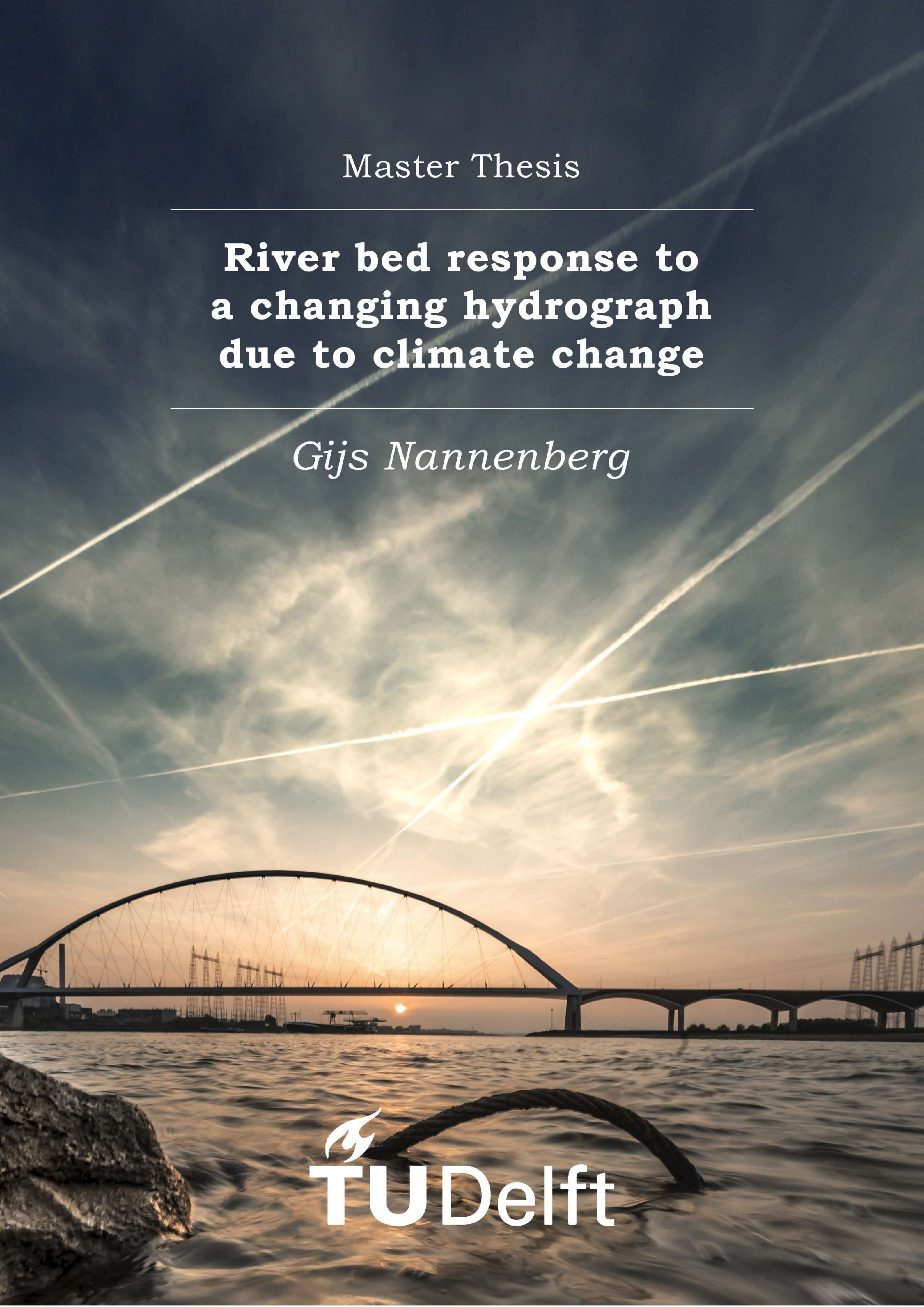
Master Thesis

# River bed response to a changing hydrograph due to climate change

*Gijs Nannenberg*



TU Delft

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# River bed response to a changing hydrograph due to climate change

by

G. Nannenberg

to obtain the degree of Master of Science
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TU Delft

# Preface

A bit more than a year ago I started the final leg in my time at Delft University of Technology: my graduation thesis for the Master of Science in Hydraulic Engineering. It was a challenging year, not in the least because of the Corona pandemic that is still going on. Therefore I'm proud to say that I am nearing the end of this journey. This past year I have learned a lot about a field that I'm passionate about: river engineering. This wouldn't have been possible without the help of many individuals who over the past year have supported, advised and helped me in many different ways.

First of all I want to thank my graduation committee. The experience and knowledge of Astrid Blom, Clàudia Ylla Arbós, Ralph Schielen and Thom Bogaard have helped me greatly in improving my thesis and aiming it in the right direction. Our committee meetings were extremely helpful. In particular I want to thank Astrid Blom and Clàudia Ylla Arbós for our regular meetings and their support, both personal and with the thesis. You have helped me not only with what I was doing, but also taught me a lot about how to do it. Thank you Astrid for getting me back on track where needed, and thank you Clàudia for the never ending enthusiasm with which you advised me. I also want to thank some of my fellow students, especially Mieke, who was working on a related topic at the same time as me. Our conversations often gave me clarity and a mirror to reflect upon.

Further I want to thank some people without whose support I would not have made it this far. I want to thank my parents, Hank and Jacqueline, who always had my back and a place for me when I needed a change of environment. Many thanks to my sister, Julie, who was also working on her own thesis at the same time as me. Our calls always helped me to see the bigger picture. Thank you to my roommates, Dion and Frank, and Naomi. The four of us spent a lot of time together during the various lock-downs. You made these periods bearable and even fun! Finally, I'm very grateful to Lara. Without your everlasting support I could not have done it.

*G. Nannenberg*
*Delft, December 12, 2021*

# Abstract


The objective of this thesis was to assess the effects of changing hydrographs due to climate change on the initial, transient and equilibrium response of mixed-sediment river. Climate change is likely going to affect river discharges, as both the frequency and extremity of dry and wet periods are increasing and snow- and ice melt are affected by the increasing temperatures (Gray, 2007). These effects of climate change are likely to affect the distribution and magnitude of discharge throughout the year, which in turn affects the sediment transport capacity of rivers and thereby the river bed profile. In order to create a better understanding of the processes in play we analysed a theoretical situation using the Lower Rhine as a reference. The river Rhine is a heavily engineered river. Since human intervention in this river is significant it is difficult to predict the exact effect of climate change, as interventions may change the planform of a river, f.e.: changing the capacity of channels, creating or removing overflow areas, adding or removing obstacles within the river boundaries or dredging or nourishing of river sediment. In this research we therefore made use of a simplified version of the Rhine, as it is not possible to take all of these unknowns into account. It can however still give us an insight into river response to climate change.

We studied the historical and expected discharges in the Lower Rhine from the year 1901, up to the year 2100. The expected discharges were based on the KNMI'14 climate scenarios (KNMI, 2015). These scenarios were used to investigate potential changes in discharge for the river Rhine (Sperna Weiland et al., 2015). It showed that in all scenarios an increased discharge was foreseen during winter, while during summer, in all but one scenario a decreased discharge was predicted. The one exception was the scenario with the least climate change, in which a small increase of discharge was predicted in the dry season.

In order to investigate the effects of hydrograph changes to the bed level and surface texture of a river, two different models were made using a 1D morphodynamic research code. One focused on unisize sediment, while the other model used a bi-modal sediment distribution, with both sand and gravel. It was found that an increase in river discharge variability causes degradation along the entire modelled river reach of 300 km. The opposite effect, aggradation along the entire river reach, was observed when decreasing the hydrograph variability. On top of this bed level change due to changes in river discharge, this research also showed that when the river bed contains bi-modal sediment, fining or coarsening of the bed surface sediment occurs, specifically: an increase in discharge variability results in fining of the river bed surface texture upstream and coarsening downstream, while a decrease of discharge variability results in coarsening of the river bed upstream and fining downstream.

When looking at the initial and transient response of the river bed on changes to the river bed, a clear distinction can be made between the upstream and downstream effects. Upstream a more direct effect is visible: locally large bed level changes occur. These changes migrate slowly downstream. This behaviour is mostly driven by the difference between sediment supply and sediment transport capacity. At the downstream end smaller bed level changes occur than upstream. While the river depth can change with a change in discharge, the downstream water level remains fixed, as a river often ends in a stable body of water (f.e. the North Sea for the Lower Rhine). This causes a change in flow velocity in downstream direction, affecting sediment transport and causing an aggradation or degradation wave, affected the to the bed level. This wave moves quickly into the river reach in upstream direction. The degradation at the downstream end of the river causes the bed slope to increase. This steeper bed slope increases the mobility difference between sand and gravel grains, causing the bed to become coarser. At the upstream end the degradation causes the bed slope to decrease, decreasing the mobility difference between sand and gravel grains, resulting in a fining of the river bed. When decreasing the discharge variability the opposite effect can be observed.

The results of our models allow us to better understand the possible effects that changes to the hydrograph can have on river beds. We can combine our understanding of these responses for example with the predictions based on the KNMI'14 climate scenarios, which indicated a likely increase of the discharge variability in the future. With our understanding from the models this would cause lowering of bed level, or

degradation, of the river, with both upstream- and downstream migrating degradation waves. This would be combined with fining of the river bed at the upstream end and coarsening at the downstream end of the river reach. Our model, even though it is a simplified version of reality, gives us valuable information on the effects of hydrograph changes on the river bed. It can help us in better understanding the complex relationship between climate change and our rivers.

# Contents

# 1
# Introduction

## 1.1. Context

Over the past few decades the consequences of climate change have become more and more prevalent. According to the most recent report by the Intergovernmental Panel on Climate Change (Gray, 2007), each of the last four decades were subsequently warmer than the decade before, and warmer than any decade since 1850 (Stocker et al., 2013). Glaciers (Pfeffer et al., 2014), ice sheets and sea-ice (Comiso & Nishio, 2008) have been decreasing in mass and extent and the global mean sea level rose by 0.20 m over the period 1901 to 2018. Changes in precipitation and melting snow and ice are affecting hydrological systems. Climate change also affects many species, sometimes leading to extinction (Field et al., 2014) and crop yields are more often than not negatively affected, increasing the risk of food shortages (Lobell et al., 2011). The IPCC states that 'it is *unequivocal* that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.' If no extra measures are taken to reduce greenhouse gas emissions, the global mean temperature is expected to increase up to 5.7°C by the end of the 21st century. Only if very drastic measures are taken right now, is it possible to limit the increase of the global mean temperature to 2°C (Gray, 2007). Many of the changes due to climate change in past and future are however irreversible for centuries to millennia.

One area that will face large consequences due to climate change are river basins. According to Kummu et al. (2011), more than half of the world's population lives closer than 3 km to a freshwater body. Especially in areas where a large river is nearby, population densities are high. These populations experience the effects of climate change, which can vary from droughts to an increase in magnitude and frequency of flooding (Nikula, 2008). Sometimes these can be visible within the same river basin. With the continuing climate change these negative effects are only expected to get worse.

An example of a river that is experiencing the effects of climate change is the Rhine river in Europe. The river Rhine has its origin in the Swiss Alps and flows down along the German-French border, into Germany and finally into the Netherlands, where it discharges out into the North Sea (see figure 1.1). Due to climate change the Rhine is expected to shift from a mixed precipitation and snow and ice melt regime to a mostly precipitation dominated regime (Barnett et al., 2005; Hurkmans et al., 2010). This change will result in higher discharges during winter, with a higher frequency and magnitude of flooding (see Figure 1.2)(Blöschl et al., 2019; Hegnauer et al., 2015), and lower discharges during summer with an increase in frequency of periods of low flow.

A negative effect of low flow in the Rhine was visible in the summer of 2018, when low flows caused low water levels in the river Rhine, making parts of the river unnavigable for larger cargo barges (Ellyatt, 2019). It is estimated that this caused a 0.7% drop in Germany's GDP in 2018 (Gordon, 2019), as producers dependent on the Rhine for transportation of raw materials were forced to find alternative means of transportation, such as smaller barges.


Figure 1.1: The Lower Rhine river (Ylla Arbós et al., 2020)

A change in river discharge, such as caused by climate change, can have an effect on the river bed. Rivers always tend towards an equilibrium profile in which the sediment supply from upstream is in balance with the sediment transport rate. In a controlled river like the Rhine, where the river banks are fixed, this is accomplished by a change to the river bed. We define the equilibrium profile as the one that the river approaches when flow, sediment supply and base level vary around stable values for a long time in the absence of subsidence or uplift (Blom et al., 2017).

When a change in river discharge occurs, the river will tend towards a new equilibrium. The initial response to this change occurs at the boundaries of the river reach and will over time affect the entire river reach, eventually approaching the new equilibrium. These changes in the river profile can have far reaching consequences, as changes in depth and slope of the river channel can increase flood risk or decrease river depth in the case of a steeper slope, possibly causing issues for shipping. In the spectrum of climate change it is interesting to know the time in which a river reaches its new equilibrium state. Climate change is not a sudden change, but is something that gradually happens. Due to this gradual change the equilibrium state of a river will be constantly changing. While the river discharge is directly affected by climate change, the response of the river bed is much less instantaneous; it takes time for the river bed to reach its new equilibrium. A river bed may therefore be continuously approaching an ever changing equilibrium state, but never reach it. It is therefore also important to know what the river bed looks like at different points in time before reaching its equilibrium state. This phase between the initial response and the equilibrium response is called the transient response.

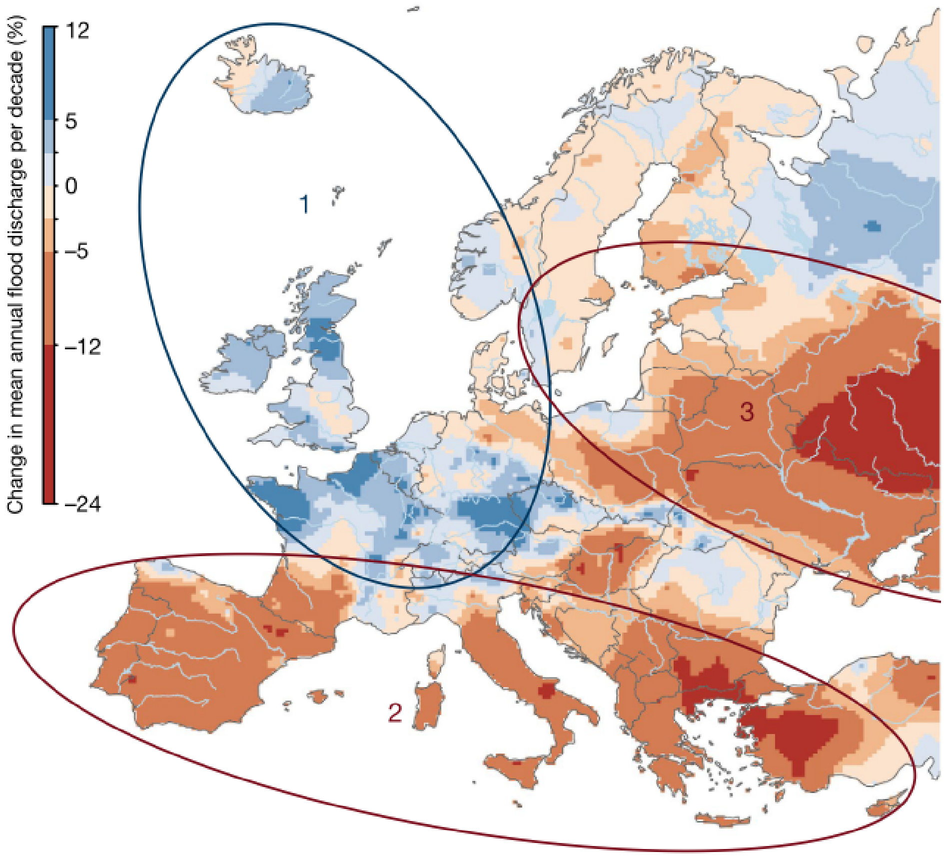


Figure 1.2: Observed regional trends of river flood discharge in Europe (1960-2010) (Blöschl et al., 2019)

## 1.2. Objectives and research questions

The objective of this thesis is to assess the effects of climate change on the initial, transient and equilibrium response of mixed-sediment river reaches. Climate change will cause changes to hydrographs, which in turn affects sediment transport capacity and thereby the river bed profile. In order to create a better understanding of the processes in play, we perform a case study using the Lower Rhine as reference. The river Rhine is a heavily engineered river. The effects of climate change are difficult to predict and human intervention is significant. A strongly schematised model of the Rhine River can give an insight into river response to climate change.

This brings us to the research questions:

1. What are the expected changes to the hydrograph of the Lower Rhine, considering the KNMI'14 climate scenarios, up to the year 2100?
2. How does the bed level of a river reach with unisize sediment react to changes in the river hydrograph?
3. How do the bed level and surface texture of a river reach with bi-modal sediment react to changes in the river hydrograph?

