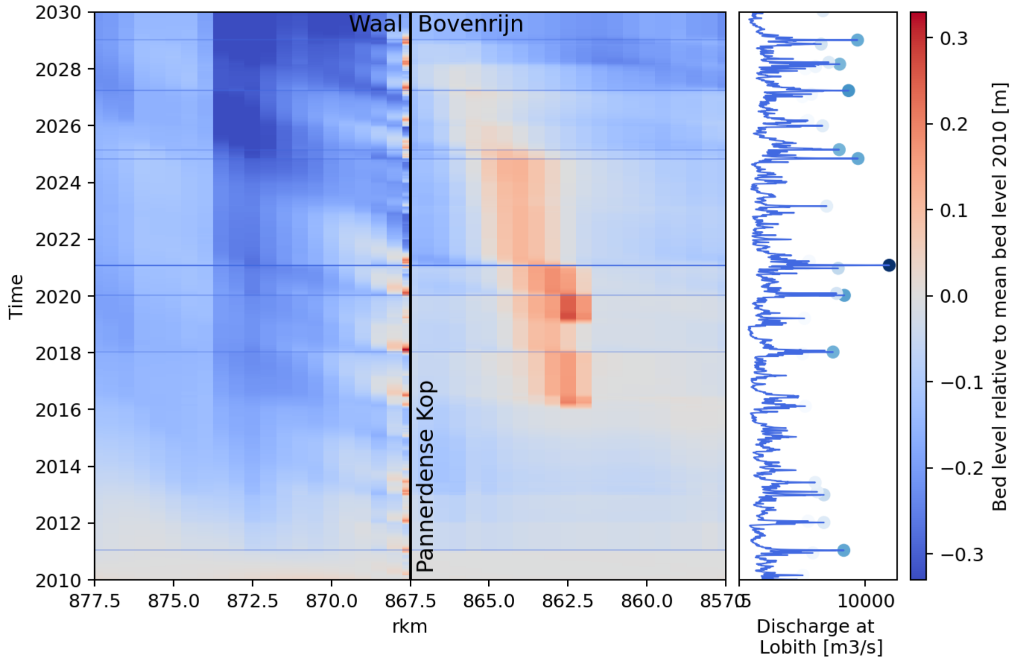


Figure 4.4: Bed level changes in the Bovenrijn and Waal according to the 1D model (reference case) over a 20 year period. The mean bed of 2010 is used as reference bed level.

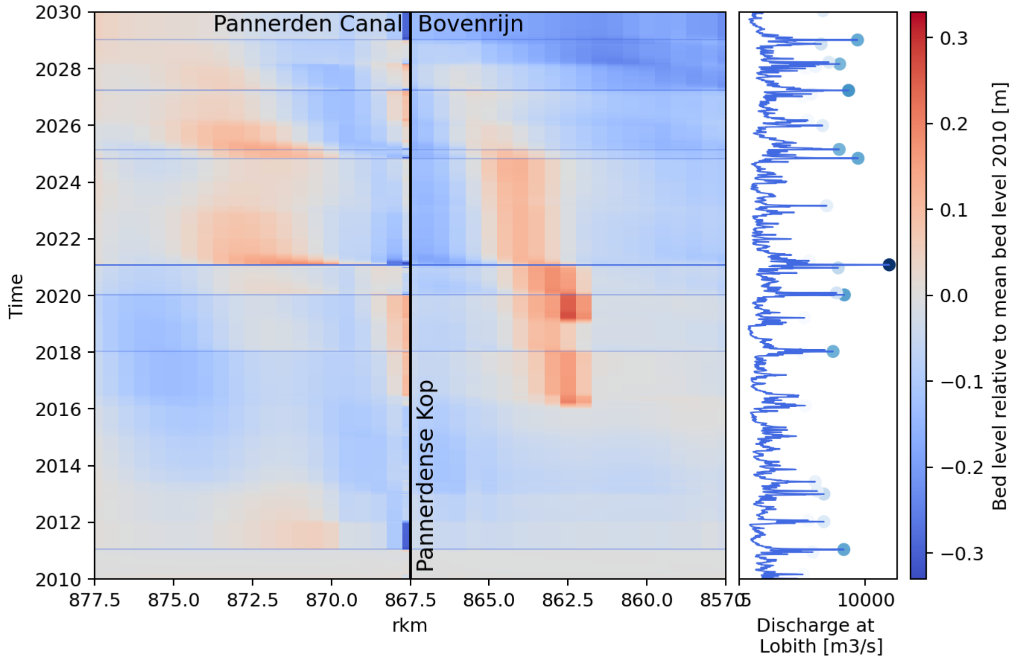


Figure 4.5: Bed level changes in the Bovenrijn and Pannerden Canal according to the 1D model (reference case) over a 20 year period. The mean bed of 2010 is used as reference bed level.

The 1D model response of the Bovenrijn in Figures 4.4 and 4.5 clearly shows the nourishments of 2016 and 2019. The nourishments at rkm 862-864 travel downstream and disperse during the peak flows of 2018, 2020, 2021, 2025, and 2028. Besides the movement of nourishments, the ongoing erosional trend possibly intensifies after a peak flow, which is slightly visible after the 2021 peak flow close to the Pannerdense Kop and after groups of somewhat lower peak flows in 2012 and 2028.

Figure 4.4 shows the bed level changes in the Waal in the 1D model, where deposition is observed at the upstream end of the Waal after a peak flow and the erosional limit seems to be reached for the fixed layer at rkm 874-876. The deposition at the upstream end of the Waal correlates with the occurrence of peak flows. Such deposition is visible after many peak flows and this deposition travels downstream and disperses. A similar aggradation wave is harder to distinguish for peak flows after 2021, as the first grid cells of the Waal erode faster than the downstream area. Still, a closer look shows that aggradation still occurs in each cell, starting at the upstream end of the Waal and moving in downstream direction. At rkm 874-876, at the location of the bendway weirs of Erlecom, the impact of the fixed layer becomes visible and the erosional limit of 1.5 m below the initial bed level seems to be reached there.

The bed level changes in the Pannerden Canal in Figure 4.5 show a clear peak flow response and deposition at the upstream which may be related to the nourishments. The response to peak flows is most clearly visible after the large peak flows of 2011, 2021 and 2025, showing erosion at the upstream kilometer and deposition at rkm 870-873. This erosion and deposition travel downstream and disperse in the years after a peak. Besides, some deposition at the upstream kilometer of the Pannerden Canal is observed in 2016-2020 and 2025-2029. This deposition does not seem to be linked changes in discharge. Possibly, this deposition is the result of sediment from the nourishments that travels downstream.

The bed level change until 2150 around the Pannerdense Kop is shown in Figures 4.6 and 4.7 and these figures likely show the impact of fixed layers. A sharp transition of erosional trend becomes apparent at rkm 862 from 2050 onwards. Upstream of rkm 862, the erosion is limited and downstream the erosion accelerates and travels downstream across the Pannerdense Kop. Similarly, an erosional limit seems to be reached at rkm 874-876. These locations of erosional limits match with the fixed layer locations. Erosion directly downstream of fixed layers is observed downstream of fixed layers in real-life cases (Klijn et al., 2022) and the erosion in the 1D model observed at rkm 862 travelling downstream may similarly be linked to the fixed layer of Spijk. This accellerated erosion downstream of the fixed layer of Spijk travels downstream into the Waal and the Pannerden Canal and thereby play a crucial role in the bed level behaviour around the Pannerdense Kop towards 2150. The impact of peak flows is less evident than the impact of the fixed layers on this timescale.

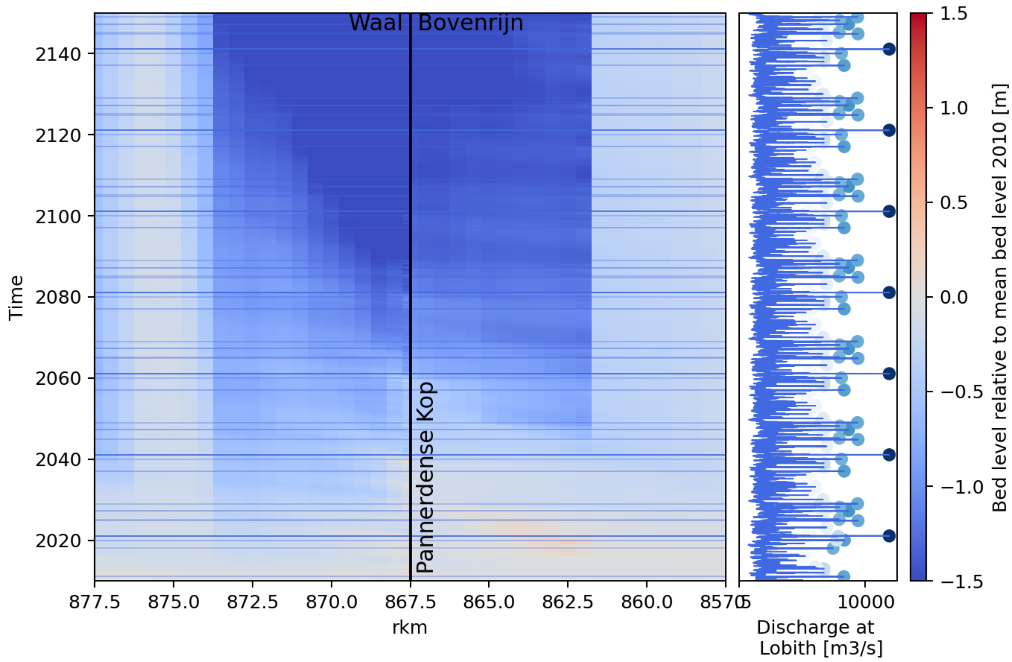


Figure 4.6: Long-term bed level changes in the Bovenrijn and Waal according to the 1D model (reference case) over a 140 year period. The mean bed of 2010 is used as reference bed level. The fixed layers at Spijk and Erlecom are in the model at rkm 857.5-862 and at rkm 874-876.

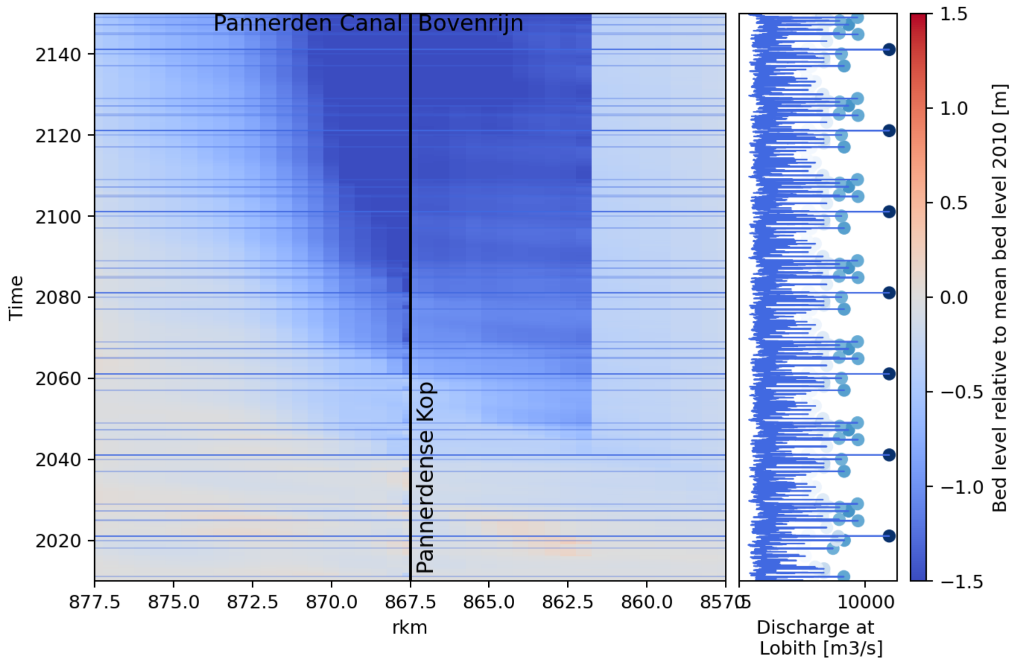


Figure 4.7: Long-term bed level changes in the Bovenrijn and Pannerden Canal according to the 1D model (reference case) over a 140 year period. The mean bed of 2010 is used as reference bed level. The fixed layers at Spijk is in the model at rkm 857.5-862.