## 1.3. Methodology

In this section the methodology used in this research is discussed.

### Research question 1

*What are the expected changes to the hydrograph of the Lower Rhine, considering the KNMI ´14 climate scenarios, up to the year 2100?*

Part of this thesis is a case study on the long-term bed changes in the Lower Rhine, up to the year 2100. The year 2100 is chosen as this is in line with the KNMI'14 climate scenarios that are used in this research, and the Rivers2Morrow project.

In order to make meaningfull predictions for the river bed of the Lower Rhine, it is important to first know what changes to the river hydrograph can be expected. The goal of the first sub-question is therefore to identify hydrograph predictions for the river Rhine up to the year 2100 and analyse them. After we identify these hydrograph predictions, we discuss which predictions should be used in the further case study.

As a first step in answering this research question we perform a short study on historical discharges in the Lower Rhine from the year 1901, the start of measurements. This data is then used as a reference to the predictions later investigated in this research question. Next we discuss the current discharges of the river Rhine. These current discharges will form the basis of the future discharge prediction. For this we explain the KNMI'14 climate scenarios, as these form the basis of any hydrograph predictions that are used in this research. The KNMI'14 climate scenarios consist of four possible scenarios. These scenarios are used in Sperna Weiland et al. (2015), using GRADE, to investigate potential changes in discharge for the river Rhine.

Using the climate scenarios the actual hydrograph predictions are made. These predictions are made by GRADE and the resulting predictions are compared and it is decided which predictions are used in the further research.

### Research question 2

*How does the bed level of a river reach with unisize sediment react to changes in the river hydrograph?*

This research question will try to create understanding on the bed behaviour of unisize sediment rivers in low lying regions, specifically the bed level. In order to achieve this, first a literature study is performed on river response to changing parameters, in particular attention is paid to the morphological response of river beds to changes in discharge. we discuss the initial, transient and equilibrium response of the river bed to these changes.

In order to answer this question we define and analyse a 1D model using Elv. A model will allow us to create a simplified case in which we can focus on the effects of water discharge. Since we are interested in how the bed level is affected in streamwise direction, a 1D model is used. For this model unisize sediment is used. An initial stable situation is defined after which multiple modelling runs are mode.

To understand the effects of changes in hydrograph we vary the upstream hydrodynamic boundary condition. First multiple runs are performed with a constant discharge. Next multiple runs with varied hydrographs are imposed. In this way we will create understanding about to which extent a varying discharge affects the river bed level. We analyse the initial, transient and equilibrium response of the river bed to these imposed conditions. We also investigate the time scale on which bed changes are visible.

### Research question 3

*How do the bed level and surface texture of a river reach with bi-modal sediment react to changes in the river hydrograph?*

Research question 3 is different from research question 2 in that it focuses on a river reach with bi-modal sediment distribution, one sand and one gravel fraction. This allows us to look at the more complex, and more realistic, situation in which the surface texture of the river bed changes. For this a 1D model is made using ELV. An initial stable situation is defined, after which multiple runs are made.

The method of investigating the effect of hydrograph change on the river bed is similar to that in the previous research question, the differences being the initial situation, which is different due to the bi-modality of the sediment and the upstream sediment input, which is of the same magnitude but divided in two grain sizes. Again multiple runs are performed with both constant discharge and hydrograph. In the different scenario runs changes are imposed on these upstream hydrodynamic boundaries. The effects of these changes on the river bed, both the bed level and the surface texture, are then investigated. We analyse the initial, transient and equilibrium response to these imposed conditions and also investigate the time scale on which bed changes are visible.

## 1.4. Thesis outline

Chapter 2 deals with research question 1. This chapter discusses and analyses historical discharge in the lower Rhine from 1901 onwards and compares this to recent discharges. We discuss both trends in discharge and noticeable events. We also discuss what human interventions took place in this period of time and how these affected the Lower Rhine. Finally, using GRADE and historical discharges, we define possible discharge scenarios for the year 2100.

Chapter 3 deals with the theory of research questions 2 and 3. This chapter explains the initial, equilibrium and transient response of rivers and also discusses the role of variation in discharge and sediment size distribution on these responses.

Chapter 4 defines the model and model input that is used to predict changes to the river bed profile up to the year 2100, while Chapter 5 presents the results for research question 2, regarding unisize sediment. Chapter 6 present the results for research question 3, a bi-modal sediment distribution.

Chapter 7 discusses the choices made in this research and the possible limitations and uncertainties of the results.

Chapter 8 answers all research questions. Finally some recommendations are made.

# 2

# Expected changes to the Lower Rhine hydrograph

A river bed is driven by three different boundary conditions, the upstream morphodynamic boundary, or sediment supply, the upstream hydrodynamic boundary, or discharge and the downstream hydrodynamic boundary, or in our case the sea level. This chapter will focus on the upstream discharge and will answer research question 1:

*What are the expected changes to the hydrograph of the Lower Rhine, considering the KNMI´14 climate scenarios, up to the year 2100?*

This chapter looks at both historical discharge and discharge predictions for the river Rhine. For this three periods are defined: past discharge, which covers the period from 1901 up to 1980, present discharge, which covers the period from 1981 up to 2020, and future discharge, which covers the period up to 2100, 80 years in the future. These periods are analysed and compared by looking at discharge trends and extreme events at Lobith, the Netherlands. In order to understand the effects of precipitation vs snow-melt on the discharge we also look at the differences between discharge at the up- and downstream end of the river Rhine, respectively Basel, Switzerland, and Lobith, the Netherlands (see figure 2.2. The daily discharge data for both Basel and Lobith are taken from The Global Runoff Data Centre (2020). One should note that even though the present discharge is said to cover the period from 1981 up to 2020, at the date of retrieval the daily discharge data for Basel runs until the end of 2018, while the daily discharge data for Lobith runs until the end of 2016. The historical discharge data at Lobith are shown below in figure 2.1.

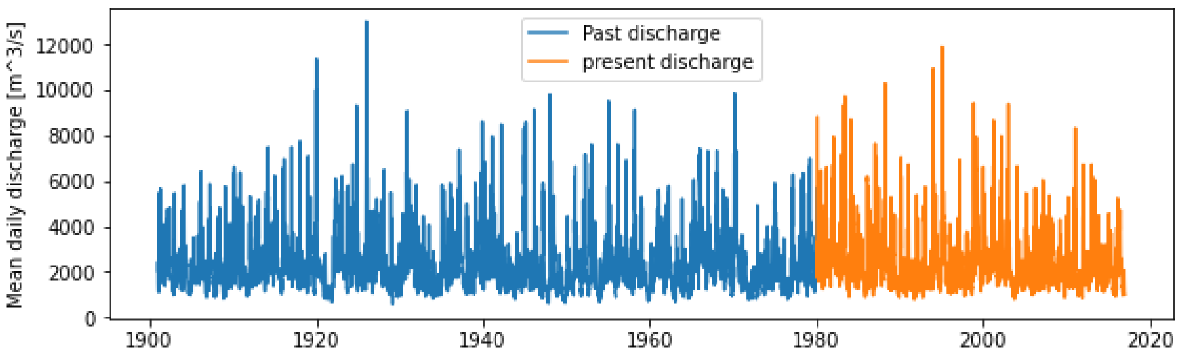


Figure 2.1: Mean daily discharge over the period 1901-2020 at Lobith, The Netherlands (data from the GRDC, 2018).

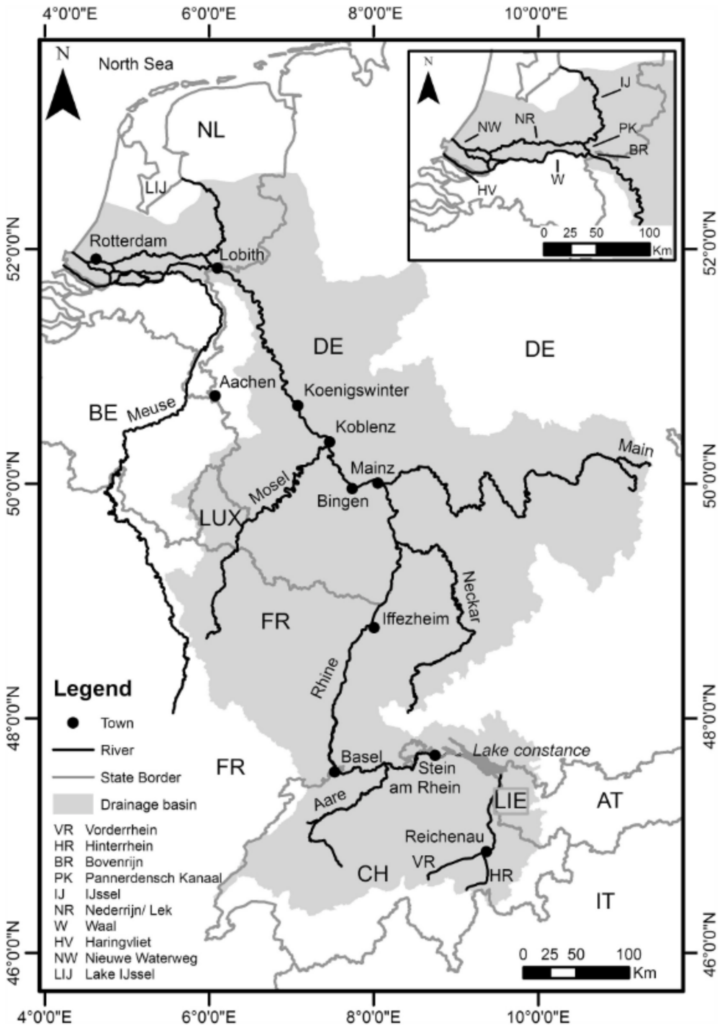


Figure 2.2: The Rhine river and its basin, with its major tributaries and delta distributaries. NL = Netherlands, DE = Germany, BE = Belgium, FR = France, CH = Switzerland, LIE = Liechtenstein, AT = Austria, IT = Italy (Frings et al., 2019).

## 2.1. Past discharge (1901-1980)

The discharge of the river Rhine is controlled by rainfall in the Rhine basin and snow- and glacier ice-melt originating in the Alps and other mountain headwater regions in Central Europe (Stahl et al., 2017). This is visible when comparing discharges between Lobith and Basel. Lobith is located at the downstream end of the river Rhine, while Basel is located much further upstream, near the base of the Alps (see figure 2.2). The consequences of these different locations along the Rhine are visible in figure 2.3, which shows the hydrograph of the year 1960 at both Lobith and Basel. At Basel the highest discharges occur in the period between June and September. This discharge can in a large part be attributed to snow- and ice melt, which mostly occurs in these warmer summer months. The discharges at Lobith during this period do not deviate a lot from those at Basel. This indicates that during these months most of the discharge at Lobith originates upstream from Basel, as all water flowing past Basel needs to pass by Lobith. The difference in discharge between Lobith and Basel can be attributed to precipitation in the Rhine basin and the Rhine's tributaries.

The rest of the year however, discharges at Basel are lower, and the difference between discharge at Lobith and Basel increases. Especially in the period between November and April a significant deviation between the discharges is visible, with discharges at Lobith often being 3 or 4 times as large as at Basel. This indicates a downstream change from the river being mostly snow- and ice melt dominated, as snow and ice melts in the summer, causing higher discharge in that period, to becoming more rainfall dominated, as precipitation is more prevalent in winter time.

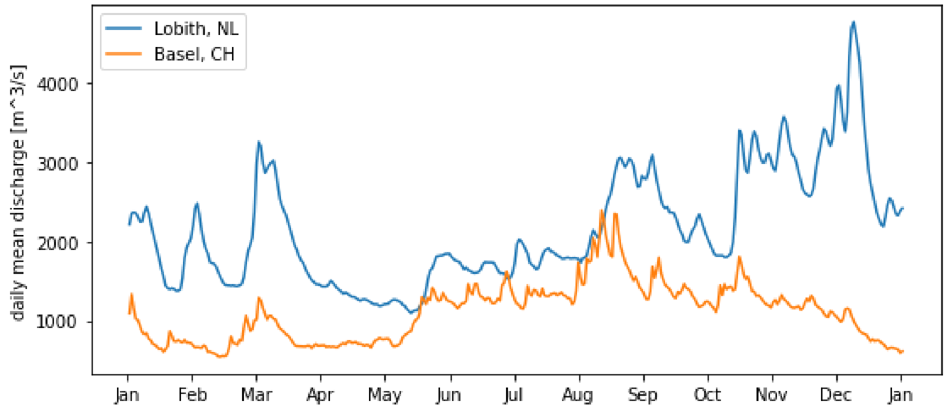


Figure 2.3: Hydrograph of the year 1960 at Lobith, The Netherlands and Basel, Switzerland (data from the GRDC, 2020).

Figure 2.1 shows the mean daily discharge from 1901 until 1980 for the river Rhine at Lobith in blue. As can be seen over this period of time large variations in discharge are visible. One event in particular that stands out is the high peak in 1926. Around new years eve of 1925, the Netherlands and Germany were dealing with exceptionally high precipitation. In the first week of 1926, the river reached a water discharge of 12600 $m^3/s$. The dikes were not able to withstand this, and breached at multiple locations (Verhoeven, 2006).

### Discharge trends

In order to better understand the development of discharge in the Rhine over time, a trend analysis is made. Since we are analysing the hydrograph of the Lower Rhine we not only look at mean discharges (Qmean over time, but also the 10% highest (Q90) and 10% lowest discharges (Q10). These three representative discharges combined give a good indication of the development of the hydrograph over time. Figure 2.4 shows the rolling average of these 3 values compared to their average over the period 1901-1980. This is done for four window sizes: 5, 10, 20 and 40 years. Here we focus on the discharges over this past period from 1901-1980.

First we look at the discharge with a 5 year rolling window. The first observation is that the discharges stay relatively stable around the average between 1901-1935, except for Q10, which deviates between factor 0.8-1.4 of the average Q10. This is notable, since during the rest of the past discharge period the Q10, Qmean and Q90 seem to be closely linked. This could be indicative of higher snow- and ice melt in the period between 1901-1935, which as explained above is formative for the lower discharges at Lobith, increasing these lower discharges relative to the higher discharge periods, decreasing the variability of the hydrograph. After 1935 larger variations in Qmean and Q90 become visible, especially around 1940 and 1970, where discharges are above average and the period in between, which sees lower discharges overall.

This above mentioned period of lower discharge between 1940 and 1970 seems to hold for all window sizes. There doesn't seem to be a large difference in variation between Q10, Qmean and Q90, unless we look at the 40 year window. While Q90 seems to vary around the average discharge and is similar to the period before 1940, Q10 is actually decreasing over time, indicating an increased variability throughout the year due to longer low discharge periods. With this decrease of Q10 the mean discharges are also slightly decreasing over time, however this effect is not as prevalent due to the relative stability of the high discharges.

This brings us to a final observation that seems to hold generally for all window sizes: the variations in mean discharge seems to be very closely linked to that of high discharge, while the variations in low discharge are generally not. One thing this could indicate is that the 10% highest discharges are relatively extreme in magnitude while the lower discharges are more stable, causing the high discharges to disproportionately affect the mean discharge.