Figures 4.8 and 4.9 show the sediment transport and distribution over the branches in the 1D model for different discharges. From Figure 4.8 follows that in the 1D model, the sediment transport ranges from less than 0.01 m^3/s during low flow conditions to 0.2-0.25 m^3/s during peak flows with Q = 12000 m^3/s. Figure 4.9 shows that in the 1D model, the share of sediment entering the Waal decreases during higher discharges, up to only 25% of sediment entering the Waal during peak flows with Q = 12000 m^3/s. This reduction is related to changes in discharge partitioning as defined in the nodal point relationship (Equation 4.3).

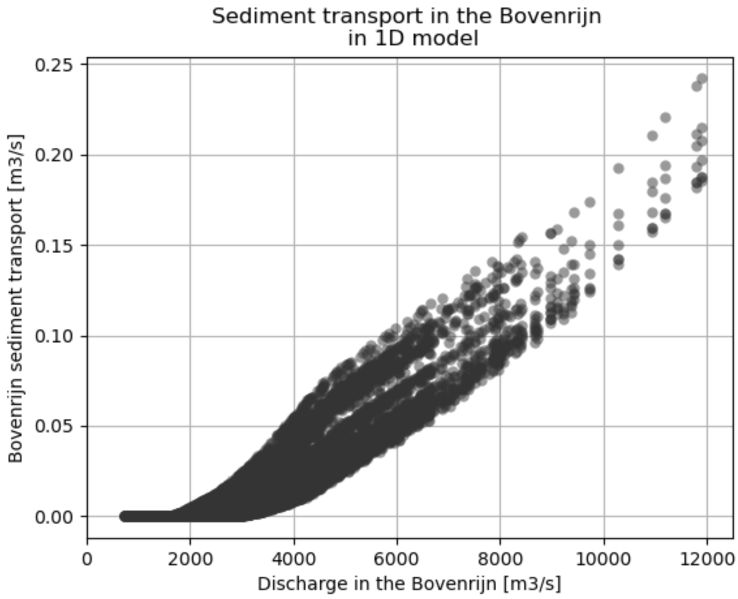


Figure 4.8: Sediment entering the bifurcation point in the 1D model.

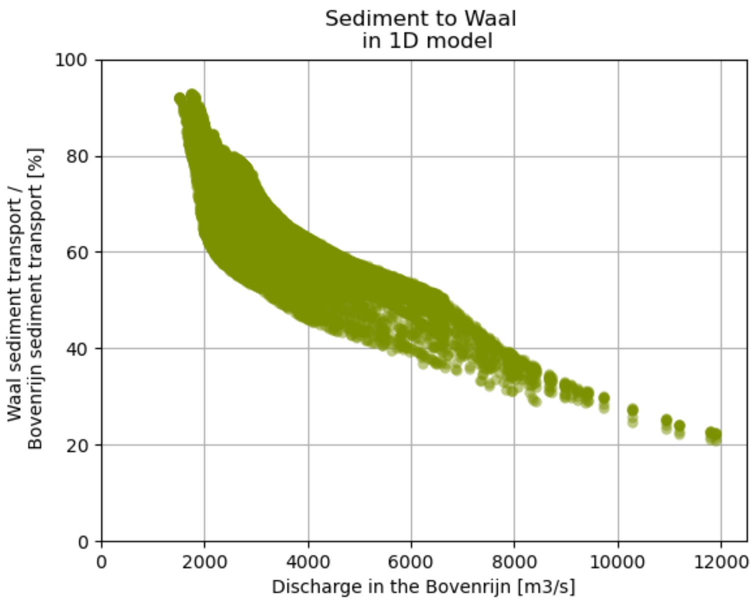


Figure 4.9: Sediment distribution at the bifurcation point in the 1D model.

2D model results

The main channel bed level change in the 2D model is shown in Figures 4.10 and 4.11. Although the full model run spans from 2018 to 2050, only the model period 2023-2033 is shown here. The first five years are omitted to prevent any remaining spin-up effects and a span of 10 years is chosen because it shows both the yearly trend and gives an impression of the ongoing trend. The bed level is averaged over the main channel.

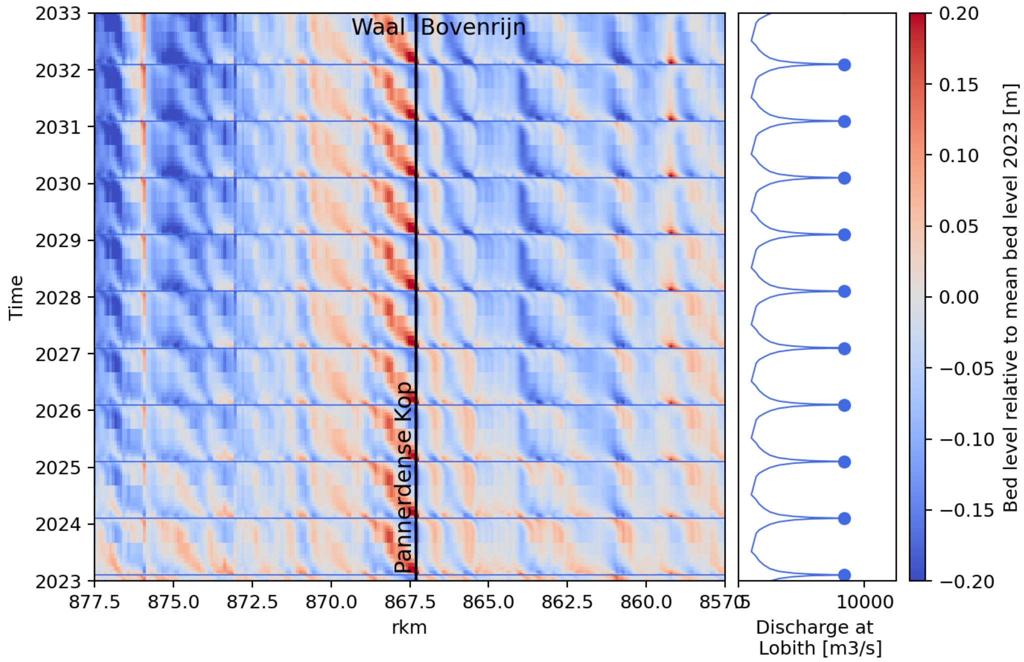


Figure 4.10: Bed level changes in the Bovenrijn and Waal according to the 2D model over a 10 year period. The mean bed of 2023 is used as reference bed level.

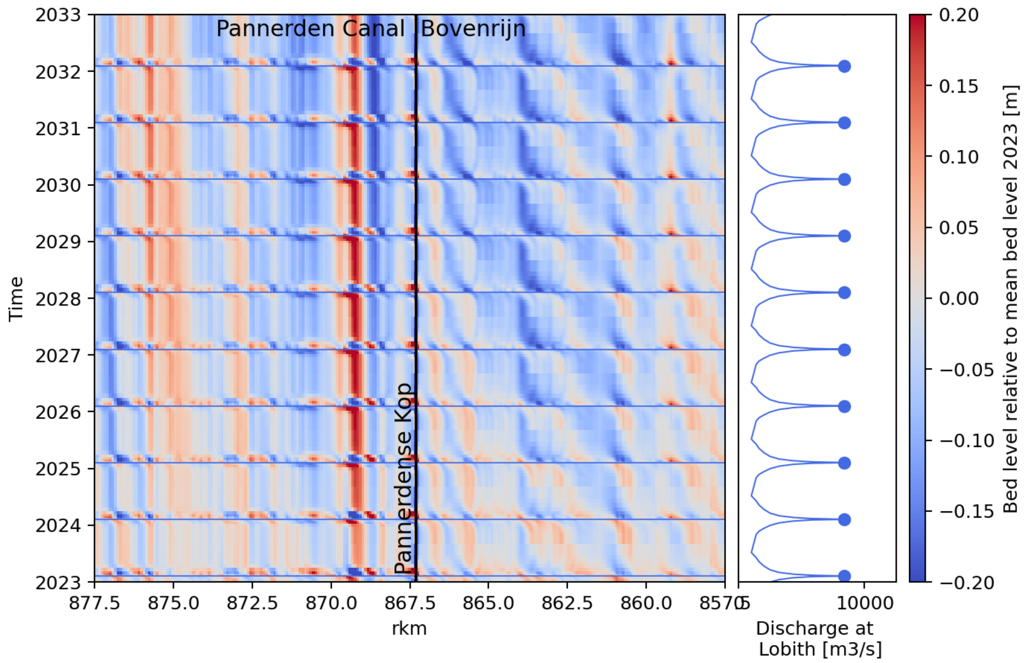
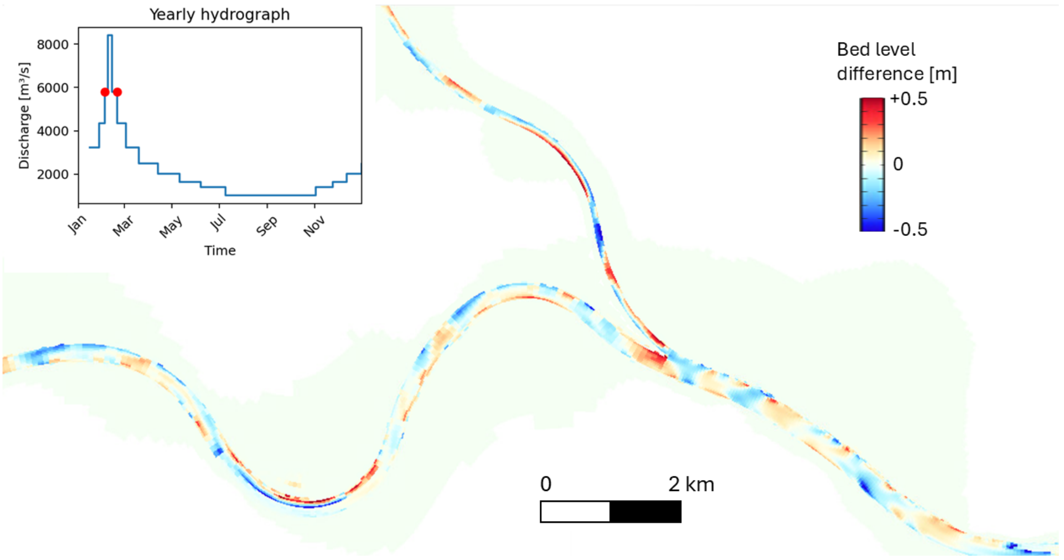
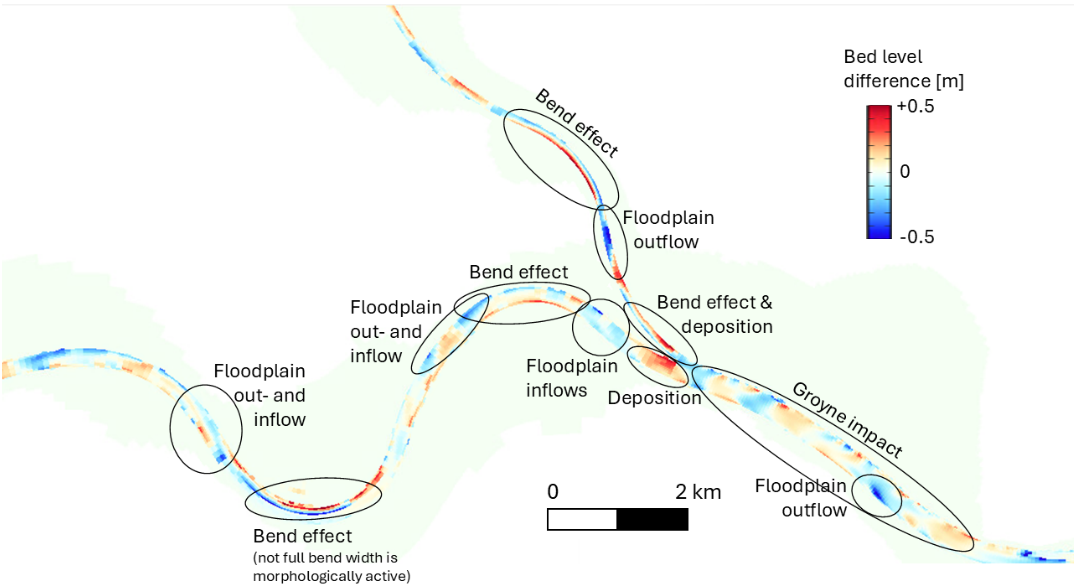


Figure 4.11: Bed level changes in the Bovenrijn and Pannerden Canal according to the 2D model over a 10 year period. The mean bed of 2023 is used as reference bed level.

A clear yearly signal is visible in Figure 4.10 and 4.11, which is a result of the cycled yearly hydrograph. This is visible as a pattern with changes of the order a few hundred meters that repeats on a yearly basis. Figure 4.10 shows that a peak flow leads to deposition at the upstream end of the Waal, which subsequently moves downstream. This aggradation wave may be the continuation of the aggradation wave that is visible in the Bovenrijn in the previous year. Figure 4.11 shows that very close to the Pannerdense Kop bifurcation, a peak flow leads to deposition over the upstream 0.5 kilometer of the Pannerden Canal. This deposition moves down slightly and dissipates during the next peak flow. In the Pannerden Canal, a slight deposition is visible after peak flows at the upstream end which disperses during lower flow, and at rkm 868-869, deposition starts during peak flows which travels slightly downstream, and downstream of this deposition, erosion is visible just after peak flows.



(a) Bed level changes in the 2D model around the Pannerdense Kop over a peak flow, based on the bed level before and after the peak flow, as indicated by the red dots in the yearly hydrograph. This image is created with the data from 2023 and similar maps for later years show the same response.



(b) The same bed level difference map resulting from the 2D model as shown in Figure 4.12a. In this figure, the impact of local geometries is indicated at specific locations.

Figure 4.12: Map of bed level changes in the 2D model due to a peak flow.

Figure 4.12 shows the difference in bed level over one peak flow event, with patches of erosion and deposition distributed over space. These patches can be linked to several river characteristics. First of all, deposition is observed at the upstream ends of the Waal and the Pannerden Canal. Secondly, erosion is observed at floodplain outflows. Deposition may be expected at the floodplain inflows (Ahrendt et al., 2022), but this is not clearly visible. A third observation is a pattern of erosion and deposition in the Bovenrijn. At the northern bank, the erosion and deposition start at the banks at intervals with a length of groyne fields and spread out into the main channel. At the river axis of the Bovenrijn, longer stretches of deposition and erosion are visible, which could be the elongated impact of groynes, but may also be large bedforms or alternating bars. A fourth impact is observed in bends: the inner bends deposit and the outer bends erode. This effect is clearest in the Pannerden Canal and least clear in the relatively straight Bovenrijn.

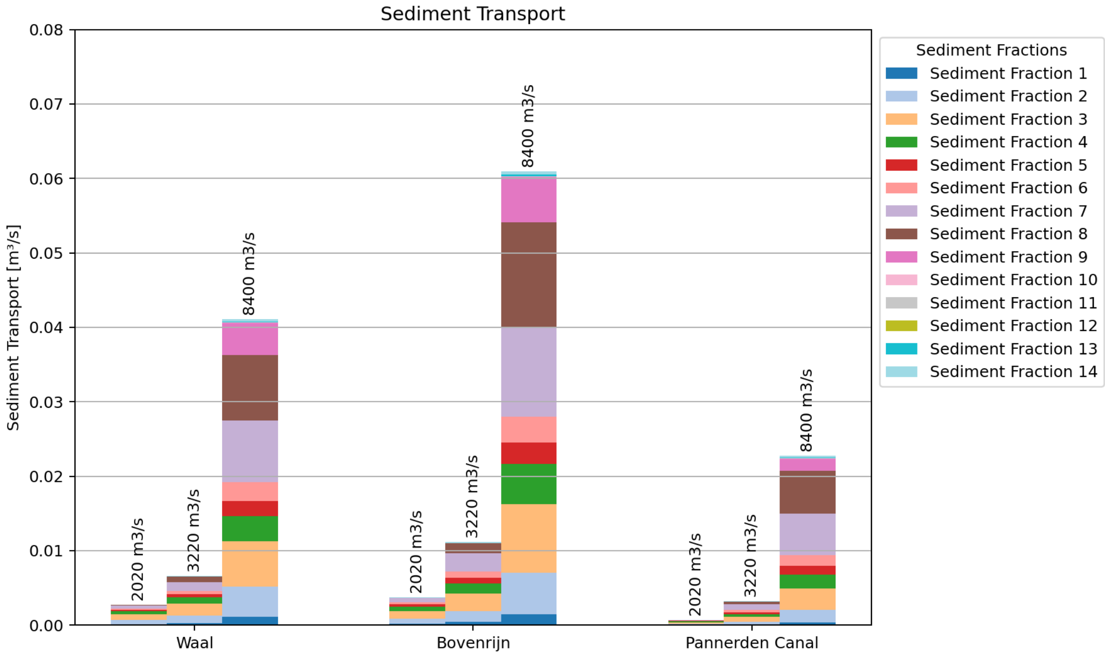


Figure 4.13: Sediment transport in the 2D model in the direction along the river at the bifurcation. Sediment class 1 is the finest sediment, sediment class 14 is the coarsest sediment. 8400 m^3/s is the yearly peak flow, 2020 and 3220 m^3/s represent normal flow conditions. The sediment transport of the Pannerden Canal and Waal do not exactly add up to the sediment transport of the Bovenrijn but deviate with a few percent, which may be related to erosion or deposition at the bifurcation or to rounding errors.

The 2D model sediment transport in Figure 4.13 shows how the sediment transport changes during higher discharges and which sediment fractions are transported. The figure shows that the sediment transport increases strongly during peak flows. Sediment fractions 11-14 play a negligible role, fractions 2-6 are already transported during normal flow conditions, and fractions 8 and 9 play an important role during peak flows. The percentage of sediment from the Bovenrijn entering the Waal are 79% during Q = 2020 m^3/s,67% during Q = 3220 m^3/s, and 64% during Q = 8400 m^3/s, so the share of sediment entering the Waal reduces during peak flows according to the 2D model.

To sum up, a 1D and a 2D morphological model are described in this chapter and their morphological response to peak flows is determined. The 1D model shows the following peak flow response: erosion at the upstream end of the Pannerden Canal followed by deposition further downstream, deposition at the upstream end of the Waal, movement of the nourishments in the Bovenrijn, possibly a slight erosion over the Bovenrijn, more sediment is transported, and a larger share of the sediment enters the Pannerden Canal. In the 2D model, the yearly peak flow leads to deposition at the upstream ends of the Waal and Pannerden Canal, to erosion at the floodplain outflows, to patterns of erosion and deposition which may be linked to groynes the Bovenrijn and to inner bend deposition and outer bend erosion. The increased sediment load is distributed slightly more towards the Pannerden Canal during peak flows in the 2D model. In the next chapter, the model responses found in this chapter are compared to the peak flow response observed in the field data.

5

Comparison of field data and model results

This chapter uses the results of Chapters 3 and 4 to compare the morphological impact of peak flows in field data, in the 1D model and in the 2D model. The presence of small-scale dunes during peak flows are compared in Section 5.1. The occurrence of intermediate-scale bed level changes in the field data and model results is compared in Section 5.2. A comparison of peak flow impacts at a large scale is provided in Section 5.3.

5.1. Comparison of small-scale changes

Although dunes are observed during peak flows in several types of field data, dunes do not appear in the 1D and 2D model. As found in field measurements in Section 3.1, dunes grow with an increasing discharge and diminish in the falling stage of the peak flow until the dunes disappear several weeks after the peak flow. The highest dunes during the 1998 peak flow had a height of 1.2 m and a length of 40 m. A grid cell in the 2D model has a length of roughly 80 m and a grid cell in the 1D model has a length of 500 m, see the model descriptions in Section 4.1. This means that both models have a grid size that exceeds the length scale of these small-scale changes, so dunes are too small to appear in the models. Furthermore, the increased bed roughness due to dunes is not considered in the modelling process: calibration of the parameters such as the Chezy coefficient and the ripple factor focus only on the long-term trends and do not separately consider the temporal increase of roughness during high discharges.