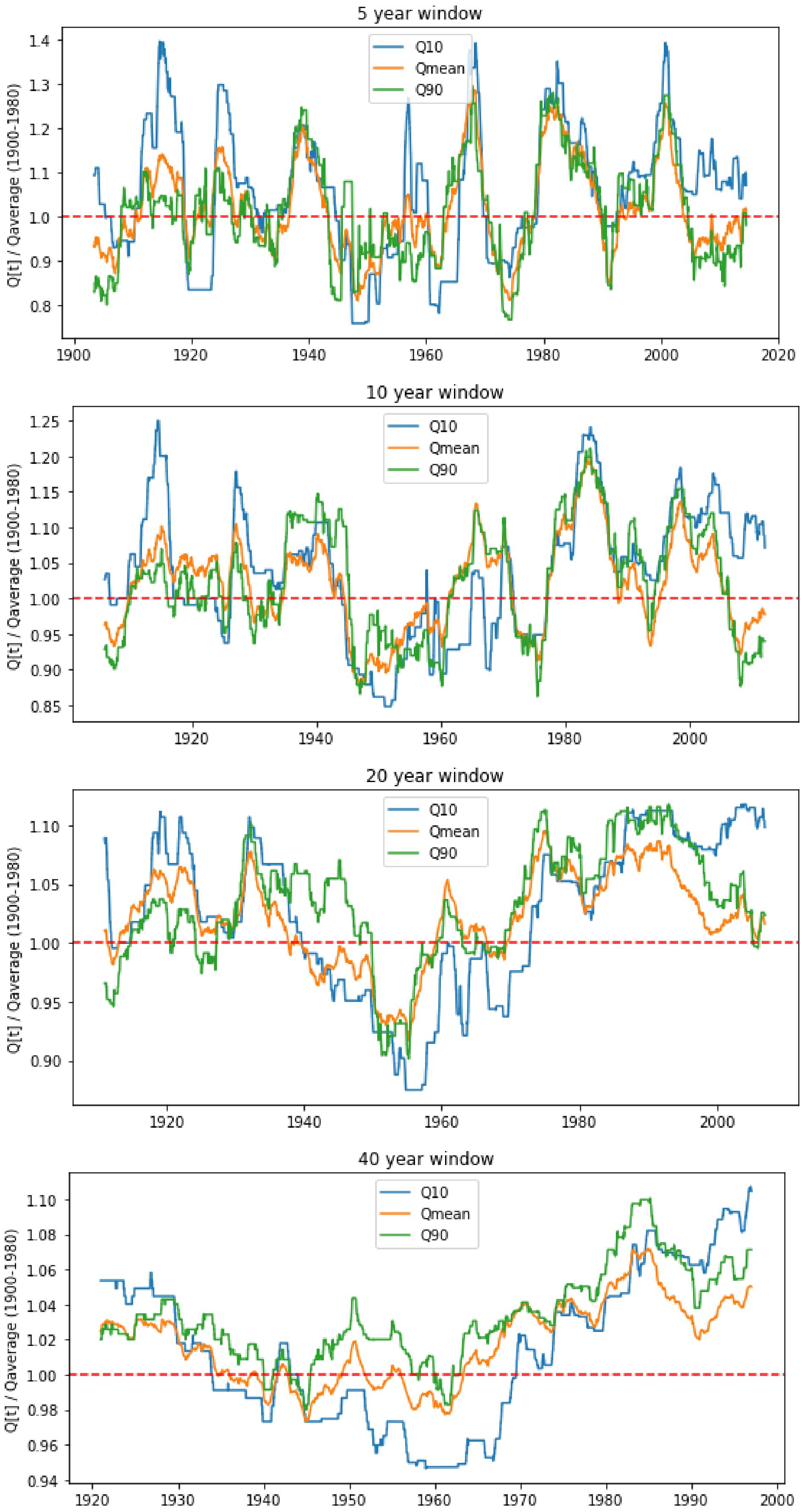


Figure 2.4: Moving average of the water discharge at Lobith of the q10, mean and q90 for different window sizes, relative to the past discharge (1901-1980) (data from the GRDC, 2018).

## 2.2. Present discharge (1981-2020)

Figure2.1 also shows the daily discharge during the period 1981-2020 (orange). Two notable discharge events during this period are the high discharge peaks in 1993 and 1995. In 1993 peak discharges of five times the mean discharge were observed (ten Brinke, 2005). Due to this an area of 18000 ha flooded in the province of Limburg and about 12000 inhabitants had to be evacuated. At the end of January 1995, due to heavy rainfall, the water levels in the Dutch rivers Maas, Waal, Rijn and IJsel raised to dangerously high levels. In the span of a few days 250000 people were evacuated from the endangered regions. In the end flooding did not occur, but it served as a wake-up call for Dutch water safety of the rivers and brought a start to the 'Room for the River' approach (Rijkswaterstaat, 2020). At the end of the summer of 2003 the opposite situation occurred: an extremely low discharge was measured of 800 $m^3/s$. It resulted in a new record low of the waterlevel at Lobith of 6.90 meters. This record low was caused by the exceptionally warm weather, causing an increase of evaporation, and a long period with relatively little precipitation (Sluijter & Jiderda, 2003).

### Discharge trends

Figure 2.4, on the previous page, shows not only the moving average of past discharge, but also those of the present discharges. Since these figures are relative to the past discharges, a comparison can be made between the past and present discharges. First we look at the shorter term windows (5 or 10 years). Between 1981-2000 the three relative discharges (Q10, Qmean and Q90) are shown to be above average compared to the reference period of 1901-1980, with deviations of up to about 1.4x for the 5 year window and up to about 1.2x for the 10 year window. This is however not outside of the expected range when comparing to past discharges: deviations of this magnitude have occurred before. More interesting is what seems to be happening after 2000: Qmean and Q90 seem to be decreasing, while Q10 stays relatively stable around 1.1x (for both 5 and 10 year window). It seems that there is a stronger correlation between mean and high discharges than there are with lower discharges, this corresponds with what we saw in the analysis of past discharges. This development could indicate that discharges during high flow periods are decreasing.

When looking at the larger window sizes of 20 and 40 years however, this seems to be a temporary trend. In the present discharge period, all representative discharges seem to be increasing. This trend seems to have started in the 1960s, where discharges were at its lowest point, and is especially visible for the 40 year rolling average. Table 2.1 shows the development of the representative discharge over the period 1960-1996 for a 40 year window (since data for Lobith only runs until 2016, the last data point in the 40 year rolling average is 1996). It shows that over this period all representative discharges have been increasing, especially Q10, which has increased by 16.6% over these 36 years, or by 0.43% a year.

| | **1960** | **1996** | **Total increase [%]** | **Average yearly increase [%]** |
|---|---|---|---|---|
| **Q10** | 1061 | 1237 | 16.6 | 0.43 |
| **Qmean** | 2139 | 2294 | 7.2 | 0.19 |
| **Q90** | 3460 | 3749 | 8.4 | 0.22 |

Table 2.1: Representative discharges for a 40 year rolling average in the years 1960 and 1996, including the total and yearly discharge increase over this period (data from the GRDC, 2020).

### Past vs present discharge

Finally we compare the discharge regime of past discharge with that of present discharge, this is shown in figure 2.5 for the 10th percentile (Q10), 90th percentile (Q90) and mean daily discharges. When only considering the mean discharges, figure 2.5 suggests that the variability of the discharge regime has increased: during (late) winter months (December-April) the mean discharge has increased, while during the summer months (July-October) discharges have decreased. When also taking Q10 and Q90 into account, the situation is more complex. During the winter months indeed both Q10 and Q90 increases, in line with the mean discharge, during the summer months this is however not the case. While Q90 shows a decrease, Q10 is actually decreasing. This indicates that the range in which discharge varies during summer is decreasing.

The analyses of the present discharge suggests that there is a trend of increasing discharge, starting at 1960. At the same time the discharge variability seems to be increasing, with the exception of the 10th percentile discharge, which seems to be increasing throughout the entire year. It is however very difficult to conclude whether a change is caused by climate change or direct human intervention, over the years many changes have been made to the river Rhine and its tributaries. When creating prediction this introduces a degree of uncertainty.

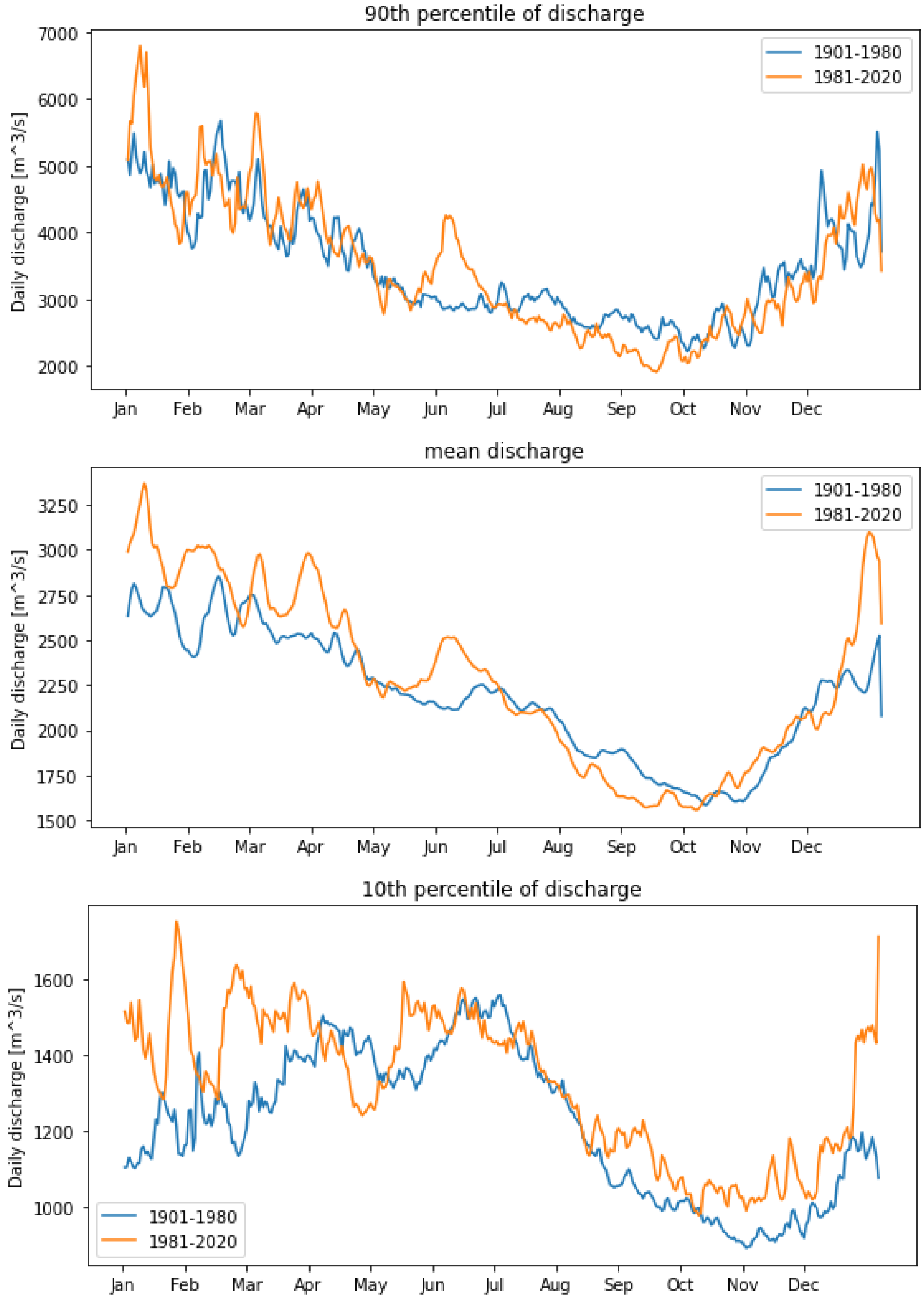


Figure 2.5: 10th percentile, 90th percentile and mean daily discharge regime of past (1901-1980) and present (1980-2020) discharge (data from the GRDC, 2018).

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## 2.3. Future discharge (2020-2100)

This section creates scenarios for the hydrograph up to the year 2100. For this GRADE is used (Hegnauer et al., 2014). GRADE (Generator of Rainfall and Discharge Extremes) is an instrument created by Deltares for Rijkswaterstaat. It is used to provide an estimation of the design discharge of a river for the Rhine and Meuse river. GRADE consists of the following components (see also figure 2.6):

**Component 1: Stochastic weather generator**: The stochastic weather generator uses nearest-neighbour resampling to produce daily rainfall and temperature series that preserve the statistical properties of the original series. The stochastic weather generator is a stand-alone application which currently runs at the Royal Netherlands Meteorological Institute (KNMI).

**Component 2: HBV model**: The HBV rainfall-runoff model uses the rainfall and temperature series created by the stochastic weather generator to calculate the runoff. The temperature is needed to take snow storage and evapotranspiration into account.

**Component 3: Hydrologic and hydrodynamic routing**: The runoff generated by the HBV model is routed through the main river in this component. GRADE uses two different models for the Rhine: one where flooding of the dikes in Germany is taken into account, and one where it is not.

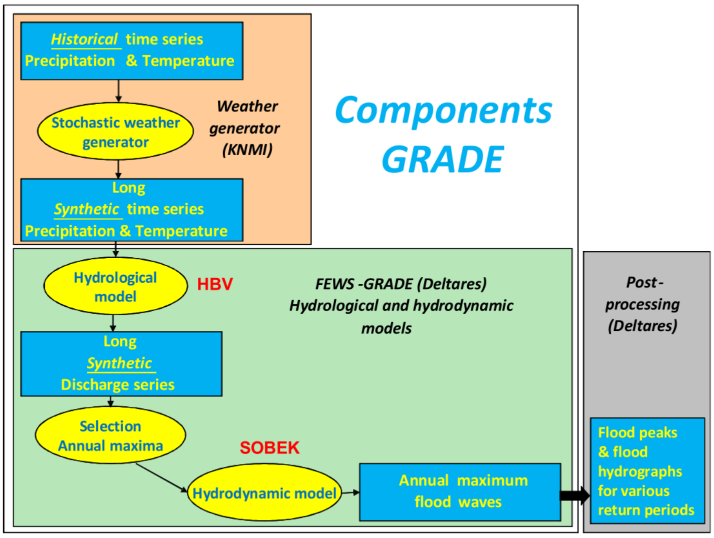


Figure 2.6: The components of GRADE (Hegnauer et al., 2014).

In the report by Sperna Weiland (2015), the KNMI'14 climate scenarios are used as input for GRADE. This resulted in predictions of discharge for the years 2050 and 2085. The predictions of 2085 are used as scenarios for this research. The KNMI'14 climate scenarios are based on the results from the 5th IPCC report (IPCC Panel, 2014). It uses climate model calculations from this report combined with KNMI's own climate model for Europe. The KNMI'14 climate scenarios define four different scenarios for the Netherlands. These scenarios are divided on two axis: global temperature rise and change in air circulation pattern (see Figure 2.7).

Besides these four scenarios, Sperna Weiland (2015) uses a 5th climate scenario. This climate scenario is a variation on the scenario with the driest conditions in summer (because of a decrease of precipitation in summer) from KNMI'14 ($W_H$). This new scenario, $W_{H,dry}$, is especially relevant when investigating the range of discharges for extremely low discharge situations which occur in summer. It is less relevant for high discharge situations.

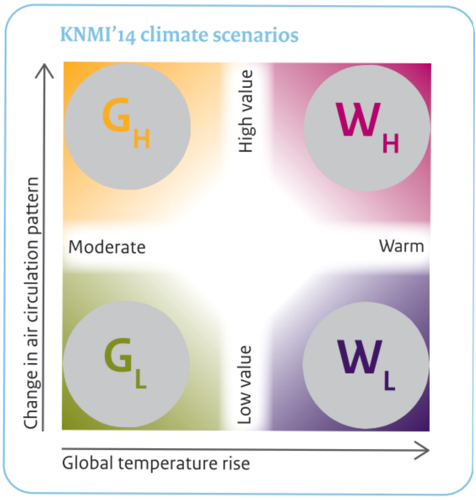


Figure 2.7: The four KNMI'14 climate scenarios (KNMI, 2015)

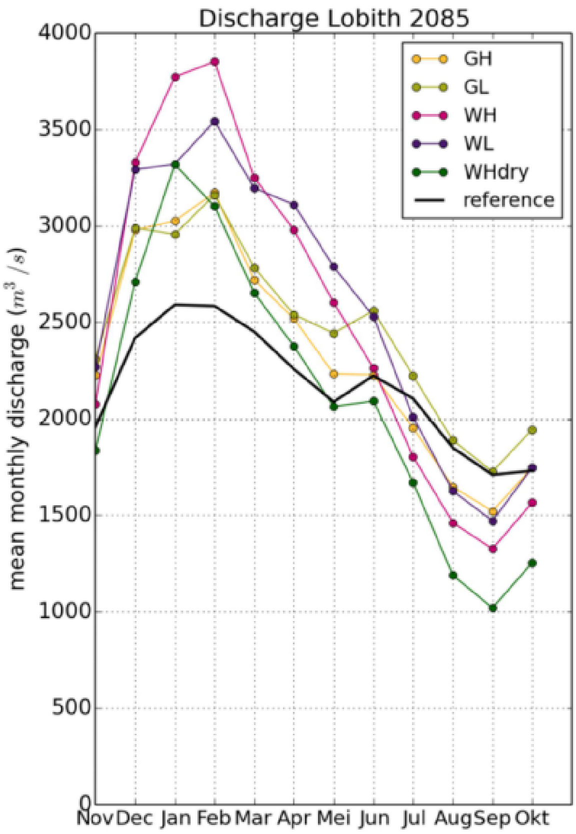


Figure 2.8: Average monthly discharge regime in 2085 for the five climate scenarios in comparison to the reference situation (Sperna Weiland et al., 2015)

Using these five climate scenarios in GRADE results in the monthly mean hydrograph for the year 2085 given below in Figure 2.8. For all scenarios an increase of discharge around February (the on average wettest month) and a decrease of discharge around September (the on average driest month) is visible. In September all scenarios except for one show a decrease of discharge of up to 40% ($W_{H,dry}$) compared to the reference period (see Table 2.2). The exception to this is scenario $G_L$, which shows a very small increase of 1%. In February all scenarios show an increase of discharge, ranging from 20% ($W_{H,dry}$) to 49% ($W_H$). All of this shows us that an increased variability of the mean monthly discharge is likely, but that the magnitude of these changes is uncertain. It is therefore important to take all these different scenarios into account.

| | **Reference (1951-2006)** | $\mathbf{G_L}$ | $\mathbf{G_H}$ | $\mathbf{W_L}$ | $\mathbf{W_H}$ | $\mathbf{W_{H,dry}}$ |
|---|---|---|---|---|---|---|
| **September** | 1710 [$m^3/s$] | +1% | −11% | −12% | −23% | −40% |
| **February** | 2585 [$m^3/s$] | +22% | +23% | +32% | +49% | +20% |

Table 2.2: Change in peak discharges (September and February) for Lobith in 2085 (Sperna Weiland et al., 2015)

Table 2.3 shows us the predicted low flow, mean and maximum discharge for 2085 at Lobith. The annual mean discharge (MQ) is predicted to increase in all KNMI'14 climate scenarios, except for the scenario $W_{H,dry}$, which shows a very small decrease. The long term mean annual lowest seven day flow (NM7Q) decreases for all scenarios, except for the scenario $G_L$, which shows a slight increase. Especially the $W_{H,dry}$ is expected to lead to a large decrease. The mean annual maximum discharge (MHQ) shows an expected increase according to all scenarios. Especially the scenarios $W_L$ and $W_H$ show a large expected increase of more than 2000 $m^3/s$.

| | Reference (1951-2006) | $G_L$ | $G_H$ | $W_L$ | $W_H$ | $W_{H,dry}$ |
|---|---|---|---|---|---|---|
| **MQ** | 2160 | 2460 | 2330 | 2570 | 2515 | 2100 |
| **NM7Q** | 1010 | 1085 | 990 | 995 | 915 | 735 |
| **MHQ** | 7060 | 8345 | 8100 | 9275 | 9710 | 8240 |

Table 2.3: Changes in long term mean annual lowest seven day flow (NM7Q), annual mean (MQ) and annual maximum (HWQ) discharges for Lobith $[m^3/s]$ (Sperna Weiland et al., 2015).