5.2. Comparison of intermediate-scale changes

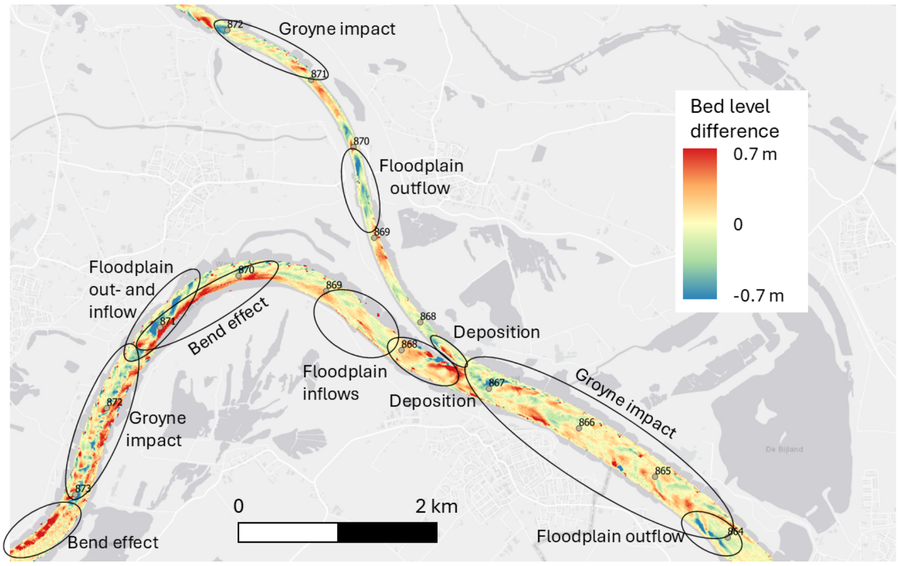
Changes with a length scale of several hundreds of meters are observed in the field data and model results. First, it is explained why there are almost no intermediate-scale changes in the 1D model results. Secondly, the spatial distribution of the intermediate-scale changes in the field data and the 2D model is compared. Third, the temporal behaviour of the intermediate-scale changes in time and space is compared by use of the field data and the 2D model results.

Limited appearance in 1D model results

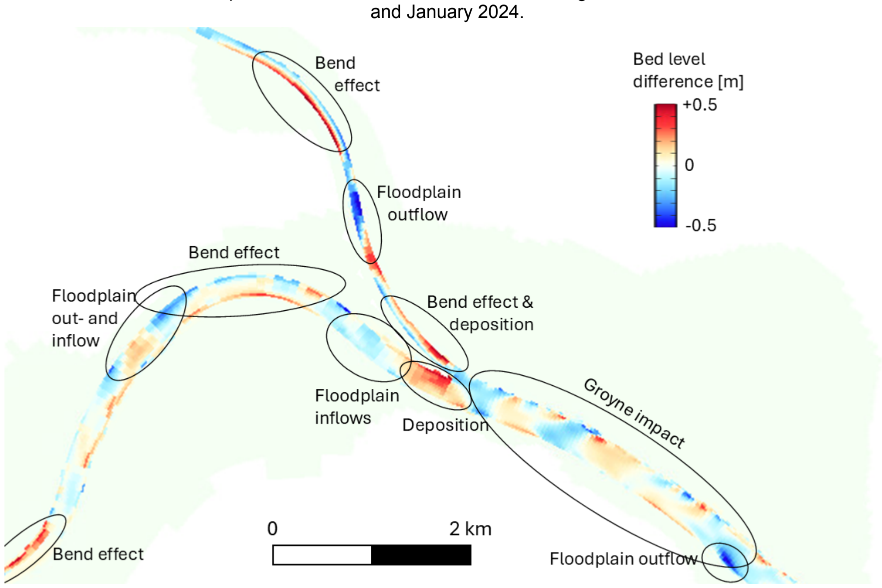
In the 1D model, intermediate-scale peak flow responses are only observed at the upstream ends of the Waal and Pannerden Canal, and not at other locations. The 1D model results in Section 4.2 show erosion at the upstream end of the Pannerden Canal and deposition at the upstream end of the Waal after peak flows. No other changes with a length scale of several hundred meters are observed in the 1D model results. This leaves out the changes that are linked to groynes, bends and floodplains observed in the 2D model results and several field data sources. The absence of these intermediate-scale changes is a result of the model schematization: as shown in Figure 4.2, the width is smoothened over multiple kilometers where only discontinuities at the bifurcations are preserved, which leaves out local effects of floodplain narrowing and widening. Additionally, groynes are not in the 1D model and the effect of helical flow in bends is not captured in the 1D model.

Differences in spatial distribution of bed level changes

The spatial distribution of the bed level changes over a the peak flow is shown using the field data around the 2023 peak flow in Figure 5.1a, and using the 2D model results in Figure 5.1b. When the field data and the 2D model results are compared, a general observation is that the order of magnitude and locations of the erosion and deposition patches are very similar.



(a) Bed level difference over the peak flow of December 2023, created using bed level measurements of October 2023 and January 2024.



(b) Bed level changes due to a peak flow in the 2D model.

Figure 5.1: The spatial distribution of bed level changes due to a single peak flow event in field data and the 2D model results.

A more detailed comparison using Figure 5.1 shows several similarities and differences in peak flow responses:

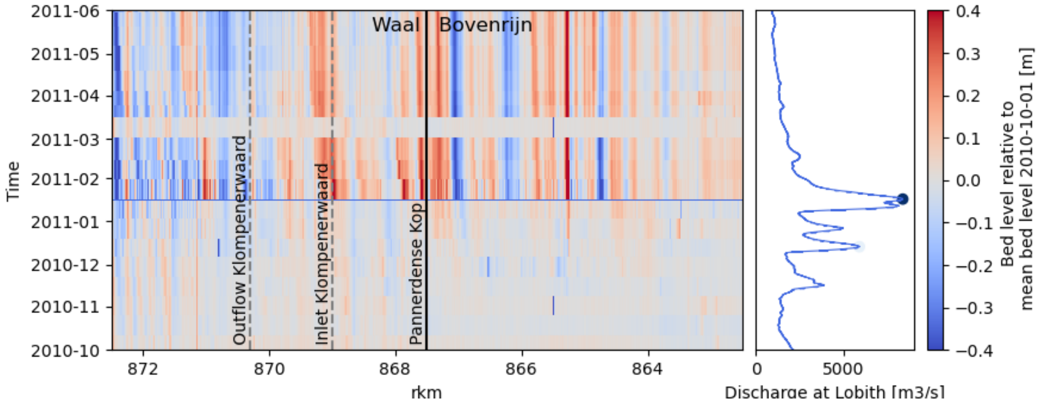
- An overall **deposition at the upstream end** of the Waal and a smaller patch of deposition at the upstream end of the Pannerden Canal is visible after both peak flow events. The deposition in the Waal is located close to the northern bank, in the area where a scour hole is also present (see the bed levels in Fig. 3.4). The deposition in the Pannerden Canal occurs over a smaller reach of ~200 m in the field data and is followed by some erosion. A difference is observed between the 2D results and the field data, as this deposition in the Pannerden Canal is located in the inner bend in the 2D model, whilst it is observed in the outer bend in the field data. The field data during the growth of the peak flow in February 2021 (Fig. 3.2) also shows a net deposition at the upstream ends of the Waal and Pannerden Canal, at the same locations as observed in the 23/24 field data. The 1D model results (Fig. 4.4 and 4.5) show deposition at the upstream end of the Waal and erosion at the upstream end of the Pannerden Canal. The erosion at the upstream end of the Pannerden Canal in the 1D model is an unexpected peak flow response compared to the peak flow responses visible in Figure 5.1.

- At locations where the **floodplains** flow into the main channel again, erosion is observed in both the 23/24 field data and the 2D model results. Patterns of erosion and deposition are expected at floodplain in- and outflows and erosion at a narrowing section is expected as the flow accelerates there (Ahrendt et al., 2022).
- A pattern of erosion and deposition in the Bovenrijn, possibly linked to the presence of **groyne fields**, is observed in both the field data and the 2D model results. Groyne flames are visible in the field data in the Bovenrijn and also occur in the field data at rkm 871-873 in the Waal and at rkm 871-872 in the Pannerden Canal, although these patterns are smaller than the ones observed in the Bovenrijn. The 2D model only shows a response near groynes in the Bovenrijn and the absence of groyne flames in the Waal and Pannerden Canal may be the result of a too coarse grid.
- The effect of **bends** is observed in the field data and the 2D model, although slightly different. The expected peak flow effect on bends is erosion at the outer bend and deposition at the inner bend (Parker et al., 2011; Pizzuto, 1994). A first difference is that the field data only shows deposition in the inner bends and no outer bend erosion, whilst the 2D model results also show outer bend erosion. This difference may be a limitation of the field data, as the erosion may have occurred in the unmeasured area in the outer bend, or the outer bend erosion is overestimated in the 2D model. Another difference is the location of the bend effects. The bend effect is only observed in the Waal in the field data, but also occurs in the Pannerden Canal in the 2D model results. This difference in bend effect between the field data and 2D model may be caused by (a) an overestimation of the secondary flow in the Pannerden Canal in the 2D model, or (b) a different response in the Pannerden Canal in the field data as a result of the groyne and river bank lowering in 2023.

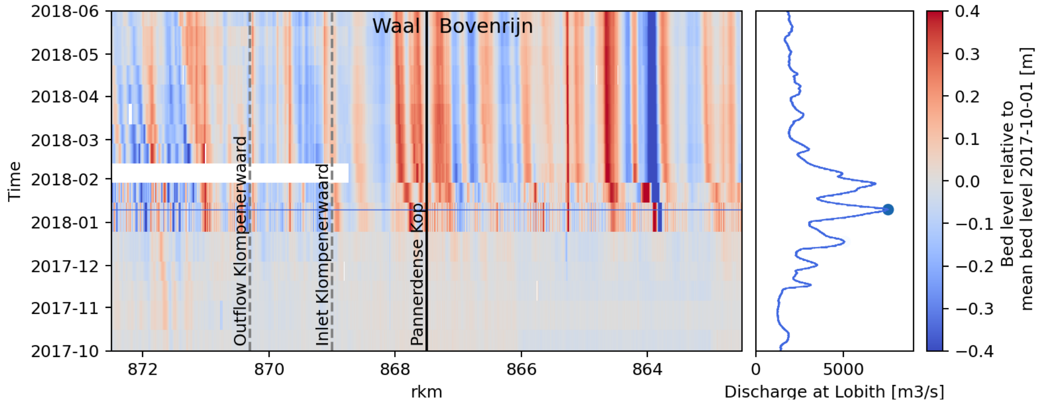
Differences in peak flow response over time

The peak flow response over time is compared using the biweekly field data and the 2D model results in Figure 5.2. The comparison shows many narrow stripes during peak flows in the field data and not in the 2D data. These narrow stripes may be related to the presence of dunes as discussed in Section 3.1.

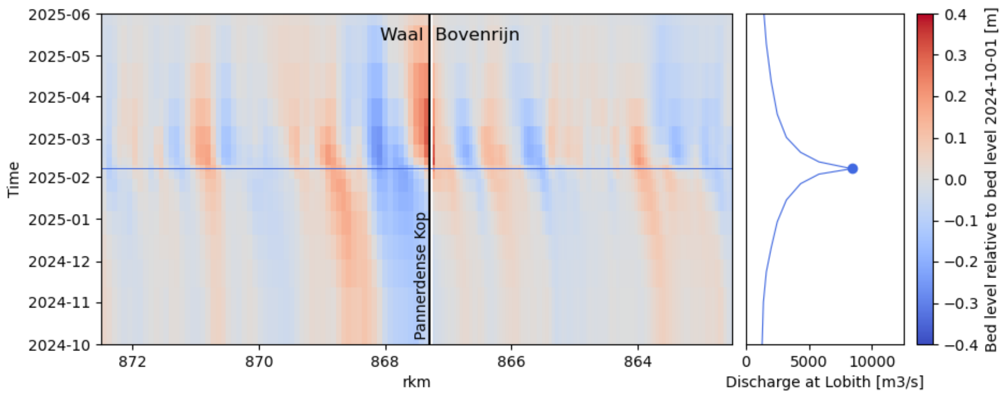
Although changes with a length of a few hundred meters are visible in both the 2D model results and the biweekly field data in Figure 5.2, these intermediate-scale responses differ on two points. First of all, the exact location of these changes differs. Secondly, the temporal behaviour differs: the peak flow response in the 2D model seems to be merely a continuation and movement of existing patterns, whilst the field data show a clear discontinuity and an initiation of new bed level changes at peak flows.



(a) The biweekly bed level measurements around the peak flow of 2011 with a maximum discharge of 8400 m^3/s.



(b) The biweekly bed level measurements around the peak flow of 2018 with a maximum discharge of 7550 m^3/s.



(c) The 2D model around a peak flow. The yearly peak discharge is 8400 m^3/s and has a duration of 3 days.

Figure 5.2: Bed level changes around a peak flow in both the biweekly field dataset and the 2D model results. The figures all show the bed levels relative to the first bed level over a period of eight months.

Several causes may explain the differences between the intermediate-scale peak flow responses in Figure 5.2:

- Differences in width-averaging. The biweekly field data is averaged over the ~150 m wide navigation channel, whereas the 2D model is averaged over the wider main channel. The impact of this difference is illustrated for two locations. First, the deposition at the upstream end of the Waal is located close to the northern bank, but the navigation channel is located around the centerline of the river at this location. This may explain why the deposition at the upstream end of the Waal is not clearly visible in the biweekly field data and is clearly visible in the field data maps and the 2D model results. Another location where the width-averaging plays a role is in bends. Navigation channels are often located in the deeper outer bends. For example, the navigation channel is located in the outer bend at rkm 869-872 in the Waal. Peak flows are expected to erode outer bends and aggrade inner bends during peak flows (Parker et al., 2011; Pizzuto, 1994), so if the bed level is only averaged over the outer bend, the inner bend deposition due to a peak flow is left out. Thus, the biweekly field data may show more erosion at bends than the 2D model results which includes the aggrading inner bends.

- Differences between peak flow events. The discharge differs between the peak flow events, which may result in different responses. The peak flows of 2011 and 2018 do not show exactly the same behaviour and part of these differences can be explained by the different hydrographs of the peak flows. Additionally, the yearly hydrograph of the 2D model also a different hydrograph which may also lead to a different response. A more elaborate intercomparison of the different peak flow events can be found in Appendix C.
- The impact of river interventions. As suggested in Section 3.2, the sediment nourishment of 2016 moves downstream during the peak flow of 2018, which may be the reason for the erosion and deposition visible around rkm 864 during the 2018 peak flow. The river interventions may impact the biweekly field data and are not in the 2D model.
- The model settings. For example, the yearly hydrograph, the grid size, the way groynes are schematised, the sediment transport coefficients, and many other settings influence the 2D model behaviour and the model will remain a tool to mimic reality being sensitive to model choices.

To conclude, this comparison of the 2D model and the biweekly bed level measurements shows differences in spatial and temporal behaviour, and the cause of these differences may be found in differences in width-averaging, different peak flows, the impact of river interventions, and model settings.

Upstream end of Pannerden Canal
In the 1990s, deposition was observed at the upstream end of the Pannerden Canal. This deposition was linked to peak flows by Chowdhury et al. (2023) and this deposition is expected to have changed the bifurcation system. The field data over the 2023 peak flow (Fig. 3.4c) also shows deposition at the upstream end of the Pannerden Canal, albeit only over a few hundred meters instead of a few kilometers. The peak flow response in the 2D model also shows deposition over several hundred meters of the upstream end of the Pannerden Canal (see Fig. 5.1b). The difference in deposition length may be related to the fact that the peaks in the 1990s were more extreme and therefore also may have led to a more extreme impact, although it may also be that the changes observed over the 1990s are not directly linked to peak flows.

In the 1D model, erosion occurs at the upstream end of the Pannerden Canal after a peak flow (see Fig. 4.5) instead of the expected deposition. This response is also unexpected regarding the sediment distribution: most sediment is distributed towards the Pannerden Canal during peak flows in the 1D model (see Fig. 4.9). Possibly, the erosion in the 1D model at this location is the result of smoothening the width: the modelled channel is ~500 m wide in the 1D model over this area, whilst in reality, the Pannerden Canal starts with a floodplain area and is therefore wide at the upstream end during peak flows and has a narrow section 2 kilometer downstream of the Pannerdense Kop. Figure 5.3 shows that during peak flows, the flow velocity from the Bovenrijn increases suddenly when entering the Pannerden Canal. A wider floodplain at the upstream end will lead to a lower flow velocity during peak flows and more settling of the sediment at the upstream end. Adjustment of the cross sections at the Pannerdense Kop are thus expected to improve the model behaviour at the upstream end of the Pannerden Canal. Still, the model behaviour is a sum of multiple settings and the sediment transport parameters also play a role here, as well as the nodal point relationship.

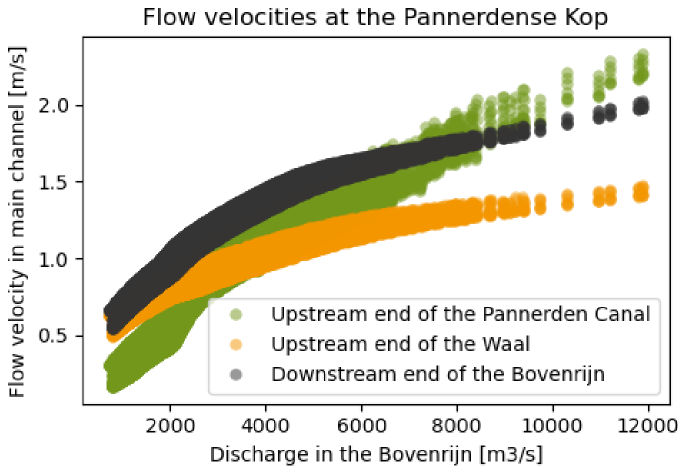
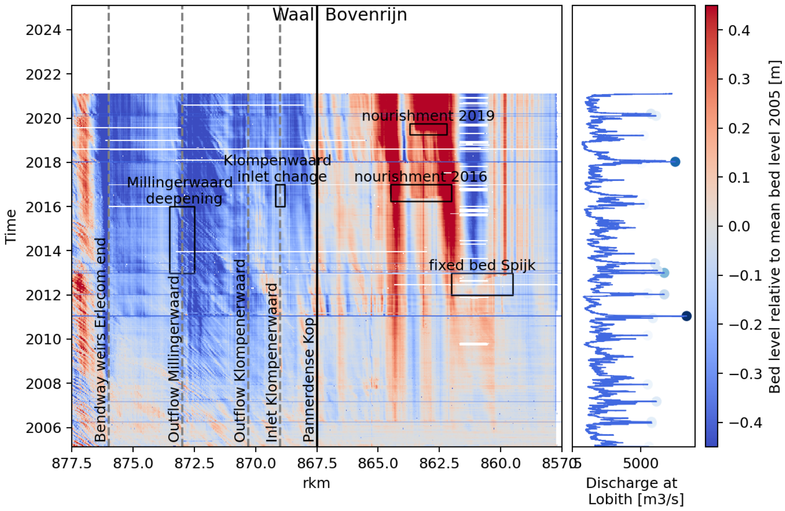


Figure 5.3: Flow velocities at the bifurcation point in the 1D model. During peak flows, the flow velocity increases at the transition from the Bovenrijn to the Pannerden Canal.

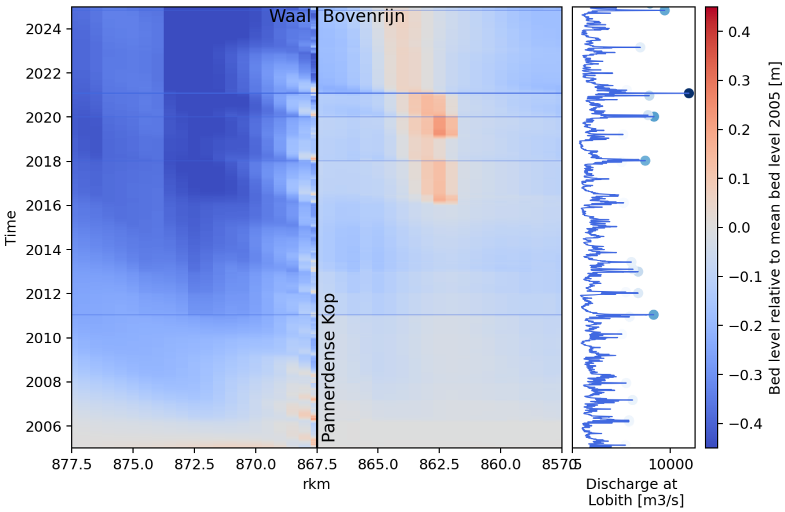
5.3. Comparison of large-scale changes

The long-term bed level trends of the field data, the 1D model and the 2D model vary, as Figures 5.4 and 5.5 show. These figures generally show erosion of different magnitudes, although deposition is also observed at the nourishments in the Bovenrijn. Sloff (2019) determined the bed level trends over 1999-2018 per branch, showing erosion of the upper part of the Waal (rkm 868-885) with -1.9 cm/y, erosion of the Pannerden Canal (rkm 868-876) with -1.0 cm/y, and a stable Bovenrijn (rkm 858-867) with 0.0 cm/y. Overall erosion in the Waal is also observed in Figure 5.4: the bed erodes in all three cases, although the ongoing erosion in the 2D model is less than in the field data and 1D model. The Pannerden Canal erodes slightly in the 1D and 2D model which is in line with Sloff (2019). The models show erosion in the Bovenrijn instead of the expected stable situation. The biweekly field data shows that the nourishments between rkm 862-865 in the Bovenrijn increased the bed level. The nourishment of 2016 may have impacted the bed level trend over 1999-2018, now showing 0.0 cm/y whilst the Bovenrijn may be eroding slightly in reality.

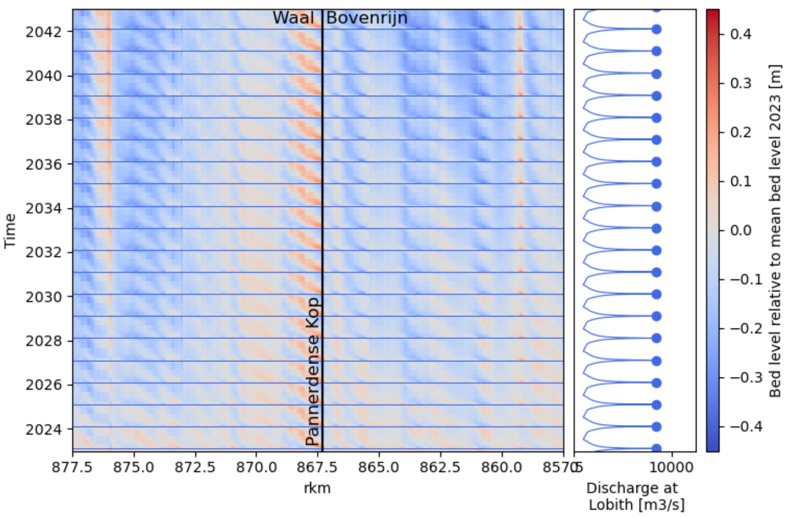
The impact of peak flows on these trends are difficult to disentangle based on Figures 5.4 and 5.5. In the biweekly field data and 2D model results, the intermediate-scale bed level changes after a peak flow are in the order of 0.1-1.0 m, whilst ongoing trends are in the order 0.1-2.0 cm/y, so an order of magnitude smaller. The alternating pattern of these intermediate scale makes it hard to distinguish the large-scale impact on the bed level over multiple kilometers of the branches. Additionally, in the 2D model, the same peak flow occurs every year, which makes it impossible to distinguish between the ongoing trend and the impact of peak flows on this trend.