## Comparison to historical discharge

In section 2.2: present discharge, we identified that when considering a 40 year rolling average, discharges over the period 1960-1996 have been increasing. Using this knowledge we calculated a yearly average increase over this period for the mean discharge and the 10th and 90th percentile of the discharge. Using the discharge regime of GRADE's reference period (1956-2006) as a base, we can calculate the new discharge in 1985, assuming the observed trends continue into the future, and compare this to the new scenarios. Instead of the annual lowest seven day flow and the annual maximum flow used by GRADE, we have used the 10th and 90th percentile of the flow, although not the same it can give a good indication of expected behaviour. The extrapolated values are shown in table 2.4. These values compared to the GRADE discharge scenarios are shown in figure 2.9.

| | Reference (1951-2006) | Average yearly increase [%] | 2085 |
|---|---|---|---|
| **MQ** | 2160 | 0.43 | 3044 |
| **NM7Q** | 1010 | 0.19 | 1424 |
| **MHQ** | 7060 | 0.22 | 9951 |

Table 2.4: Discharges extrapolated to the year 2085, using the average yearly increase observed for the 40 years rolling average. $[m^3/s$

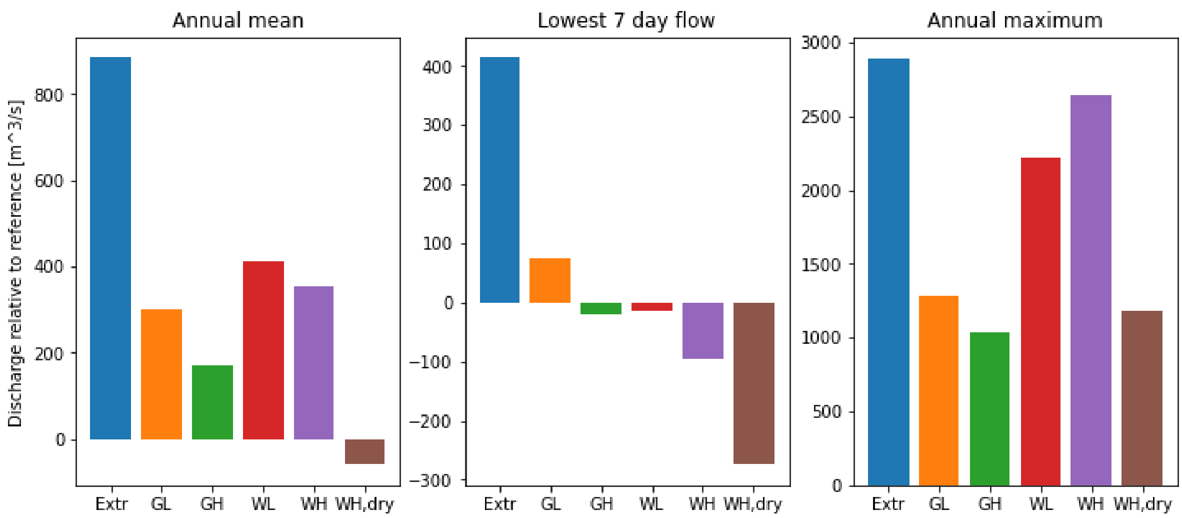


Figure 2.9: Change in discharge in 2085 compared to the reference period (1956-2006) for the annual mean (MQ, left), Lowest 7 day flow (NM7Q, middle) and annual maximum (MHQ, right).

First we consider the annual mean discharge. Extrapolating the annual mean results, just like the discharge scenarios, results in an increase of discharge. This could indicate that climate change has already been affecting the discharge at Lobith. The magnitude of the extrapolated discharge increase is however higher than the scenarios, by at least a factor 2 (when comparing to WL). When looking at the lowest 7 day flow, the extrapolated discharge shows completely different behaviour from the GRADE scenarios. While the GRADE scenarios show decreasing discharges (except for scenario GL), the extrapolated discharge is actually increasing. Finally we look at the annual maximum. Of all three categories the extrapolated discharge is here most in line with the GRADE scenarios: there is an increase of discharge of comparable magnitudes, especially when considering GRADE scenarios WL and WH, which are the climate change scenarios in which the largest temperature and precipitation changes are expected.

It is difficult to say by what the differences between extrapolated and modelled GRADE scenarios are caused by. One possible reason is that human interventions have affected historical discharge. This could mean that the average yearly increase of discharge on which the extrapolated discharge is based can not solely be attributed to climate change. Another possible limitation in this comparison is the source and base of the discharge predictions: GRADE uses precipitation data in the Rhine basin to calculate discharges, while the yearly discharge growth of the extrapolated discharge is based on discharge measurements. Finally the yearly discharge growth for the extrapolated discharge are based on the 10th, mean and 90th percentile, which doesn't match with the categories used in the GRADE models (lowest 7 day flow and annual maximum).

The change in discharge variability (more extreme discharges) and the general upward trend of annual mean discharge resulting from GRADE and the KNMI'14 climate scenarios matches partially with our observations: the general upward trend of annual mean discharge and the increase of high discharge can be recognised. It does however match with previously performed research into the expected discharge regime of the Rhine: Due to climate change the Rhine is expected to shift from a mixed precipitation and snowfall regime to a mostly precipitation dominated regime (Barnett et al., 2005; Hurkmans et al., 2010). This change will result in higher discharges during winter, with a higher frequency and magnitude of flooding (Blöschl et al., 2019) and lower discharges during the summer with an increase in frequency of periods of low flow. The GRADE discharge scenarios for Lobith will not be used directly in the further research and modelling of hydrograph effects on river bed response in this report. For this more generalised hydrographs are used. The GRADE discharge scenarios are however revered to in chapter 8: Conclusions and recommendations, to speculate what the possible effects of our modelling results on the Lower Rhine could be.

# 3

# Physics of river bed response

The bed of a lowland river such as the Rhine is affected by three different boundary conditions: The upstream discharge boundary, the upstream sediment flux and the downstream water level. In this chapter we deal with the effects of the upstream discharge boundary on the river bed response. This chapter gives the theory required to answer sub-question 2 and 3:

- *'How does the bed level of river reach with unisize sediment react to changes in the river hydrograph?'*
- *How do the bed level and surface texture of a river reach with bi-modal sediment react to changes in the river hydrograph?*

The response of a river bed can be subdivided in three different responses: the initial response, the equilibrium response and the transient response. In section 1 we deal with the initial response of the river bed. This section explains the effect of different kinds of upstream discharge boundaries and details how a variable water discharge can affect different parts of the river reach in different ways. In section 2 we deal with the equilibrium response and we also go into the effect of different sediment sizes and distribution on the equilibrium response. In section 3 we deal with the transient response.

## 3.1. Initial response

The initial response is the first morphodynamic response of a river to a change in river geometry or flow regime (Crosato, 2007). This change can be caused by an intervention in the river, for example dredging, or by a change in water discharge, for example water withdrawal. The water depth and flow velocity adapt instantly to this change, while the river bed reacts with a delay. Therefore in the initial situation the flow can be assumed to already have changed to the new situation, while the river bed is still unchanged. This disparity between flow and sediment results in a difference between sediment supply and sediment transport rate, causing either degradation or aggradation.

In the previous chapter some possible scenarios for the water discharge were discussed for the lower Rhine river. These scenarios show a seasonal variation in water discharge throughout the year; a hydrograph. The characteristics of the flow and water level vary for different parts of the river and different times of the year with a hydrograph. To understand the initial response to these variations, the effect of these different situations need to be understood. In this section we look at these different situations.

A simple way of looking at the water discharge of a river is by assuming no variation throughout the year: a single water discharge is assumed. When considering a river with a hydrograph, a single water discharge that is often used is the dominant discharge. According to Blom, Arkesteijn, et al., 2017, the dominant discharge is the steady water discharge that, given a certain mean sediment load, provides the same equilibrium channel slope as the natural long-term hydrograph. This dominant discharge is higher than the mean discharge, as higher water discharges have a relatively larger effect on sediment discharge than low discharges (see Figure

3.1). This is due to the non-linearity between water discharge and sediment transport rate.

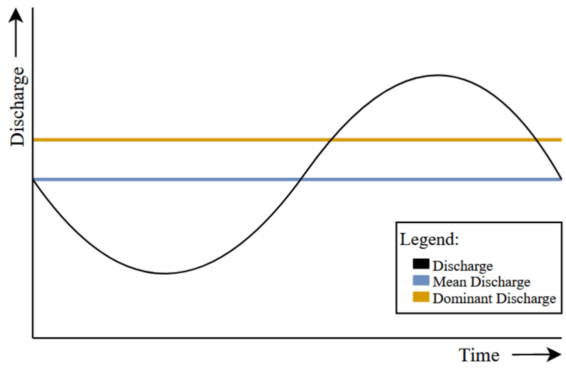


Figure 3.1: A simple hydrograph with its mean and dominant discharge.

When we consider a river with a single water discharge, two different flow segments can be identified: a backwater segment, where the water level deviates from the normal flow depth, and a steady flow segment, where the water level is equal to the steady flow depth. This is illustrated in Figure 3.2.

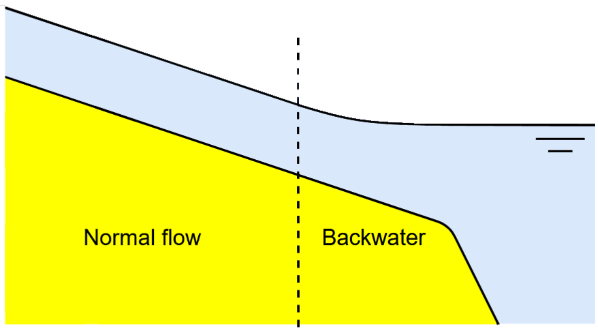


Figure 3.2: The normal flow segment and the backwater segment in a river with a single constant discharge.(Blom et al., 2017)

When considering a river with a hydrograph, the situation is a bit more complex. Instead of two, three different flow segments are now identified (Blom et al., 2017), which are also shown in Figure 3.3:

- Upstream boundary segment (UBS)
- Quasi-normal flow segment
- Backwater segment

A backwater segment forms when the downstream water level deviates from the normal flow depth. This segment not only forms at the river mouth, but for example also upstream of bifurcation, confluences and locations at which the channel width, slope or friction varies (Arkesteijn et al., 2019). The water level in the presence of a hydrograph varies between a peak flow, the moment when the water discharge is maximum, and a base flow, when the water discharge is at its minimum. Assuming a fixed water level at the downstream end, this results in a M2 backwater curve during peak flow and a M1 backwater curve during base flow. Due to this variation in flow small variations in bed level occur. An M2 backwater curve causes degradation while an M1 backwater curve causes aggradation. These variations are limited in scope: the river bed in the backwater segment is quasi-uniform, varying around a stable position. These effects are also illustrated in figure 3.4. In the case of a single water discharge a M1 backwater curve is visible throughout the year.

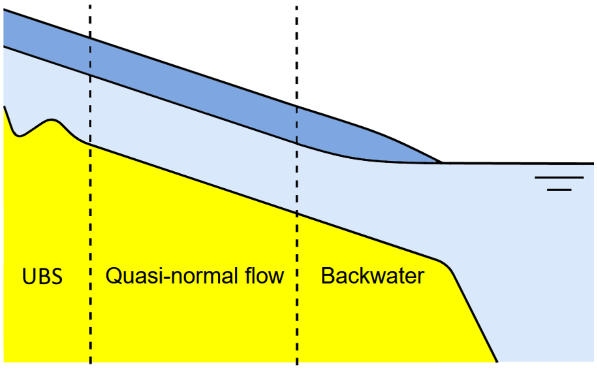


Figure 3.3: The upstream boundary segment, quasi-normal flow segment and backwater segment in a river reach with a hydrograph during base flow (light blue) and peak flow (dark blue) (Blom et al., 2017).

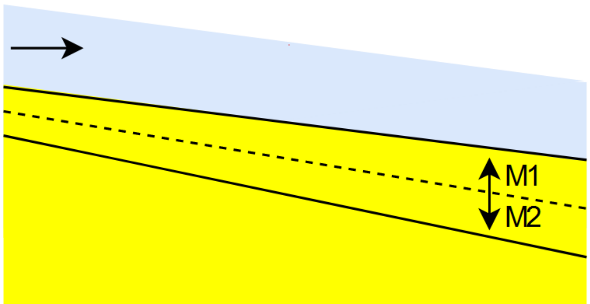


Figure 3.4: Bed level behaviour associated with variable flow at the backwater segment. (figure adapted from (Arkesteijn et al., 2019)).

The upstream boundary segment (UBS), sometimes also called the hydrograph boundary layer, forms when the sediment supply rate does not match the sediment transport capacity, even though they have equivalent time-averaged values. This causes the bed level and bed slope to fluctuate cyclically with the changing discharge, while the actual sediment transport rate remains nearly equal (Wong & Parker, 2006). This fluctuating effect on the bed level dampens out in downstream direction (Parker et al., 2007). The UBS forms downstream of bifurcations, confluences and locations at which the channel width, slope or friction varies (Arkesteijn et al., 2019).

The quasi-normal flow segment can be found where neither backwater nor UBS effects are present. In this segment, even though flow rate varies in time, it is constant at any given time. It is considered quasi-uniform. Figure 3.5 shows the presence of the three different flow segments in the lower Rhine.

During peak flow the flow velocity increases, meaning an increased sediment transport capacity, causing degradation. During base flow the flow velocity decreases, causing aggradation. This causes a mix of aggradation and degradation throughout the year. As mentioned earlier, the water discharge that eventually gives shape to the equilibrium profile is the dominant discharge. A change in the variation of the hydrograph can have an effect on the dominant discharge, even when the mean discharge does not change. It is therefore important to take the yearly variation into account when making predictions that involve sediment transport rates.

In order to illustrate the initial response we consider a simple situation: A river channel with a fixed width, unisize bed sediment, upstream sediment supply and a constant upstream water discharge. We assume the reach to be in equilibrium in its initial state. Now we impose an increase of the upstream water discharge. This increase in upstream discharge will result in a higher flow velocity. This higher flow velocity in turn causes an increase of the sediment transport rate. Since there is no change in the sediment supply from upstream, degradation will take place of the river bed.

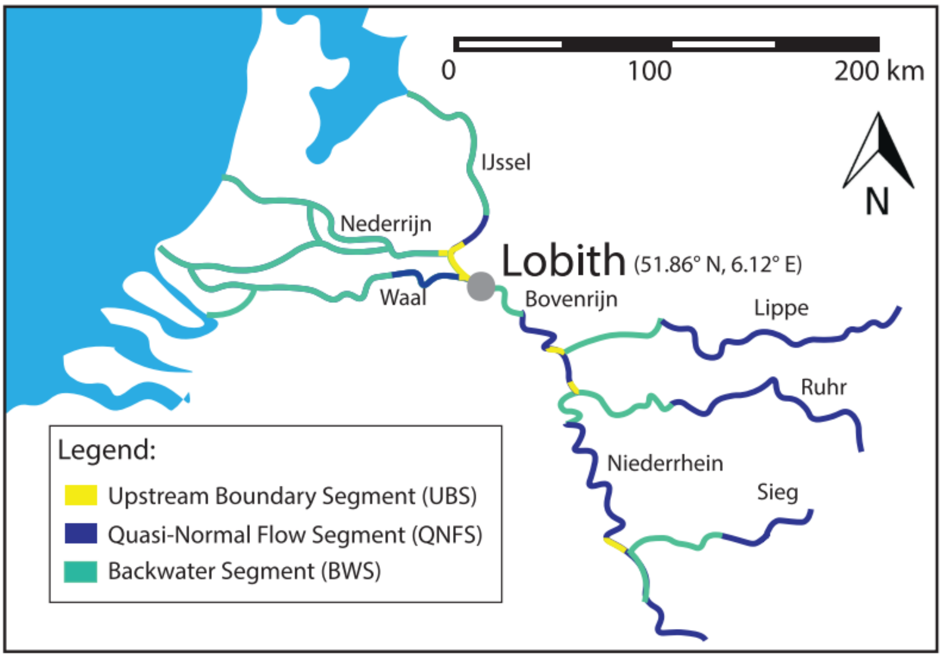


Figure 3.5: Schematic of the lower Rhine indicating the different flow segments (Arkesteijn et al., 2019).