(a) Bed level changes in the Waal and Bovenrijn in the biweekly field data. The plot shows the bed level changes over 2005-2021 relative to the mean bed level of 2005. These measurements are based on measurements of the ~150 m wide navigation channel, not on the full main channel.

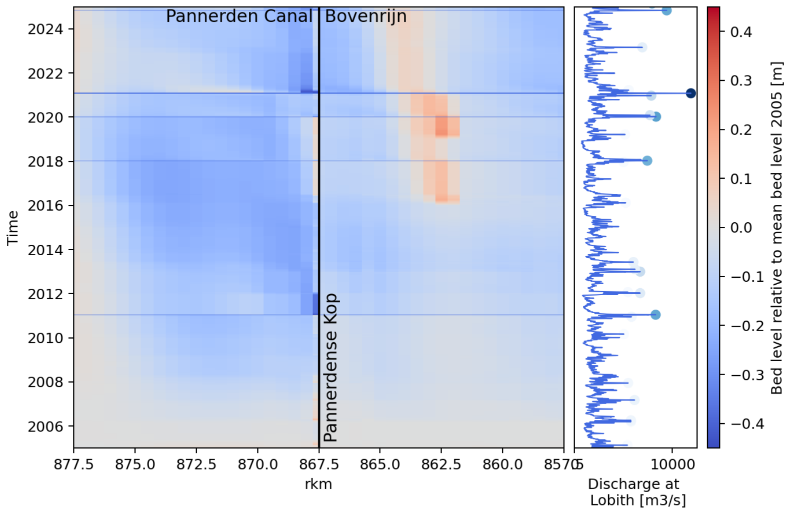


(b) Bed level changes in the Waal and Bovenrijn in the 1D model. The plot shows the bed level changes over 2005-2025 relative to the mean bed level of 2005. The 1D model has a grid size of 500 m and uses widths smoothed over long river reaches.

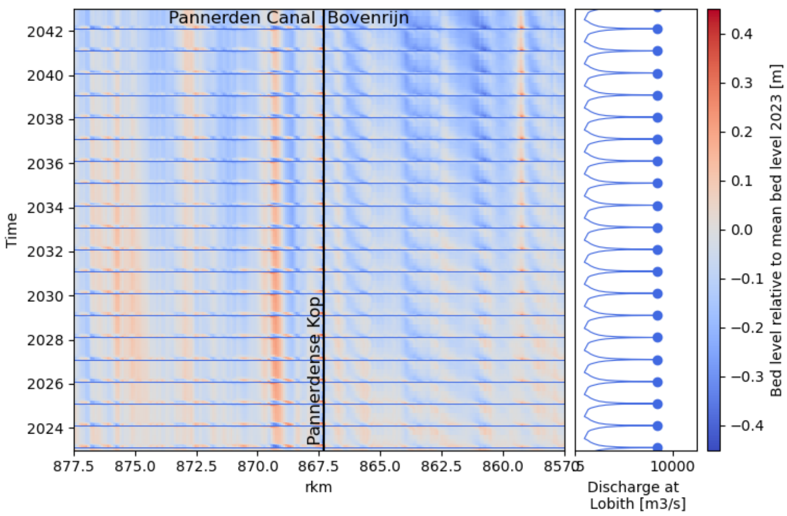


(c) Bed level changes in the Waal and Bovenrijn in the 2D model. The plot shows the bed level changes over 2023-2043 relative to the mean bed level of 2023. The yearly signal is a result of the yearly hydrograph.

Figure 5.4: Bed level changes over time in the Waal and Bovenrijn, comparing the model results and field data. The duration (20 years) and color scales are kept similar.



(a) Bed level changes in the Pannerden Canal and Bovenrijn in the 1D model. The plot shows the bed level changes over 2005-2025 relative to the mean bed level of 2005. The 1D model has a grid size of 500 m and uses widths smoothed over long river reaches.



(b) Bed level changes in the Pannerden Canal and Bovenrijn in the 2D model. The plot shows the bed level changes over 2023-2043 relative to the mean bed level of 2023. The yearly signal is a result of the yearly hydrograph.

Figure 5.5: Bed level changes over time in the Pannerden Canal and Bovenrijn, comparing the model results. Biweekly field data measurements are not available for the Pannerden Canal.

In the 1D model as shown in Figures 5.4b and 5.5a, the large-scale response to peak flows over multiple years is better visible, for the intermediate-scale changes are left out as a result of width smoothening. Some peak flow responses in the 1D model match with other observations, whereas other peak flow responses show notable differences:

- In the 1D model, deposition is initiated during peak flows at the upstream end of the Waal and this deposition moves downstream and disperses in the years after. Similarly, deposition at the upstream end of the Waal is also observed over the 2023 peak flow, in the biweekly field data and in the 2D model. The downstream migration of this deposition is less visible in the biweekly field data.
- In the 1D model, erosion is initiated at the upstream end of the Pannerden Canal during peak flows

and this erosion wave travels downstream and disperses in the years after the peak flows, which does not match with the observations over the 1990s as discussed at the end of the previous section.

- Deposition is also observed after peak flows in the Pannerden Canal at rkm 870-873, which is especially visible in the years after the spin-up period 2010-2030 (Fig. 4.5), whilst Figure 3.9 shows that this area eroded during the 1990s.
- In the Bovenrijn, the peak flow impact over multiple years is mainly found in the downstream movement of the nourishments in the Bovenrijn, which is also visible in the biweekly field data although the nourishment moves slower there.
- The peak flow responses in the 1D model are clearly visible in the year after the peak flow and after three years the response has diminished and is barely visible anymore, and the current results thus do not indicate a large-scale erosion wave travelling in the Waal over many kilometers.

The sediment distribution at the Pannerdense Kop is important for the long-term behaviour of the system. During peak flows, both the sediment size and amount of sediment supply to the branches differs compared to mean flow conditions. Field data on sediment transport at the Pannerdense Kop is very limited and have large uncertainty bandwidths related to the measurement methods and this part is therefore not treated in this report. The model outcomes give an indication of what may happen with the sediment distribution during peak flows, see Figures 4.9 and 4.13. Both models show that the sediment is redirected more towards the Pannerden Canal during peak flows compared to mean flow conditions. This effect is more evident in the 1D model where the Waal obtains roughly 50-70 % when Q = 3000 m^3/s, and only ~30-35% during Q = 8400 m^3/s, whilst in the 2D model, the share of sediment entering the Waal drops only slightly from 67% during Q = 3220 m^3/s to 64% during Q = 8400 m^3/s. This difference between the 1D and 2D model is likely linked to the nodal point relationship of the 1D model where a change in discharge distribution leads to a different sediment distribution, especially for the large grain sizes. Although the 2D model will not perfectly represent reality as a result of model limitations, it is expected that the 2D model leads to a better sediment distribution as the 2D sediment distribution is based on the flow and secondary flow effects, whilst the 1D sediment distribution is more simplified as it is only based on the discharge partitioning.

Observations of the large-scale, long-term erosion adjustment wave in the Waal after peak flows remain limited to one source of field data, although further research may show that such erosion waves are present in the models. Figure 3.11 from Chowdhury et al. (2023) shows the aggradation rate over multiple years and is the only source that indicates the erosion adjustment waves. Similar waves were not observed after peak flows in the biweekly data. The erosion adjustment waves are also not observed in the current 1D and 2D model results. In the 2D model, running the model with one extreme peak in one year is required to show the peak flow impact over multiple years and an additional model run with a more extreme peak flow in one year is required to show the multi-year impact of peak flows. In both models, the absence of erosion waves may also depend on the way model results are plotted. Plotting the results similar to Figure 3.11 may give exclusion whether the erosion waves are in the model results.

6 Discussion

The results are discussed in this chapter. Many data types are used (field data, 1D model, 2D model) and each of these data types have their own advantages and limitations. The applicability of the results to other situations is also discussed.

Field data
The field data has the advantage that the data stems from the real situation. Still, several characteristics of the field data complicate the identification of the peak flow response:

- The bed is not only impacted by natural processes as **river interventions** also impact the bed. This is for example observed in the biweekly measurements of the navigation channel, where nourishments and a fixed bed increased the bed level in the Bovenrijn. Additionally, groyne and river bank lowering in 2023 may impact the bed level difference over the peak flow of December 2023.
- Bed level measurements can be impacted by **measurement errors**. Despite the high point density and the Dutch measurement standards, there is a bandwidth of uncertainty around the bed levels. This effect is expected to be limited as the bed level is averaged over many data points. Measurements can also show an unrealistic offset. This is a known problem for the bed level measurements of the Waal and Bovenrijn of October 2023. An offset of a few centimeters may occur there and bed level trends cannot be distinguished from this data. This could be fixed by using a fixed reference point. However, the data is used here to show overall patterns of erosion and deposition in the order of several decimeters and these conclusions are not impacted by this offset of a few centimeters. Other measurement errors show up in the biweekly measurements of the navigation channel, where some measurements are already left out as they deviate unrealistically.
- The **sediment distribution** according to field measurements is not treated in this report, whilst this is important for the morphological response of the system. Estimations of the sediment transport are rough and may vary strongly for different measurement methods. Few sources were found to estimate the sediment transport in the Bovenrijn and only in Ten Brinke et al. (2001), Frings and Kleinhans (2008), Wilbers (1999) and Schielen et al. (2007) statements about the sediment distribution over the Waal and Pannerden Canal were found. Further research is required for a better understanding of the sediment distribution at the Pannerdense Kop.
- The discharge and exact morphological situation varies per **peak flow event** and therefore the bed level changes during one peak flow of 1998, 2021, and 2023 cannot be taken as general statements valid for every peak flow.
- The **limited width of the biweekly bed level dataset** may impact the peak flow response visible. The biweekly field data is averaged over only the ~150 m wide navigation channel, whilst the main channel is wider, especially in the Bovenrijn and Waal. As explained in 5.2, this may lead

to an underestimation of the deposition at the upstream end of the Waal and to the exclusion of inner bend deposition.

1D and 2D models

Before treating the precise morphological response to peak flows, two general comments are made regarding the models:

- Morphological modelling is challenging and **estimations of sediment transport are always rough**. Erosion and deposition at the correct location and of a good order of magnitude is already a good result. Calibration and verification is therefore often focused on the order of magnitude and not on precise values. Sediment transport variations of a factor two are thus not worrisome, although this uncertainty shows that modelling of morphology has large uncertainty bandwidths.
- The peak flow response as described in this report is based on **current versions of the models**. The models are both still in development and changes in settings may lead to a different peak flow response in future versions. For example, changes in the parameters of the sediment transport formula (Equation 4.1) or nodal point relationship (Equation 4.3) will impact the morphological response. Other parameters may also change the morphological response to peak flows, such as the Chezy roughness that impacts the sediment transport through the Shields parameter and parameters for secondary flow in the 2D model that impact the peak flow impact on bends.

This report analyses current morphological models, with the aim of determining the morphological response to peak flows at the Pannerdense Kop. These outcomes are compared to the morphological response to peak flows in field data. This comparison gives an indication whether the peak flow response in current models is correct:

- The current analysis of the **large-scale peak flow response** reveals inconsistencies between sources, preventing the derivation of a consistent and comprehensive interpretation. First of all, the yearly field data show an erosion wave in the Waal which is not visible in the biweekly data, so the field data contradict each other. Generally, the intermediate-scale changes are an order of magnitude higher (0.1-1 m) than large-scale responses (order cm/y), which challenges the visualisation of large-scale peak flow response. Using a moving average may provide a solution to filter out large-scale impacts although intermediate-scale changes may still impact these results.

  In the 2D model, the impact of a peak flow over multiple years cannot be discerned using the current model run as the same peak flow occurs every year, which makes it impossible to disentangle the peak flow impact on the ongoing trend. Running the model once more with a more extreme peak flow in one year could be compared to the current run and that will give insight in the impact of a peak flow over multiple years in the 2D model.

  In the 1D model, a large-scale response is visible up to at least three years after the highest peak flows, although this impact is different compared to field data in the 1990s and the figure showing the erosion waves. These differences may well relate to the 1D model limitations such as the width smoothening, and the current large-scale 1D response may deviate from reality.
- Several **intermediate-scale responses** are not in the 1D model. Only at the upstream end of the Waal and Pannerden Canal, intermediate-scale responses are observed in the 1D model and erosion is observed after a peak flow at the upstream end of the Pannerden Canal instead of the expected deposition. The peak flow impacts linked to floodplains and groynes is not in the 1D model as a result of the width smoothening over the river reach, and the bend effect is not in the model as the secondary flow in bends is not included in the 1D model.

  In the 2D model, the intermediate-scale changes are visible and match quite well in location and magnitude compared to the field data of the peak flow in December 2023. Still, there are also differences as the groyne impact is not visible at every location in the 2D model and the bend effect is more pronounced in the 2D model.
- **The small-scale dunes** are not in the models. Dunes are an important mechanism of sediment transport during peak flows and neglecting this effect leads to less difference in bed roughness between low and high flow situations. Julien and Klaassen (1995) indicate the order of roughness increase during peak flows: the Chezy roughness coefficient was 44 $m^{1/2}/s$ during peak flows

and value up to 55 $m^{1/2}/s$ after the flood of 1998. A rougher bed during peak flows would lead to more sediment transport during peak flows (see Equations 4.1 and 4.2).

The important follow-up question is whether the differences found are problematic. This depends on the model goal: every model is a tool to mimic reality with a certain goal, thus the goal of a model must be considered to determine whether a model functions well. If the goal were to model peak flows, these differences would be problematic. However, the model goals of the current 1D and 2D models focus more on the long-term behaviour of the complete river system.

Some peak flow responses are more important than other peak flow responses for the long-term model behaviour. Generally, the short-scale peak flow responses remain in the system for several weeks to a few months, whilst the large-scale changes impact the system for multiple years. Thus, the large-scale peak flow responses are especially important for the model behaviour. Additionally, the area just downstream of the Pannerdense Kop has a pivotal role in the distribution of discharge and sediment which stresses the importance to model this area well. The area just upstream of the Pannerdense Kop is impacted by the bend effect which must be modelled carefully to obtain a feasible sediment distribution for each grain size class. In contrast, erosion and deposition at floodplain in- and outflows and any bend effect downstream of the bifurcation point are not expected to be of great importance for the long-term morphological behaviour of the river system and are thus less important in the modelling process. The short duration of the river dunes makes the dunes unimportant for the long-term model behaviour, although the temporal effect on the bed roughness may influence how the discharge and sediment is distributed.

In the 1D model, peak flows currently have a limited effect on the relevant outcomes, although the results of this report may point towards shortcomings of the discharge distribution in the 1D model. The 1D model focusses on the discharge partitioning towards 2150 and on that timescale, the erosion starting at the downstream end of the fixed layer at Spijk seems to impact the bed level around the Pannerdense Kop more than peak flows. However, from the sensitivity analysis follows that the fixed layers have a negligible impact on the discharge partitioning towards 2150 (Chowdhury et al., 2025). The sensitivity analysis shows that the governing factors are bed level changes and the impact of climate change on the hydrograph, where changes from the medium to high flows impact the bed more than the most extreme peak flows. Figure 4.9 further clarifies this behaviour, as the sediment is distributed more towards the Pannerden Canal during higher discharges, so the Pannerden Canal obtains more sediment on the long term and the Waal less when the medium to high discharges increase. This change in sediment distribution may result in more discharge flowing into the Waal and less into the Pannerden Canal, which is the observed result of Chowdhury et al. (2025). The pivotal question to further examine the behaviour of the model is whether the change of sediment distribution during higher discharges is realistic and how changing this impacts the model results. At least in the 2D model, this redistribution of sediment during high discharges is far less.

Other bifurcations

This research focusses on the Pannerdense Kop bifurcation. Other bifurcations will respond differently to peak flows for several reasons. Firstly, the morphological response will also differ in bifurcations with finer or coarser sediment or differently graded sediment compared to the gravel-sand bed at the Pannerdense Kop. Secondly, the morphological impact of peak flows on the total morphological impact differs per climate. For example, in a region with a monsoon season, almost all geomorphic activity takes place during the monsoon season (Goodbred, 2003; Kale, 2003), whilst the morphological activity is more spread over the year for the Rhine river. Still, this report is useful for research of other bifurcation points, as it provides a source of inspiration for the type of peak flow impacts at bifurcations, and because it shows that peak flows impact the bed level at bifurcation on several temporal and spatial scales. Thirdly, natural river systems are not impacted by a fixed planform and peak flows can therefore also result in width changes (Bertoldi, 2012) and initiation of new branches (Kleinhans et al., 2013; Syvitski & Brakenridge, 2013).

7

Conclusion and recommendations

In this chapter, the research questions are answered in the conclusion section 7.1 and recommendations are given in Section 7.2.

7.1. Conclusion

The research question of this report is:

> *What is the influence of peak flows on the bed level at the Pannerdense Kop and to what extent can we model this response?*

The research question is answered in three parts using the subquestions, first describing the peak flow response in the field data, then describing the peak flow response in the model results, and finally comparing the field data and model results.

The morphological peak flow response can be divided into three categories: small-scale responses with a length < 100 m, intermediate-scale responses with a length of several hundred meters, and large-scale responses with a length of several kilometers.

> *1. What is the morphological response to peak flows at the Pannerdense Kop according to field measurements?*

The field data shows small-scale bed level changes during peak flows in the form of dunes which impact the flow by increasing the roughness of the bed. The bed level was measured daily during the peak flow of 1998 and this dataset is used in previous studies to describe the dune behaviour during peak flows: the dunes grow as the discharge increases and begin to decrease at or a few days after the maximum discharge. Differences in dune geometry per branch lead to a different bedform roughness per branch. The larger dunes in the Bovenrijn lead to more bedform roughness compared to the smaller dunes in the Waal, and the geometry of the dunes in the Pannerden Canal fall in between the Waal and Bovenrijn dunes. Dunes are also visible in measurements during the 2021 peak flow, where these dunes also grow as the discharge increases. Dunes also seem to be present during peak flows in the biweekly dataset.

Intermediate-scale changes are observed in several field data sources. The bed level difference between October 2023 and January 2024 is used to indicate the impact of the peak flow of December 2023 with a maximum discharge of 7550 m^3/s. That difference map shows patches of erosion and deposition with a length scale of a few hundred meters and a height in the order of several decimeters. These changes may be related to river characteristics, showing (i) a net deposition at the upstream ends of the Waal and Pannerden Canal which is also observed during the rise of the 2021 peak flow, (ii) erosion at the locations where floodplains narrow and enter the river again, (iii) a pattern of erosion and deposition which may well be linked to groynes, also called 'groyne flames', and (iv) deposition in the Waal inner bends. However, these impacts cannot be directly linked to every peak flow because recent interventions in the Pannerden Canal may also have impacted the bed in this case, and because the morphological response may be different for peak flows with another peak discharge and duration. Intermediate-scale changes are also observed in the biweekly bed level measurements. In the kilometers upstream of the bifurcation, a pattern of erosion and deposition is visible, possibly related to groynes. Other areas erode during peak flows and the effect of river interventions also play an important role in the biweekly dataset.

The statements regarding the large-scale peak flow response in the field data originate from Chowdhury et al. (2023), who link the deposition over the upstream kilometers of the Pannerden Canal to the peak flows of the 1990s and who show erosion adjustment waves in the Waal for peak flows with a Lobith discharge of more than 9000 m^3/s. Attempts to show large-scale responses in the biweekly dataset failed: there are no signs that an erosion adjustment wave is initiated after the peak flows in the period 2005-2021. This difference may be related to differences between peak flows, assumptions in the analysis, or changes of the river system.

2. What is the morphological response to peak flows according to existing 1D and 2D models?

The 1D model developed for Chowdhury et al. (2025) is used and this model shows several peak flow responses. The upstream end ($\pm$ 1 km) of the Pannerden Canal erodes and deposition occurs further downstream after peak flows. In the Waal, an aggradation wave is initiated during peak flows at the bifurcation and this wave travels in downstream direction and disperses. The nourishments of 2016 and 2019 move downstream and disperse during peak flows. Sediment transport increases and an increasing share of sediment enters the Pannerden Canal during peak flows. In the long-term response over 150 years, the bed level is probably influenced by the fixed layers, which seem to have reached their erosional limit and cause erosion travelling across the Pannerdense Kop.

The 2D model *delft3d_4-rijn-j18* (version of April 2025) is used. The 2D model results show a clear yearly signal as a result of the yearly hydrograph, with erosional and depositional patches of a few hundred meters. A map of the bed level difference around a yearly peak show how these changes may be linked to the local river geometry: (i) deposition is observed at the upstream ends of the Waal and the Pannerden Canal, (ii) erosion occurs at locations where the floodplains enter the main channel, (iii) patterns of erosion and deposition in the Bovenrijn may be linked to groynes, and (iv) inner bends aggrade and outer bends erode. The sediment transport increases during higher discharges and a slightly lower percentage of sediment enters the Waal during peak flows.

3. What differences and similarities are observed when comparing the peak flow responses of the field data and model results?

The small-scale dunes are only observed in several field data sources and do not appear in the models. The grid size in the models is longer than the length of dunes, so the dunes do not appear in the bed level, and the effect of the increased bed roughness due to dunes is also not explicitly modelled.