## 3.2. Equilibrium response

We define the equilibrium river profile as the mean profile that the river approaches when flow, sediment supply, and base level vary around stable values for a long time in the absence of subsidence or uplift (Blom et al., 2016). It is the situation in which there is no difference between the sediment transport capacity and the sediment transport rate up- and downstream; there is no ongoing erosion or aggradation in the river reach (Crosato, 2007). When we consider the situation of this research, an increased upstream water discharge, this would cause an increase in sediment transport capacity. The new equilibrium situation would then be reached when the initial sediment transport capacity and flow velocity is restored. This is accomplished by changing the river bed slope and the water depth.

A river takes time to reach its new equilibrium state. The timescale over which a river will reach its new equilibrium timescale is often considered to be the engineering timescale, or about 50 to 100 years. Variations on a smaller timescale, for example in seasonality of discharge, might not have an effect on the equilibrium state. This is not always the case though, for example a seasonal variation in water discharge might cause a part of the river sediment to be less mobile during part of the year. Whether or not this has an effect on the equilibrium response is linked to the sediment size distribution. Sand grains are more mobile at lower discharges than gravel grains, which have a mobility threshold, under which they are immobile (Frings, 2007). Therefore a period of very low flows could affect sediment transport rates of different grain sizes differently.

Sediment transport in a river can be considered according to origin or according to transport mechanism. When considering the origin, a distinction is made between bed material load and wash load. When considering the transport mechanism, a distinction is made between bed-load transport and suspended load transport (see Figure 3.6). Relevant for this research is the sediment load that interacts with the bed, the bed material load.

One way of simplifying a river reach is by using a single grain size. Although very rough, this can create an initial understanding of river bed response. With a larger grain size, a higher flow velocity is required to transport the sediment downstream. Therefore the equilibrium state of a gravel river has a steeper slope and a lower water level than a river with a sand bed.

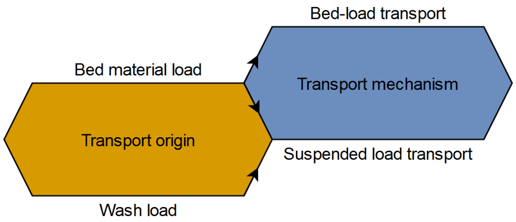


Figure 3.6: Transport modes of sediment in a river.

For this research however we consider a situation in which both gravel and sand are present. This can be modelled by using a bi-modal sediment size distribution. A situation with this distribution was investigated by Siele (2018). Figure 3.7 shows that the new equilibrium state is characterised by a smaller bed slope and a higher water level without a change in the bed surface texture. Since the sediment supply from upstream does not change, the flow velocity required to transport this sediment downstream also doesn't change. This equal flow velocity implies that mobility difference between sand and gravel is the same in the initial and new equilibrium state, causing the bed surface texture in the new equilibrium to be the same as in the initial equilibrium state. In the transient response the increase in water discharge causes an increase in sediment transport capacity, leading to a degradation and coarsening wave. This is followed by a fining wave. Why this transient response occurs is explained in further detail in the next section, section 3.3.

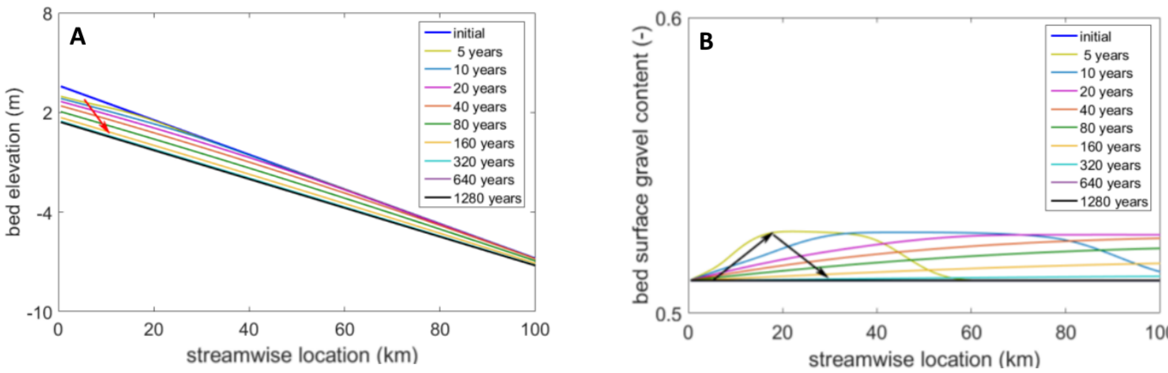


Figure 3.7: Bed elevation (A) and bed surface gravel content (B) response of a graded river to a 25% increase of the water discharge. Arrows show the direction of change in the transient phase (Siele et al., 2018)

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## 3.3. Transient response

As was mentioned in the previous section, the change to the new equilibrium state is not instantaneous. In some cases a river might not even reach its new equilibrium state, as the conditions can change beforehand. Therefore it is also important that we look at and understand the intermittent period. This period between the initial response and the equilibrium response is called the transient response.

During the transient response the river bed slowly adapts to the new equilibrium. How and where this adaptation finds place is dependent on where an intervention or change takes place. For this research we take the upstream water discharge boundary as the variable one. We assume an increase of upstream water discharge, as was also the case in section 3.1. The initial response to this situation was an increased flow velocity and in turn an increased sediment transport rate. The effect of this in the transient phase is a degradational wave starting upstream that moves downstream through the river reach. The downstream end of this river reach is also affected. With our increase in discharge the equilibrium water level increases. The downstream water level is however fixed, causing the formation of an M2 backwater curve. Due to this backwater curve flow velocity increases in downstream direction, causing degradation at the downstream end until the new equilibrium depth is reached.

The transient response is a bit more complex for the situation with a bi-modal sediment size distribution. The initial response of an increased discharge is an increase in flow velocity and thereby an increased sediment transport capacity. Since the sediment supply stays constant a degradational wave moving downstream occurs as a transient response, decreasing the bed slope (see figure 3.7a). This degradation is accompanied by coarsening of the bed, as the mobility difference between sand and gravel is increased by the increase in flow velocity, causing relatively more sand to be eroded from the river bed than gravel (see figure 3.7b). The smaller bed slope caused by this degrading wave leads in turn to a fining wave, as this smaller bed slope decreases the flow velocity again. This flow velocity keeps decreasing, and with it the bed becomes finer, until the new equilibrium is reached in which the bed surface texture is the same as the initial situation, now with a smaller bed slope. This is as we mentioned in the previous section: the equilibrium response to an increased discharge in a bi-modal river is a smaller bed slope and a higher water level without a change in the bed surface texture ((Siele et al., 2018).

The downstream end of a river with bi-modal sediment is also affected when discharge increases. Just as the case with unisize sediment this is due to the occurrence of a backwater curve. The M2 backwater curve causes increased flow velocity in downstream direction, causing degradation and coarsening of the river bed at the downstream end, as the mobility difference between sand and gravel increases. As opposed to the upstream end, the degradation at the downstream end initially increases the bed slope (see figure 3.8). This means that the secondary fining wave that occurs at the upstream end won't occur initially at the downstream end, since flow velocities do not decrease. Eventually fining will happen, but due to the upstream fining wave that has migrated downstream.

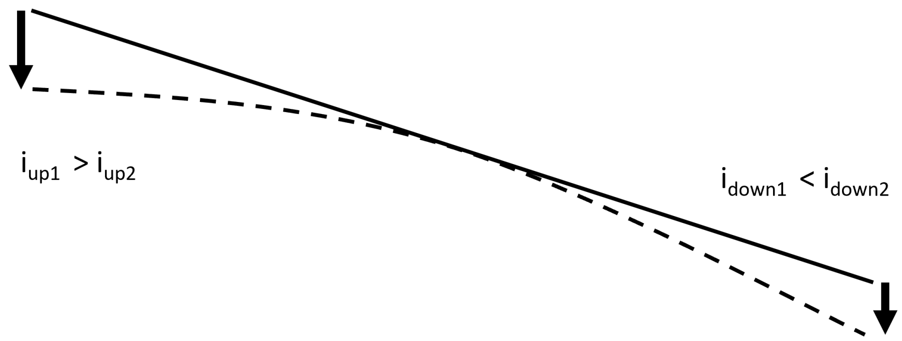



Figure 3.8: When a river degrades at both the up- and downstream end, this results in a decreased bed slope upstream and an increased bed slope downstream.

Finally we consider the time scale on which these responses happen. Figure 3.7 shows that it can take a long time before the river reach reaches the new equilibrium state. While the coarsening wave travels relatively fast through the river reach (order of decades), for the river to return back to the equilibrium bed surface texture it takes a long time (order of hundreds of years). As these timescales are longer than the engineering scale of a river (50 - 100 years), it is important to know how the river develops in the transient phase.

# 4

# Modelling of river bed response to hydrograph changes

The previous chapter detailed the theory behind river bed response. This chapter continues this line by setting up models to investigate the effects of changes in discharge on river beds. In order to do this first it is explained what model is used and which modelling choices are made. Next the runs that are performed are mentioned. For all of these runs the boundary conditions and initial conditions are defined and finally a choice is made for the numerical parameters.

## 4.1. The model

The model runs are made using Elv. Elv is a 1D morphodynamic model, written in Matlab. Elv is modular and solves the morphodynamic and hydrodynamic behaviour of a single branch of a river in a decoupled fashion. The model uses a space-marching scheme (Euler forward) to provide a numerical solution to the backwater equations from the downstream end in the upstream direction. It assumes a sub-critical flow ($Fr < 1$).

For modelling morphodynamic processes in the case of bi-modal sediment we use the active layer model Hirano (1971) is used to describe the conservation of mass of gravel and sand at the bed surface. We will make use of the Meyer-Peter & Müller (1948) transport closure relation with Egiazaroff (1965) for the hiding function. Hirano assumes that all the dynamics of the bed surface are captured by a homogeneous, but varying with time and stream wise position, top layer that interacts with the flow. A drawback of the active layer model is that under certain circumstances it can be ill-posed: negligible perturbations in the initial or boundary condition can produce significant differences in the solution (Chavarrías et al., 2018). One option is using a regularisation strategy (Chavarrías et al., 2019). In this research multiple runs were made to check whether a well-posed result is achieved.

### Simplifications and assumptions

We make the following assumptions in regards to the model:

- We assume a rectangular river cross-section and assume that there are no floodplains.
- We assume that the width of the channel is constant and fixed along the river reach.
- We only consider bed material load.
- The non-dimensional friction coeficient ($c_f$) is assumed constant, and independent of the flow parameters and surface texture.
- We assume a constant value of the bed sediment porosity.

## 4.2. Cases

To understand river bed behaviour two characteristics of the river are varied. The first one is the sediment size distribution. Both a unisize and a bi-modal sediment size distribution are investigated. Secondly we will look at both constant discharge and the use of a hydrograph. These model inputs are explained in more detail in the next section, section 4.3. Combined this gives us the following four cases:

- A river channel with a unisize sediment size and a constant discharge (UC).
- A river channel with a unisize sediment size and a hydrograph (UH)
- A river channel with a bi-modal sediment size distribution and a constant discharge (BC).
- A river channel with a bi-modal sediment size distribution and a hydrograph (BH).

Each of these cases will start from an equilibrium situation after which the upstream hydrodynamic boundary is changed over time while all other boundaries are kept constant. These scenarios are explained in more detail in section 4.4. Each case mentioned above brings an added layer of complexity. By modelling this way we can more easily see the effects of a more complex, but realistic bi-modal sediment distribution. The advantage of modelling cases with constant discharge is that we can use this as a reference to the hydrograph cases and separate the effects of yearly averaged changes to the discharge from discharge variations, which both will be imposed in the different scenario runs.

## 4.3. Model inputs

The base case parameter values are inspired by the river Waal. We assume a river width of 300 m. For the river bed we assume a bed porosity of 0.35 and a frictional constant ($c_f$) of 0.007 (Arkesteijn et al., 2019). A period of 100 years is modelled with a time step of $\Delta t$ = 5 days and a streamwise discretization of $\Delta x$ = 1000 m. These values ensure stability of the numerical model by ensuring the Courant-Friedrich-Lewy (CFL) condition, while at the same time limiting computational time. A total reach of 300 km is modelled. These and other parameters that apply to all four base cases are shown in table 4.1 below. These parameters are kept constant in all modelling runs.

| **Parameter** | **Symbol** | **Unit** | **Value** |
|---|---|---|---|
| River length | $L$ | [km] | 300 |
| River width | $W$ | [m] | 300 |
| streamwise discretization | $\Delta x$ | [m] | 1000 |
| Modelled time | $T$ | [years] | 100 |
| Time step | $\Delta t$ | [days] | 5 |
| Bed porosity | $p$ | [-] | 0.35 |
| Frictional coeficient | $c_f$ | [-] | 0.007 |
| Gravity | $g$ | [m/s$^2$] | 9.81 |
| Density water | $\rho_w$ | [kg/m$^3$] | 1000 |
| Density sediment | $\rho_s$ | [kg/m$^3$] | 2650 |

Table 4.1: General model inputs

### Boundary conditions

Three different boundary conditions are considered. Two upstream: a hydrodynamic and a morphodynamic boundary condition, and a hydrodynamic boundary condition downstream.

The upstream hydrodynamic boundary is the one that is being investigated in this research and will be varied through multiple scenarios. For the cases with a constant discharge a discharge of 1500 $m^3/s$ is used. For the cases in which we investigate a variable discharge, the same discharge, 1500 $m^3/s$ is used as the mean discharge, while a variabilty of 50%, or 750 $m^3/s$ is imposed. The upstream hydrodynamic boundary conditions for the four base cases are shown in table 4.2.

| Case | $Q_{mean}$ [$m^3$/s] | Variability [$m^3$/s] | Sediment type | Sediment size(s) [mm] | Upstream supply [Mt/year] |
|---|---|---|---|---|---|
| UC | 1500 | | Unisize | 2 | 0.6 |
| UH | 1500 | ± 750 | Unisize | 2 | 0.6 |
| BC | 1500 | | Sand<br>Gravel | 0.5<br>10 | 0.5<br>0.1 |
| BH | 1500 | ± 750 | Sand<br>Gravel | 0.5<br>10 | 0.5<br>0.1 |

Table 4.2: Upstream hydrodynamic and morphodynamic boundaries for the four cases

A water level is imposed for the downstream hydrodynamic boundary condition. This will allow us to investigate the backwater effects of the changes imposed through the upstream hydrodynamic boundary condition. Since we assume no sea level rise, the downstream hydrodynamic boundary is assumed to be constant in time. This means that for all cases and scenarios a fixed downstream water level is imposed.

For the upstream morphodynamic boundary two base cases are investigated: a unisize and bi-modal (sand and gravel) sediment size distribution. Sand has a grain size between 0.063 and 2 mm. Gravel has a grain size between 2 and 125 mm. For gravel we assume a $D_{50}$ of 10 mm and for sand a $D_{50}$ of 0.5 mm. In the case of a unisize sediment a grain size of 2 mm is used.

The annual sediment transport rates are not directly available for the Waal. Using annual sediment transport rate data at Lobith from Frings et al. (2014), combined with the distribution at the Pannerdensche Kop from Van Hamel (2018) the annual sediment transport rates in the Waal can be calculated, see Table 4.3. The data is based on measurements in the period 1991-2010. Even though this data has a high degree of uncertainty, they are representative of the orders of magnitude of annual sediment transport rates. Since it is not our goal to accurately predict the behaviour of the Waal, it is only loosely based on this river, these sediment transport rates suffice for our model.

For this model we only look at at the bed material load, as this is the part of the sediment that will affect the river bed. This results in a sand transport rate of 0.5 Mt/a and a gravel transport rate of 0.1 Mt/a and a total transport rate of 0.6 Mt/a. For the single sediment size case the total transport rate is used as the sand transport rate. The density of silica is assumed to be 2650 kg/$m^3$. An overview of the upstream morphodynamic boundary conditions for all four cases is given in table 4.2.

| Mode | Sediment type | Grain size [mm] | Transport rate at Lobith [Mt/a] (95% confidence) | | Lobith flux to the Waal [%] | Transport rate to the Waal [Mt/a] |
|---|---|---|---|---|---|---|
| Suspension | Silt, flocculated clay minerals | 0.006-0.063 | 2.22 | (1.8-2.9) | 70% | 1.55 |
| Suspension | Sand | 0.063-2 | 0.48 | (0.37-0.60) | 86% | 0.41 |
| Bed load | Sand | 0.063-2 | 0.078 | (0.033-0.123) | 86% | 0.067 |
| Bed load | Fine gravel | 2-16 | 0.090 | (0.039-0.157) | 86% | 0.077 |
| Bed load | Coarse gravel, cobbles | 16-125 | 0.016 | (0.016-0.024) | 86% | 0.014 |

Table 4.3: Annual loads for different grain size fractions at Lobith and into the river Waal (Frings et al., 2014; Van Hamel, 2018).

## Initial conditions

Using the model inputs and boundary conditions mentioned in this chapter now we calculate the initial conditions for all four base cases. This initial condition is used for any scenario run that is made. For this the equilibrium states of the base cases are taken. This is done by running ELV for each base case until an equilibrium state is reached. This equilibrium state is taken as the initial conditions for any scenario runs that are performed. The initial conditions for each base case are shown in table 4.4.

| **Initial condition** | **Symbol** | **Unit** | **Location** | **UC** | **UH** | **BC** | **BH** |
|---|---|---|---|---|---|---|---|
| Water level | $h$ | [m] | Upstream | 7.8 | 4.9 - 10.4 | 6.4 | 4.4 - 9 |
| | | | Downstream | 7.8 | 9.3 | | 8.8 |
| Flow velocity | $u$ | [m/s] | Upstream | 0.64 | 0.51 - 0.72 | 0.93 | 0.57 - 0.83 |
| | | | Downstream | 0.64 | 0.27 - 0.80 | | 0.28-0.85 |
| River bed slope | $\eta_b$ | [m/m] | Upstream | $3.7e^{-5}$ | $3.6e^{-5}$ | $6.85e^{-5}$ | $5.5e^{-5}$ |
| | | | Downstream | $3.7e^{-5}$ | $4.2e^{-5}$ | | $5.5e^{-5}$ |
| Bed sand fraction | $F_{ak}$ | [-] | Upstream | | | 0.425 | 0.47 |
| | | | Downstream | | | | 0.55 |

Table 4.4: Initial conditions for the four cases

## 4.4. Model runs

In this section we describe the modelling runs that are being performed for this research. As mentioned before we focus on the effects of the upstream hydrodynamic boundary; the discharge. This boundary condition is varied in the various runs while the other parameters and boundary conditions are kept constant. This means a fixed water level downstream and fixed sediment supply upstream, as explained in section 4.3.

Table 4.5 shows the scenario runs performed for the cases with a constant discharge (UC and BC), while table 4.6 show the scenario runs for the cases with a hydrograph (UH and BH). Figure 4.1 visualises the initial state and final state of the hydrographs for each of the discharge scenarios.

| **Scenario** | $Q_w$ $[m^3/s]$ |
|---|---|
| Base scenario | 1500 |
| 1 | **3000** |
| 2 | **750** |

Table 4.5: Scenarios for the cases with constant discharge. Both case UC and BC use a constant discharge. The values changed from the base case are in bold.

| **Scenario** | **Qmean** $[m^3/s]$ | **Peak discharge** $[m^3/s]$ | **Base discharge** $[m^3/s]$ |
|---|---|---|---|
| Base Scenario | 1500 | 2250 | 750 |
| 3 | 1500 | **2500** | **500** |
| 4 | 1500 | **2000** | **1000** |
| 5 | | **3000** | 750 |
| 6 | | 2250 | **500** |

Table 4.6: Scenarios for the cases with a hydrograph. Both case UH and BH use a variable discharge. The value changed from the base case is in bold.

The model is run over a period of 100 years. The discharge will gradually change from the base case situation to the situation that is described in each scenario run. For the cases with a constant discharge (UC and BC), the discharge change is imposed by means of a linearly changing discharge. For the cases where a hydrograph is imposed (UH and BH) a step-wise change of discharge is used, in which the initial discharge is imposed in the first year and the final discharge in the last modelled year. The discharge changes in steps of 1 year. As an example figure 4.2 shows the change of discharge for scenarios 1 and 3. Modelling the discharge changes this way will give us an insight in how a gradually changing upstream hydrodynamic boundary condition (like can be expected with climate change) can affect river bed behaviour in the transient response. However it will give no further insight into the new (quasi-)equilibrium situation that may form. The limitations of this are further discussed in chapter 7. But first the results of these modelling runs are described and analysed in chapters 5 and 6.

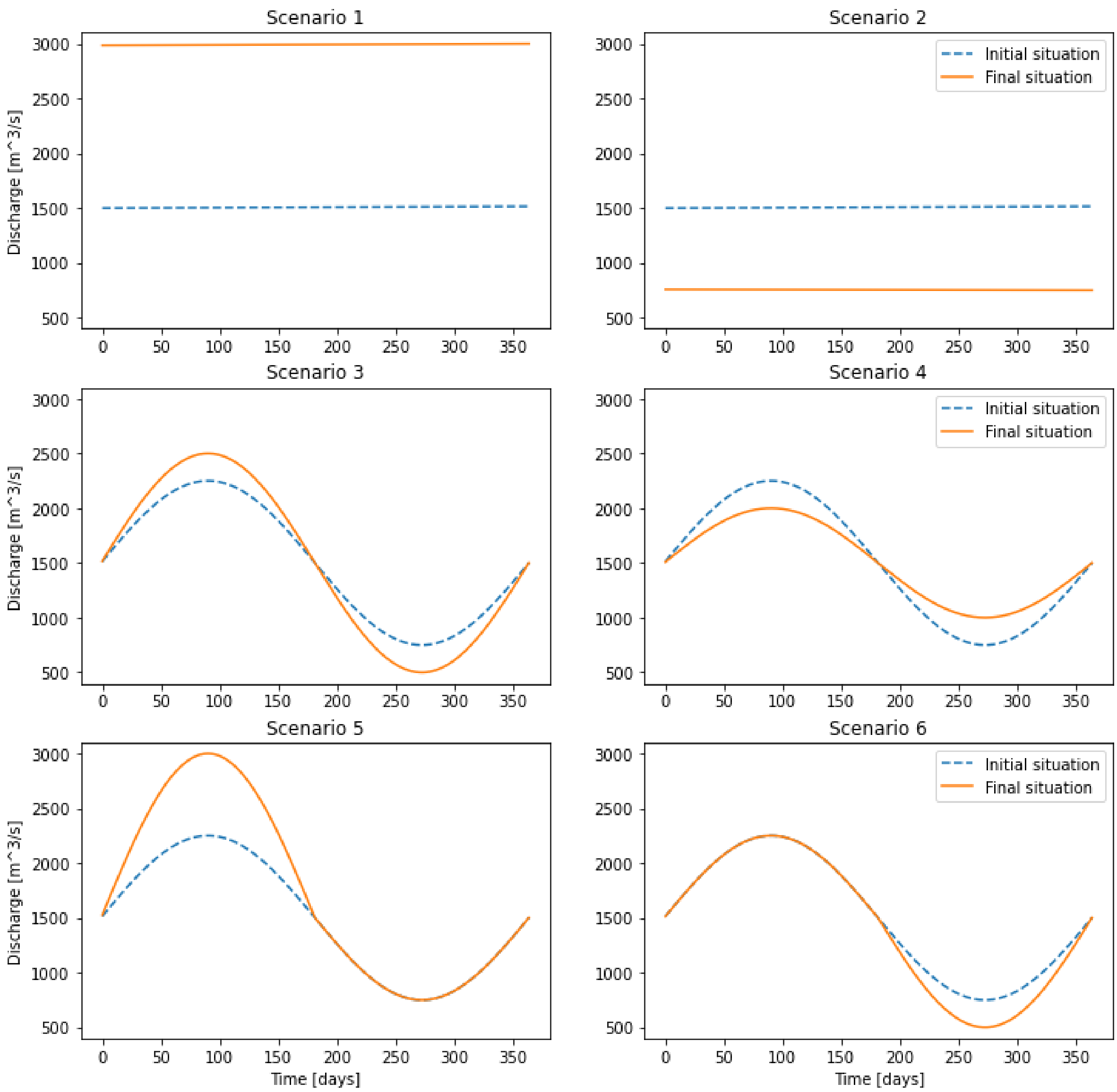



Figure 4.1: The initial hydrograph and the hydrograph after 100 years for the 6 scenarios.

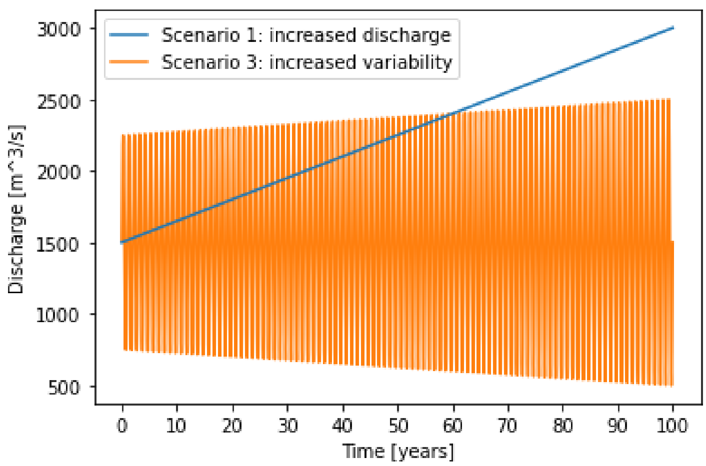



Figure 4.2: Development of discharge over a period of 100 years for the scenarios 1 and 3.

# 5

# A river with unisize sediment

In this chapter the results from the modelling runs for unisize sediment, as described in chapter 4 are described. In the first part of this chapter we will look at the scenarios in which a constant water discharge is imposed. In the second part of the chapter the scenarios in which a hydrograph is imposed are analysed. The modelling results are completely focused on the initial- and transient response. This is because of how the upstream hydrodynamic boundary is set-up: it is constantly changing throughout the entire 100 year that is being modelled. Since the upstream hydrodynamic at no time becomes stable, neither does the solution. This is further explained at the end of the previous chapter, chapter 4. In this chapter the expected new equilibrium state is mentioned at times, as this can give an insight in the observed behaviour of the river bed. It is important to remember that this new equilibrium state is based on reasoning, and not the model.

For each case first a short description of the case and its scenarios is given. Next we will look at the bed level change in more general terms: is there aggradation or degradation? And where does this take place? Does this correspond to what we might expect? Finally the results are analysed in more depth and any possible trends will be identified.

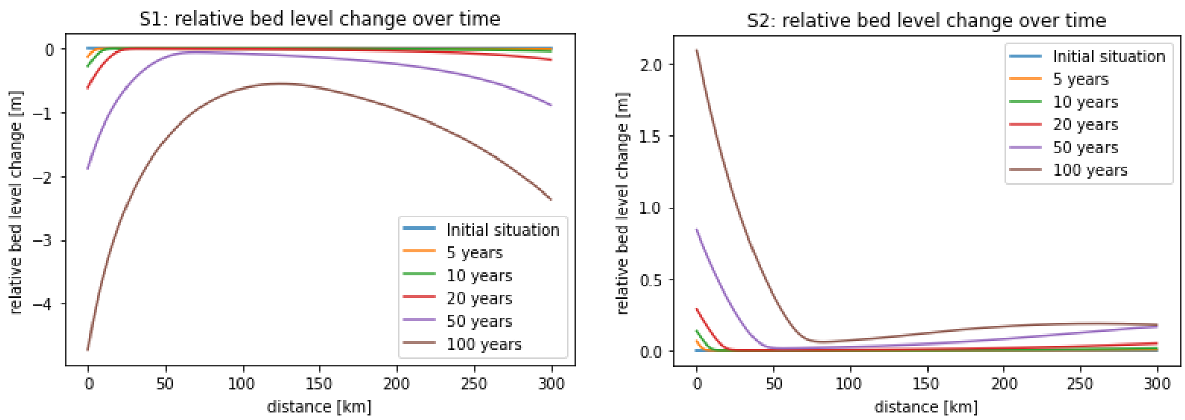
## 5.1. The effects of a changing constant water discharge

This section deals with case UC: a river channel which has a single sediment size and a constant water discharge. We analyse the results of two different scenarios:

- S1: A gradually increasing water discharge from 1500 $m^3/s$ to 3000 $m^3/s$ over a period of 100 years.
- S2: A gradually decreasing water discharge from 1500 $m^3/s$ to 750 $m^3/s$ over a period of 100 years.

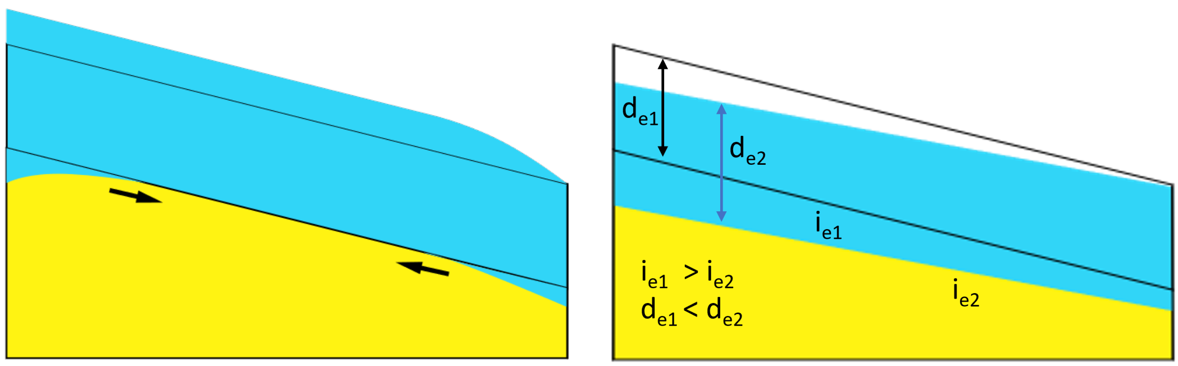
Figure 5.1a and 5.1b respectively show the relative development of the bed level for S1 and S2. From these figures we can see that with an increasing water discharge the bed level decreases, while with a decreasing water discharge the bed level increases. This degradation or aggradation of the river bed is visible both at the up and downstream end of the river reach.

The upstream bed level change can be explained by the difference between sediment supply from upstream and sediment transport capacity. The upstream morphodynamic boundary, the sediment supply, has been taken as a constant in all cases. We now take the scenario 1 (S1) in which the water discharge increases. This increase in water discharge causes an increase in flow velocity, which in turn causes an increase in sediment transport capacity as the initial response. Since the sediment transport capacity is now higher than the actual sediment supply, degradation occurs upstream. In the transient response this degradation wave moves downstream through the river reach (see figure 5.2a). When the river is able to reach its equilibrium state it would show a decreased bed slope (see figure 5.2b). As explained at the beginning of the chapter this new equilibrium state will never occur, as the upstream hydrodynamic boundary is constantly evolving.




(a) (b)

Figure 5.1: Relative development of the river channel bed over a period of 100 years for an increasing discharge (a) and a decreasing discharge (b).




(a) (b)

Figure 5.2: The transient (a) and equilibrium (b) response to a river reach with a fixed downstream water level and sediment supply due to an increase of water discharge.

When looking at figures 5.1a and b, we also see a bed level change starting at the downstream end. First we consider scenario 1: an increasing water discharge. This increase in discharge causes an increased equilibrium depth ($d_e$). However the downstream water level is fixed. This means an M2 backwater curve occurs. Due to this backwater curve degradation occurs at the downstream end until the new equilibrium depth is reached. This behaviour is illustrated in figure 5.2.

When considering scenario 2 (S2) the opposite effect as described above occurs upstream, in short: the decrease of water discharge causes a decrease in sediment transport capacity, causing aggradation upstream. This aggradation wave moves through the reach downstream (figure 5.3a) and would reach an equilibrium state, in which the bed slope is steeper (figure 5.3b), if the upstream hydrodynamic boundary was not constantly evolving.

At the downstream end of the river reach we also observe an increase of bed level with a decreasing discharge. This, similar to scenario 1, is due to backwater effects. The decrease in discharge causes a decreased equilibrium depth. Since the downstream water level is fixed, an M1 backwater curve is formed. In order to reach the equilibrium depth, the river bed aggrades. This behaviour is illustrated in figure 5.3.