The intermediate-scale peak flow responses are observed in the field data and in the model results after peak flows. In the 1D model, the only intermediate-scale changes observed are located at the upstream ends of the Pannerden Canal and Waal, leaving out changes linked to groynes, bends, and floodplains as a result of the model schematization. The erosion observed at the upstream end of the Pannerden Canal in the 1D model is not in line with the observed deposition at that location in field data and the 2D model. The 2D model and bed level difference over the 2023 peak flow show similar patterns of erosion and deposition: (a) deposition at the upstream end of the Waal and a slight deposition at the upstream end of the Pannerden Canal, (b) erosion at locations where floodplains flow into the main channel again, (c) erosional and depositional patterns linked to groynes in the Bovenrijn, and (d) deposition in the inner bends of the Waal. The groyne impact is also observed at other locations in the field data, which may not appear in the 2D model as a result of a too coarse grid. The bend effect is more pronounced in the 2D model results compared to the field data: the 2D model results also show erosion at the outer bend and bend effects in the Pannerden Canal, and this difference may relate to model settings, limitations in the measured area, or the impact of groyne and river bank lowering in the Pannerden Canal during 2023. Regarding the bed level over time, the bed level change in the biweekly field data and the 2D model results both show intermediate-scale responses, although these changes appear at slightly different locations and the peak flow response in the 2D model seems to be merely a continuation and movement of existing patterns, whilst the biweekly field data show a clear discontinuity and an initiation of new bed level changes at peak flows. These differences are linked to differences in width-averaging, hydrograph differences, river interventions, and model settings.

The current analysis of large-scale peak flow response reveals inconsistencies between sources, preventing the derivation of a consistent and comprehensive interpretation. One source of field data describes a large-scale erosion adjustment wave in the Waal. However, a similar peak flow impact is not visible in the biweekly field data, which may be related to differences in peak flows, limitations of the analysis, or changes in the river system. The current 1D and 2D model results also do not show an erosion wave in the Waal after a peak flow, which may also be related to the way the results are plotted. Ultimately, the statements on the large-scale peak flow impact are based on a single source and the coherence between sources lacks in this research. Therefore, more research is required to determine the large-scale impact of peak flows.

7.2. Recommendations

For the 1D model, it is recommended to further study the distribution of sediment for medium to high flow conditions. From this study follows that in the 1D model, the Pannerden Canal obtains a significantly larger percentage of the sediment during higher flow conditions. The 2D model seems to show this behaviour only slightly, and changing the 1D model sediment distribution during medium to high discharges is expected to change the relevant model results. The best data source to examine the sediment distribution at the Pannerdense Kop during various discharges would be field data, yet this data is limited and comparison to the 2D model provides a good additional data source for the comparison.

The impact of a peak flow over multiple years could not be determined using the current 2D model run and therefore an additional model run is recommmended. The current 2D model has a yearly hydrograph with the same peak flow in every year, which makes it impossible to distinguish between the ongoing trend and a peak flow. It is recommended to run the model once more with one extreme peak flow -for example 12.000 m^3/s- in one year. These results can be compared to the current 2D model run and this will give insight in how a peak flow impacts the bed level over multiple years.

The large-scale impact of a peak flow on the Pannerdense Kop remains unclear and further research is required on this topic. Large-scale changes are the changes that remain longest in the system and may influence the long-term trends, which are important for the future of the river system. In this research, the erosion adjustment wave in the Waal is found in only one source. The lack of coherence between the sources on this topic shows that more research is required to determine the large-scale impact of peak flow. The first step in would be to further analyse the current data by (a) plotting the model outputs as aggradation rates averaged over space and time as in Figure 3.11, and (b) by testing whether the observed erosion waves in Figure 3.11 are sensitive to the choice of moving average, which is currently set to 2 km and 5 years. These steps will facilitate a more precise assessment of whether large-scale peak flow impacts, such as the erosion adjustment wave, are manifesting within the system. Still, determining changes with a height of centimeters and a length of kilometers will remain challenging using bed level data when many shorter and higher changes also interfere. As additional steps, the sediment distribution can be used to determine how peak flows impact the river system on the long term.

The current model goals do not focus on the impact of peak flows. If the goal of the models was to model peak flows well, several adjustments are recommended. A 3D model of the area around the Pannerdense Kop may appear ideal as it contains flow in all directions and therefore models the bend effect better and models flow variations over the width. However, such models are computationally heavy and the added quality for morphological modelling compared to a 2D model is questionable as sediment transport formulations remain highly uncertain and calibration and validation data is limited. A 2D model provides a good alternative. The current 2D model can be used as a basis to model peak flows, yet several recommendations are presented here to better model the peak flow impact. First, a more realistic hydrograph can be used instead of the strongly simplified hydrograph with discharge levels, and to limit computational times the duration of the model run can be limited to a few years. Second, compared to the current 2D model, it would be better to use a finer grid to model local flow effects -for example in groyne fields- better, and the total model domain can be reduced to the area around the Pannerdense Kop to limit computational times. Third, the bend effect as a result to peak flows seems to be exaggerated compared to field data and spiral flow parameters can be adjusted to lower the spiral flow impact. Fourth, dunes can be introduced in the roughness using the van Rijn (1984) formulation. Besides, additional ways of calibration are required for the morphological modelling. A possibility would be to use the movement of local deposition and erosion patches. This can for example be done using the original biweekly field data showing the movement of the nourishments of 2016 and 2019 or by using naturally present variations of the bed level. Modelling of the morphological response to peak flows can also be done using a 1D model, although a 2D model is preferred because of the simplifications in a 1D model: the sediment distribution defined by the nodal point relationship is more simplified compared to the sediment distribution in the 2D model, and variations over the width are left out in a 1D model. Still, if the 1D model is used to model the peak flow impact at the Pannerdense Kop, it is recommended to create more realistic widths, especially at and in the first kilometers downstream of the Pannerdense Kop, and it is required to further investigate the sediment partitioning during high flow conditions.

Measuring more will add to the current understanding of the impact of peak flows on the river bed and will increase the amount of calibration and validation material for the models. First, more multibeam measurements before, during and just after peak flows will add statistical proof to current observations and may show differences for different peak types. Second, bed surface grain size measurements at higher spatial and temporal frequency are required to understand the morphological processes around the Pannerdense Kop. Measuring the bed surface grain size before, during and after peak flows at many locations around the Pannerdense Kop will help to understand the morphological impact of peak flows at the Pannerdense Kop. Third, sediment transport rates during peak flows are highly uncertain and measuring sediment transport during peak flows can reduce this uncertainty. Such measurements of the sediment transport will also add a valuable source for calibration of the models and may therefore lead to more reliable models.

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A
Field data sources

Several datasets are used in Chapter 3 to describe the morphological impact of peak flows at the Pannerdense Kop. These datasets and their sources are listed in this appendix.

Biweekly dataset
The biweekly dataset contains bed level measurements of the Bovenrijn and Waal in the period 2005-2021. Data of the Pannerden Canal was not available. The 150m wide navigation channel was measured every two weeks using multibeam measurements. The spatial resolution is 2.5x2.5 m in 2005-2011 and 1x1 m in 2011-2021. At least 95% of the raster cells contain at least 10 points, but the point density is generally much larger (van Denderen et al., 2024). The measurements are width-averaged and averaged over 5 m reaches to obtain the 1D bed level. More information about the dataset can be found in van Denderen and van Hoek (2022), van Denderen et al. (2024), and van Denderen et al. (2022)

This dataset was provided by Michiel Reneerkens (Rijkswaterstaat). The provided data also contains an additional functionality to filter out bed level differences by their length, which is called wavelet filtering. This wavelet tool is a tool developed by Pepijn van Denderen and Mattijn van Hoek (HKV) for Rijkswaterstaat. In the end, the wavelength filtering is not applied because the length scale of the peak flow-induced bed level changes was unknown. Additionally, a bed level step may be expected at the bifurcation but this discontinuity was not considered in the wavelet tool.

Bed level measurements during the 2021 peak flow
The multibeam bed level measurements around the Pannerdense Kop during the 2021 peak flow were provided by Kifayath Chowdhury (TU Delft).

Bed level measurements during the 2023/2024 peak flow
The bed level of the Bovenrijn, Waal and Pannerden Canal was measured before and after the peak flow of December 2023, in October 2023 and January 2024. Both measurements are multibeam measurements. The data of 2024 was provided by Kifayath Chowdhury (TU Delft), the 2023 data of the Pannerden Canal was provided by Emiel Olink (Rijkswaterstaat), and the 2023 data of the Waal and Bovenrijn was provided by Michiel Reneerkens (Rijkswaterstaat). The data of October 2023 of the Waal and Bovenrijn is known to have an offset of a few centimeters and therefore this dataset is usually not provided.

Discharge data
Discharge data is used for the discharge plots and to determine the peak discharges.The discharge data from the measurement station at Lobith in the Bovenrijn is used and originate from Waterinfo (Rijkswaterstaat, 2025).

Other sources
Yearly bed level measurements are used by Chowdhury et al. (2023) to determine the large-scale bed level trends. The figures and resoning of Chowdhury et al. (2023) are used in this report and not the original yearly data.

The daily multibeam measurements during the 1998 peak flow were used in research of Frings and Kleinhans (2008), Julien et al. (2002), Kleinhans et al. (2007), and Ten Brinke (2002) to examine dune behaviour. This report repeats the findings based on this dataset and the original dataset is not used for this research.

B

River interventions in the Pannerden Canal during 2023

The groynes and river banks in the Pannerden Canal were lowered in 2023, see Figure B.1.

Figure B.1: Groyne and river bank lowering in the Pannerden Canal during 2023 (Rijkswaterstaat, n.d.). The red bars represent groynes that were lowered with about 1.5 m, the orange bars represent groynes that were lowered with about 0.5-1.0 m. The river banks are lowered with 1.5 to 2.0 m in the black striped areas. The right upper corner indicates the effect of these interventions: the water level drops with 5 cm during very high discharges.

C

Differences in discharge per peak flow event

The peak flow events considered are summarised in Table C.1. Defining a peak flow is often done using the discharge only; however, the duration, sediment flux, and peak sequence also influence whether a peak is morphologically effective (Lisenby et al., 2017). In addition, peak succession is important as previous peaks impact the sediment transport rates of peaks shortly after (Mao, 2018). Here, only the peak discharge and duration are used as indications of the peak flow effect.

Table C.1: List of considered peak flow events. The duration of the peak flow is determined using a threshold of Q = 6200 m^3/s; Q > 6200 m^3/s occurred on average 3 days per year during the period 2011-2020 (Rijkswaterstaat, 2025; Sloff et al., 2024).

Peak flow event	Q_{max} $[m^3/s]$	Days with Q > 6200 m^3/s
December 1993	11.000	22
January 1995	11.900	11
November 1998	9500	10
January 2003	9450	10
January 2011	8400	11
January 2018	7550	5
February 2021	7400	10
December 2023	7550	13
Yearly peak in the 2D model	8400	3

The description of the large-scale response in the field data is based on observations over the 1990s, whilst the observations on the short and intermediate scale are mainly based on the lower peak flows that occurred after 2005.

The 1D model uses the 2000-2020 hydrograph for the first twenty years which were also used as spin-up and calibration period. The hydrograph in the model period 2020-2150 is based on the discharge measurements during 1994-2013 and therefore also contains the extreme peak flow event of 1995. The hydrograph in the 2D model is an artificial yearly hydrograph with 9 discharge levels that statistically represent the yearly hydrograph.