Another thing to note is that for S2 at the downstream end of the reach, at a certain point in time the bed level doesn't seem to increase anymore. When comparing the lines for year 50 and 100, there is barely a difference at km 300 (see figure 5.1b). This behaviour downstream can be explained when looking at the sediment transport of the river as a whole. The upstream sediment input is 0.6 Mt/a, as defined in the previ-

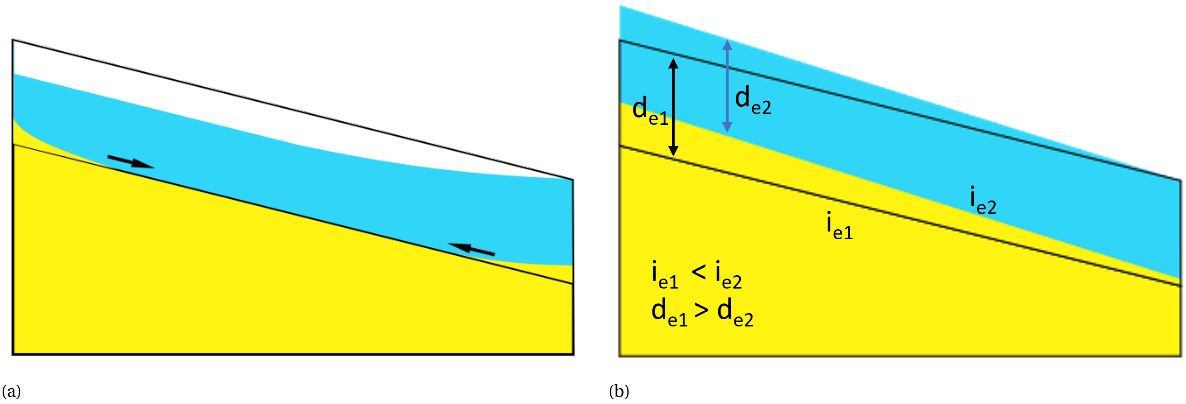



Figure 5.3: The transient (a) and equilibrium (b) response to a river reach with a fixed downstream water level and sediment supply due to a decrease of water discharge.

ous chapter. Over time the water discharge is decreasing, causing a decrease in flow velocity and in extension in sediment transport capacity. This has the additional effect that over time more and more sediment is deposited upstream. Eventually so much sediment is deposited upstream each year that no sediment reaches the downstream reach, stopping aggradation at those locations. This is also illustrated in figure 5.4, which shows the sediment transport rate for different years over the river reach for scenario 2: a decreasing discharge. This figure shows that while in the initial situation (T = 0 years) the 0.6 Mt/a is being transported throughout the entire river reach, as the sediment input into the river is equal to the sediment output, over time more and more sediment is being deposited in the river reach (indicated by the decreasing sediment transport rates over time). Eventually a situation is reached in which all sediment is deposited in the river reach (after about 50 years). When going even further no sediment is being deposited anymore downstream, as due to decreased discharge sediment deposition happens upstream (visible in this figure at T = 100 years, where sediment transport rate reaches zero after about 170 km).

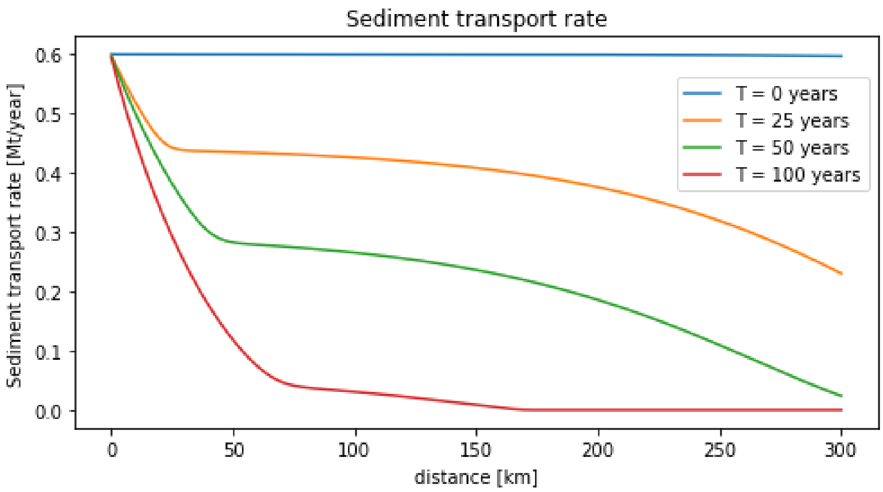



Figure 5.4: The sediment transport rate for multiple years over the river reach for scenario 2.

Now we look at the development of these sedimentation waves over time. Figure 5.5 shows this development. This figure shows the location of the front of the sedimentation waves as a function of time for both S1: increasing discharge and S2: decreasing discharge. Initiation of movement is taken as 1/100th of the maximum bed level change over 100 years. First we consider S1. When looking at this figure we can see that after 47 years the up- and downstream degradation waves converge at 63 km from the upstream boundary. The steeper slope of the downstream wave graph tells us that the velocity of the downstream wave is larger than the upstream wave. This larger velocity of the downstream wave can be explained by looking at what drives the aggradation/degradation downstream vs upstream. As mentioned earlier: the upstream wave is driven by a difference between sediment supply and sediment transport capacity, while downstream the bed level change is driven by the presence of a backwater. The backwater is present over a longer reach of the river, affecting the entire bed of this reach. At the upstream end however the bed level change is very local, as the bed starts adapting locally until the new equilibrium slope is reached, before affected the river further downstream.

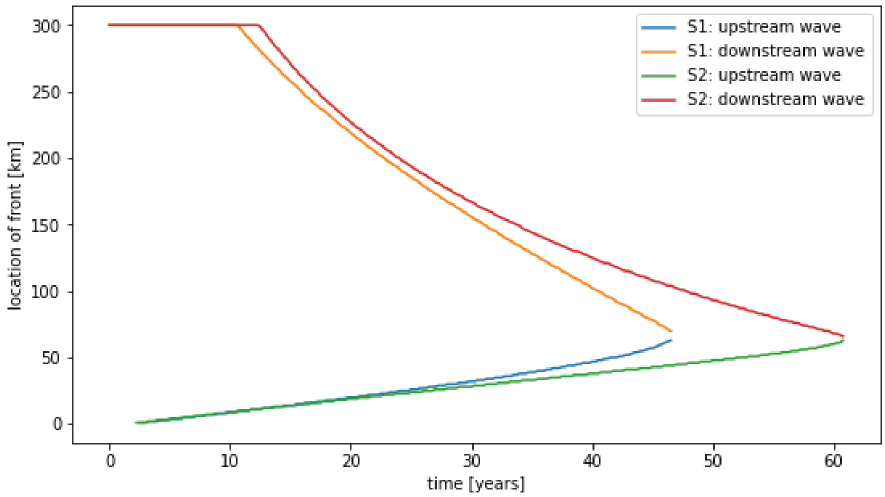



Figure 5.5: Location of the sediment wave front both up- and downstream for S1: an increasing discharge and S2: a decreasing discharge.

Note that it takes a few years before significant bed level change is noticeable at the downstream end of the river reach, indicated by the fact that the downstream wave line starts after 11 years. This is due to the fact that initially there is very little change in the water level at the downstream end. This is also visible in figure 5.6, which shows the water level at the downstream end over time. Note that until about 10 years there is barely any change in the water level. Figure 5.6 not only shows the flow depth at the downstream end, but also the flow depth at the upstream end and the calculated equilibrium depth over time. The first thing to note is that the downstream water depth follows the equilibrium depth, but slightly lags behind. This reinforces our earlier statement that at the downstream end of the reach degradation is driven by a change in equilibrium depth. Since the river bed needs time to adapt to changes in discharge, there is a lag in bed response that is never overcome: the discharge boundary constantly evolves, meaning the river bed never reaches a new equilibrium. At the upstream end of the river the flow depth seems completely decoupled from the equilibrium depth. this reinforces the statement that it is not the equilibrium depth that drives degradation upstream, it is the change in local sediment transport capacity.

Next we consider S2: a decreasing discharge. When looking at figure 5.5 we can see that the aggradational wave downstream moves faster into the reach than the upstream wave does. The sedimentation waves converge after 61 years at km 63. This seems to correspond with figure 5.1b, where the up and downstream sedimentation waves also seem to meet around the same place and time. At the same time the location where the waves meet corresponds with S1.

When comparing the location of the sedimentation wave fronts with the actually occurring aggradation or degradation it should be noted that while the downstream wave moves faster along the reach, it constitutes a smaller total sedimentation height. For S1 the downstream wave only accounts for half the degradation compared to the upstream wave (-5 m vs -2.5 m after 100 years), while for S2 it is close to the order of 10 to 1 (2 m vs 0.2 m). This again indicates that even though the direction of bed level change between the two scenarios is different (degradation vs aggradation), with more sedimentation upstream than downstream. The differences in proportion between up- and downstream (2:1 for S1, 10:1 for S2) could be explained by the lack of sediment being transported downstream in S2, as indicated before in figure 5.4, limiting the aggradation occurring here.

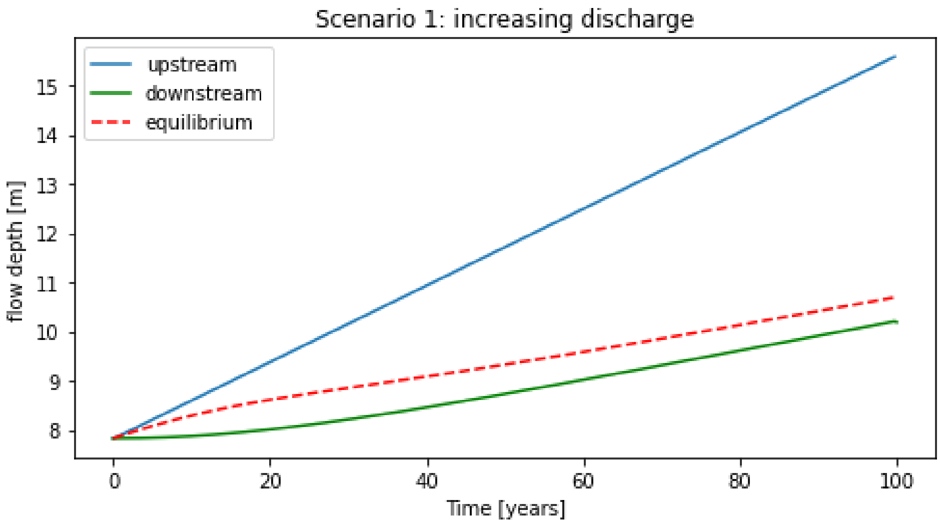



Figure 5.6: Development of the water level at the upstream end (x = 0 km) and the downstream end (x = 300 km) of the river reach for S1: an increasing constant discharge.

## 5.2. The effect of changes in the hydrograph

Case UH deals with a river channel with unisize sediment size and a variable water discharge. In the initial situation, the mean water discharge is 1500 $m^3/s$ with a variability of 50%, or 750 $m^3/s$. In this section the results are shown from the different scenario runs. First the scenarios in which the variability is decreased or increased, but the mean water discharge stays the same are discussed. Next it is investigated what the effects of an increased peak discharge are. Finally the effects of a decrease in base discharge is investigated. As in all cases, the upstream morphodynamic and downstream hydrodynamic boundary do not change over time.

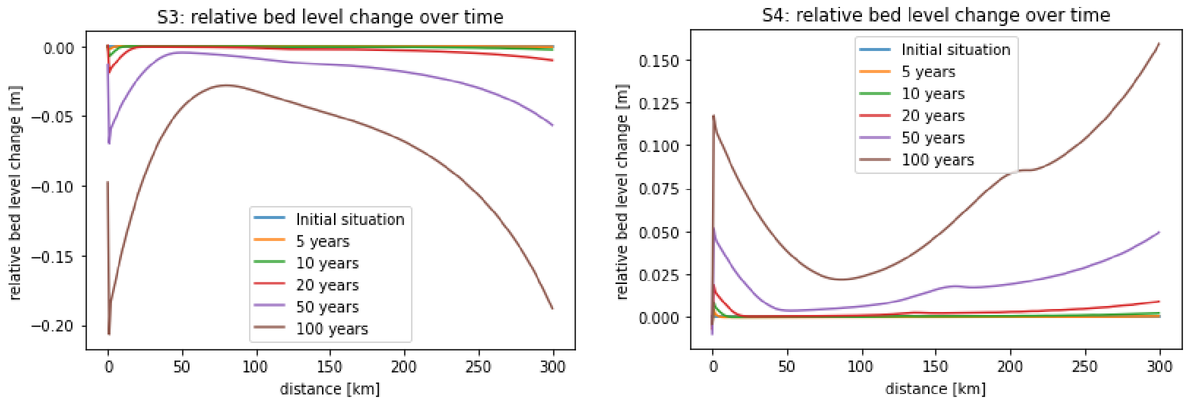
### 5.2.1. Increased discharge variability

In this part the scenarios in which a change in discharge variability occurs are discussed. These scenarios, together with the base case, are shown in table 5.1.

| **Scenario** | **Qmean** [$m^3/s$] | **Peak discharge** [$m^3/s$] | **Base discharge** [$m^3/s$] |
|---|---|---|---|
| Base Case | 1500 | 2250 | 750 |
| S3 | 1500 | **2500** | **500** |
| S4 | 1500 | **2000** | **1000** |

Table 5.1: Increased variability of discharge scenarios for case UH. The values changed from the base case are in bold.

Figure 5.7a and 5.7b show respectively the relative bed level change over time compared to the initial situation for the increased variability (S3) and the decreased variability (S4). From these figures we can see that an increased variability leads to a decrease in bed level and that a decrease of discharge variability leads to an increase in bed level. This bed level change is visible both up and downstream. Clear parallels can be made with the simple cases of scenario 1 and 2 explained in section 5.1. An increase of variability seems to have the same effect as in increase of discharge and a decrease of variability has the same effect as a decrease in discharge. This can be explained as follows: The discharge that is formative for the river channel is the dominant discharge, which is to a larger extend affected by the peak discharge, and therefore higher than the mean discharge (see chapter 3). An increase in variability therefore results in an increased dominant discharge and in extension increased sediment transport, and thus degradation.




(a) (b)

Figure 5.7: Relative bed level change compared to the initial situation for an increased variability (a) and a decreased variability (b) of discharge over a period of 100 years.

There are however differences in the response of scenario 3 and 4 compared to the previous section. One clear difference is the sharp change in relative bed level change at the upstream end of the river reach. This is due to the presence of the upstream boundary segment (UBS). The UBS forms when the sediment supply rate does not match the sediment transport capacity, even though they have equivalent time-averaged values. This causes the bed level and bed slope to fluctuate cyclically with the changing discharge, while the actual sediment transport rate remains nearly equal (Wong & Parker, 2006). This is more clearly visible in figure 5.8, which shows the relative bed level development of three points close to the upstream boundary in the first 25 years. At the upstream end (x = 0 km) the bed level has a large variation of about 0.7 m each year, even though on the yearly average the bed level slowly decreases. A bit further downstream (x = 1 km) this variation is limited to about 0.1 m, to completely dampen out further downstream.

One more thing to note is the kink that is visible in the relative bed level change for S4 further downstream. Looking at figure 5.7b, this kink seems to start near the middle of the river reach and slowly move downstream ( 140 km after 20 years and  200 km after 100 years). This kink coincides with the location at which sediment is no longer being transported during lower flows, as is also visible in figure 5.9a, which shows sediment transport rates at base flow. This happens because sediment is being deposited upstream, decreasing the sediment transport rate moving downstream. Over time the upstream bed slope has increased, meaning the sediment can be transported further downstream. One would therefore expect degradation downstream of this point. However when taking the yearly average, aggradation still occurs, as can be seen in figure 5.9b, since during periods of higher discharge sediment is still being transported.

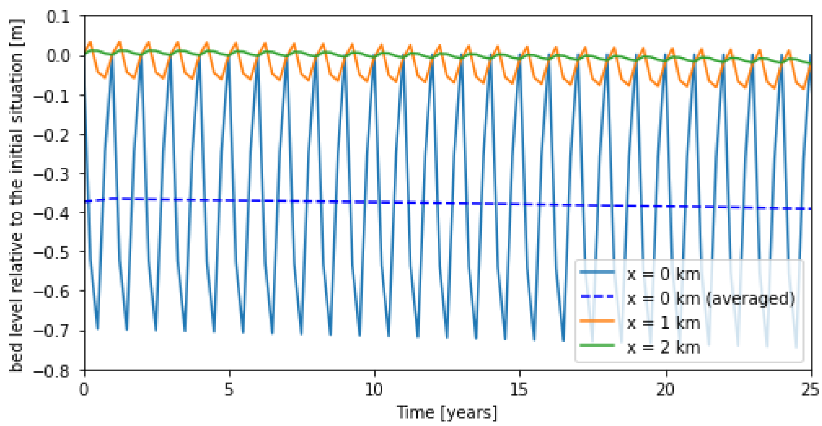



Figure 5.8: Relative bed level change over time for 3 locations at the upstream end of the river reach. The effect of the upstream boundary segment dampens out in downstream direction.

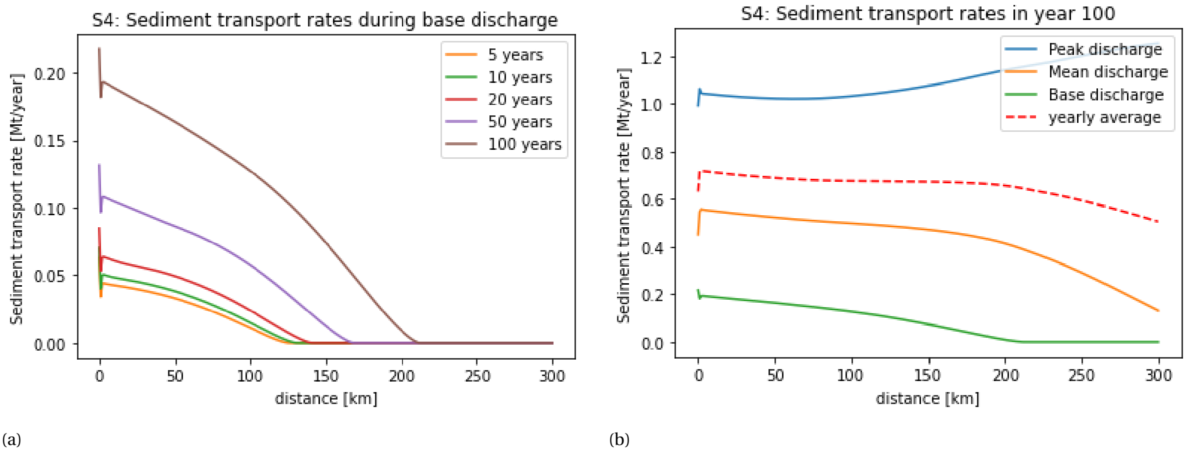



Figure 5.9: Sediment transport rates during base discharge at different moments in time (a) and sediment transport rates in the modelled year 100, including the yearly average (b) for S4: a decreasing water discharge variability.

### 5.2.2. Increased peak discharge

In this part we discuss the scenario in which the peak discharge increases, as shown in table 5.2 below.

| **Scenario** | **Qmean** $[m^3/s]$ | **Peak discharge** $[m^3/s]$ | **Base discharge** $[m^3/s]$ |
|---|---|---|---|
| Base Case | 1500 | 2250 | 750 |
| S5 | | **3000** | 750 |

Table 5.2: Increased peak discharge scenario for case UH. The value changed from the base case is in bold.

Figure 5.10 shows the relative bed level change over time compared to the initial situation for an increased peak discharge of 3000 $m^3/s$. This figure shows that with an increased peak discharge the whole river reach will start degrading. This degradation is initially visible both up- and downstream. Over time this degradation moves into the modelled domain: a degradation wave moves from the upstream boundary downstream and from the downstream boundary upstream. This behaviour is in line with the expected behaviour. In 5.2.1, we discussed the effect of an increase of dominant discharge. The same occurs here: due to the increase of the peak discharge the dominant discharge increases. This increase causes an increase in sediment transport and thus degradation. Another similarity with the previous variable discharge scenarios is the presence of a UBS upstream, recognisable by the sudden change in relative bed level change at the upstream end of the river.

### 5.2.3. Decreased base discharge

In this part the scenario in which the base water discharge decreases is discussed. This scenarios, together with the base case, is shown in table 5.3.

| **Scenario** | **Qmean** $[m^3/s]$ | **Peak discharge** $[m^3/s]$ | **Base discharge** $[m^3/s]$ |
|---|---|---|---|
| Base Case | 1500 | 2250 | 750 |
| 6 | | 2250 | **500** |

Table 5.3: Increased peak discharge scenarios for case II. The value changed from the base case is in bold.

Figure 5.11 shows the relative bed level change over time compared to the initial situation for a decreased base discharge of 500 $m^3/s$. This scenario has a lot in common with scenario 4; in both scenarios the variability of the discharge decreases. The scenarios therefore have some shared characteristics. For starters, there is an aggradational wave starting upstream which moves downstream into the reach. This is due to the decreasing discharge, which causes a decreased sediment transport capacity. This combined with the fixed upstream sediment supply means deposition of sediment upstream, causing aggradation. A second shared characteristic is the presence of the UBS upstream, recognisable by the sudden change in relative bed level change at the upstream end.

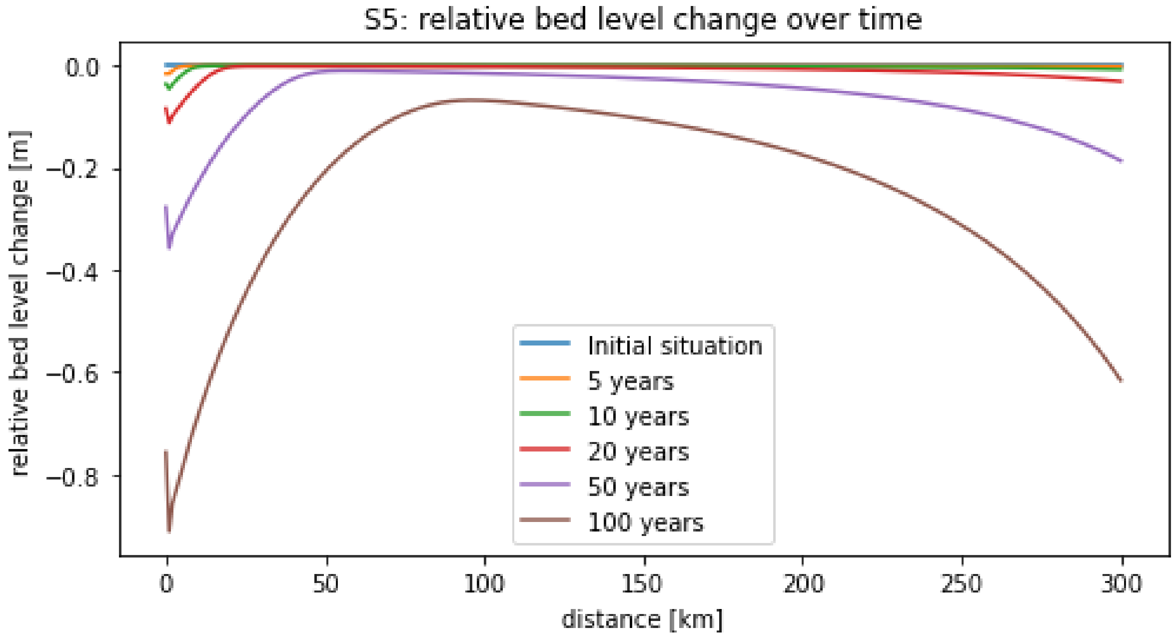



Figure 5.10: Relative bed level change compared to the initial situation for an increased peak discharge of 3000 $m^3/s$.

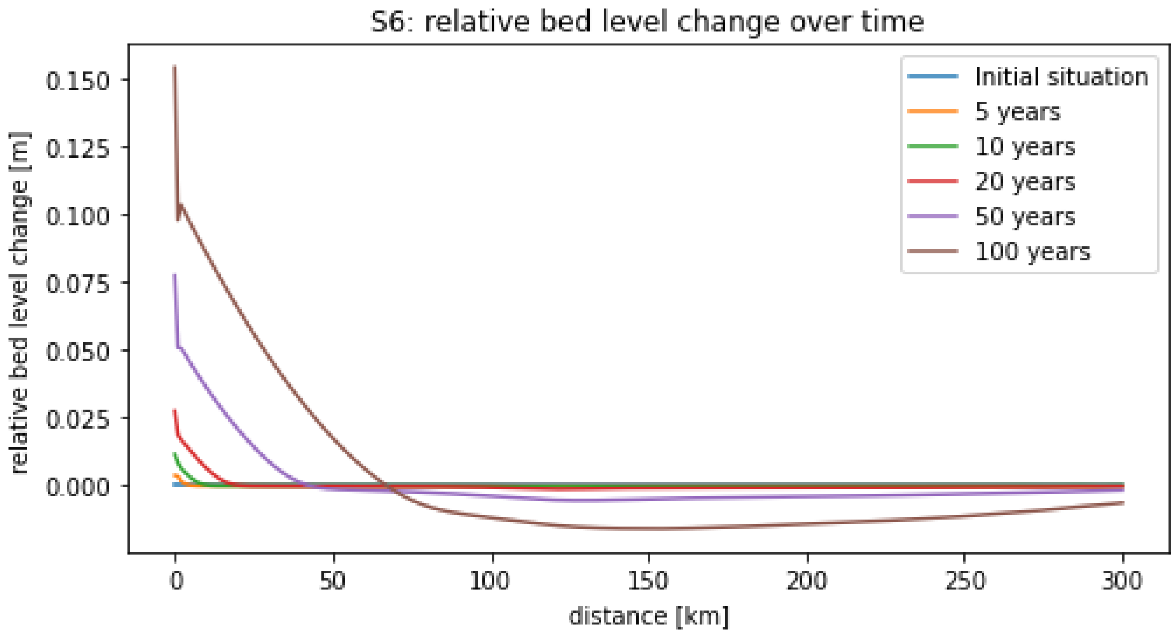
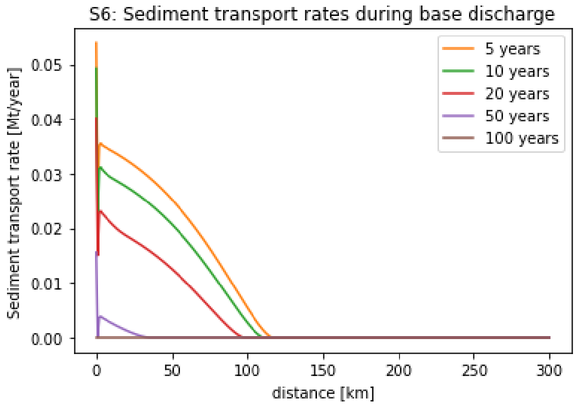
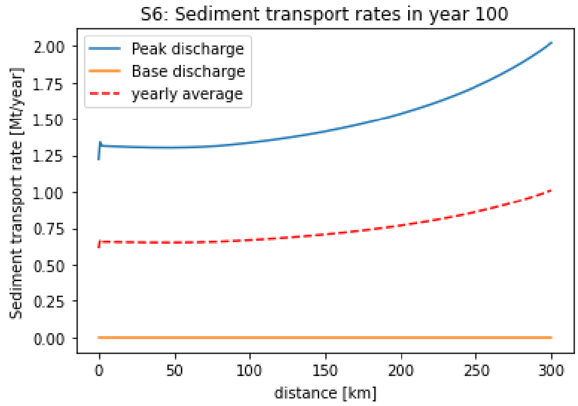



Figure 5.11: Relative bed level change compared to the initial situation for a decreased base discharge of 500 $m^3/s$.

Where the modelled results from this scenario diverts however from scenario 4, is at the downstream end of the river: instead of aggradation, degradation occurs. This difference can be explained by looking at the differences in hydrograph development between the two scenarios. While S4 sees an increasing base discharge (due to decreased variability) S6 sees a decreasing base discharge. Even though both of these scenarios result in a decreasing dominant discharge, the river beds are affected differently. The decreasing discharge in S6 means that the sediment will become less mobile during low flow periods, meaning a larger part is being deposited upstream. This is also visible in figure 5.12a. This figure shows the sediment transport rate at base discharge for different years. It shows that over time the reach over which sediment is being transported actually decreases. What this means for the average yearly transport is illustrated in figure 5.12b. The yearly averaged transport rate actually increase in downstream direction. This illustrates sediment being eroded from the river bed, confirming our observation of degradation at the downstream end of the river.




(a) Sediment transport rate during base discharge over the river reach at different moments in time.




(b) Sediment transport rate in the year 100 during peak and base discharge (solid lines) and the yearly average (dashed line).

Figure 5.12: Sediment transport rates during base discharge at different moments in time (a) and sediment transport rates in the modelled year 100, including the yearly average (b) for S6: an increasing base discharge.

# 6

# A river with bi-modal sediment

In this chapter the results from the modelling runs for bi-modal sediment, as defined in chapter 4, are described. In the first part of this chapter we will look at the scenarios in which a constant discharge is imposed. In the second part of the chapter the scenarios in which a hydrograph is imposed is dealt with. The hydrodynamic boundary condition is constantly changing throughout the entire modelled time period, as explained at the end of chapter 4. While starting at an equilibrium state, the river will never reach an equilibrium state throughout the run. We will however look at the expected equilibrium response of the cases, as these can give an insight in the observed behaviour of the river bed.

For each case first a short description of the case and its scenarios is given. Next we will look at the bed level change in more general terms: is there aggradation or degradation? And where does this take place? Does this correspond to what we might expect? Finally the results are analysed in more depth and any possible trends will be identified.

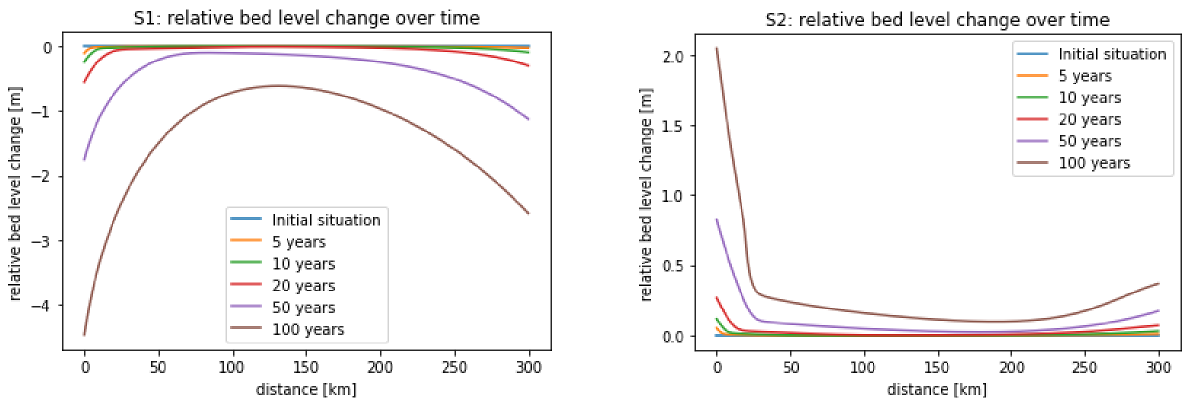
## 6.1. The effects of a changing constant discharge

This section deals with case BC: a river channel which has a bi-modal sediment size distribution and a constant discharge. We analyse the results of two different scenarios:

- S1: A gradually increasing discharge from 1500 $m^3/s$ to 3000 $m^3/s$ over a period of 100 years.
- S2: A gradually decreasing discharge from 1500 $m^3/s$ to 750 $m^3/s$ over a period of 100 years.

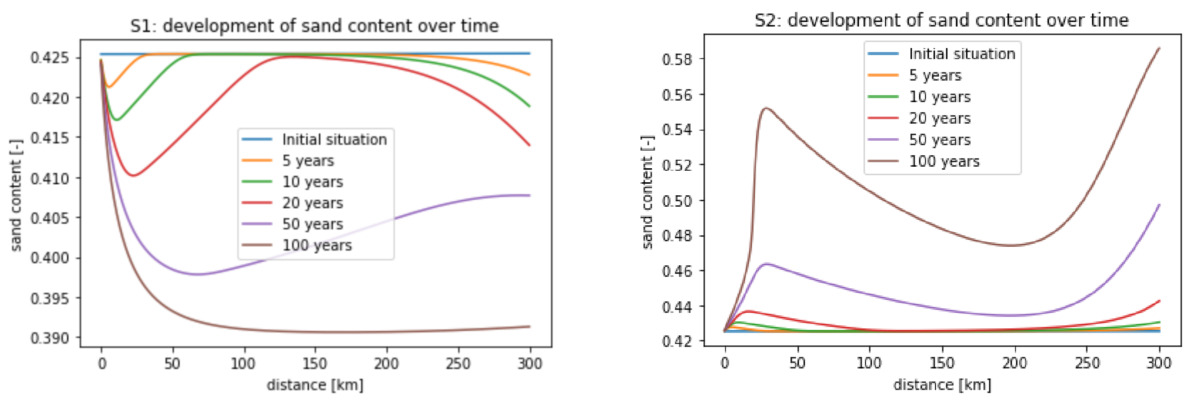
Figures 6.1a and b show respectively the development of the bed level with an increasing discharge and a decreasing discharge. These scenarios show similar behaviour as the same scenarios with unisize sediment that were analysed in the previous chapter: an increasing discharge causes bed degradation, while a decreasing discharge causes bed aggradation. An added complexity for our new case however is the bi-modality of the sediment. Not only are we observing a change in bed level, but also a change in bed surface texture that coincides with this bed level change. The development of the sand fraction for the two scenarios is shown in figure 6.2a and b. When the river bed starts degrading coarsening of the bed occurs, while an aggrading bed shows fining.

The behaviour of S1: an increasing discharge was already explained in section 3.3 and seems to match the modelled results. The initial response of an increased discharge is an increase in flow velocity and thereby an increased sediment transport capacity. Since the sediment supply stays constant, degradation occurs at the upstream end of the river. This degradation is accompanied by coarsening of the bed, as the mobility difference between sand and gravel is increased by the increase in flow velocity, causing relatively more sand to be eroded from the river bed than gravel. This behaviour is visualised in figure 6.3b.




(a) (b)

Figure 6.1: Relative development of the river channel bed over a period of 100 years for an increasing discharge (a) and a decreasing discharge (b).



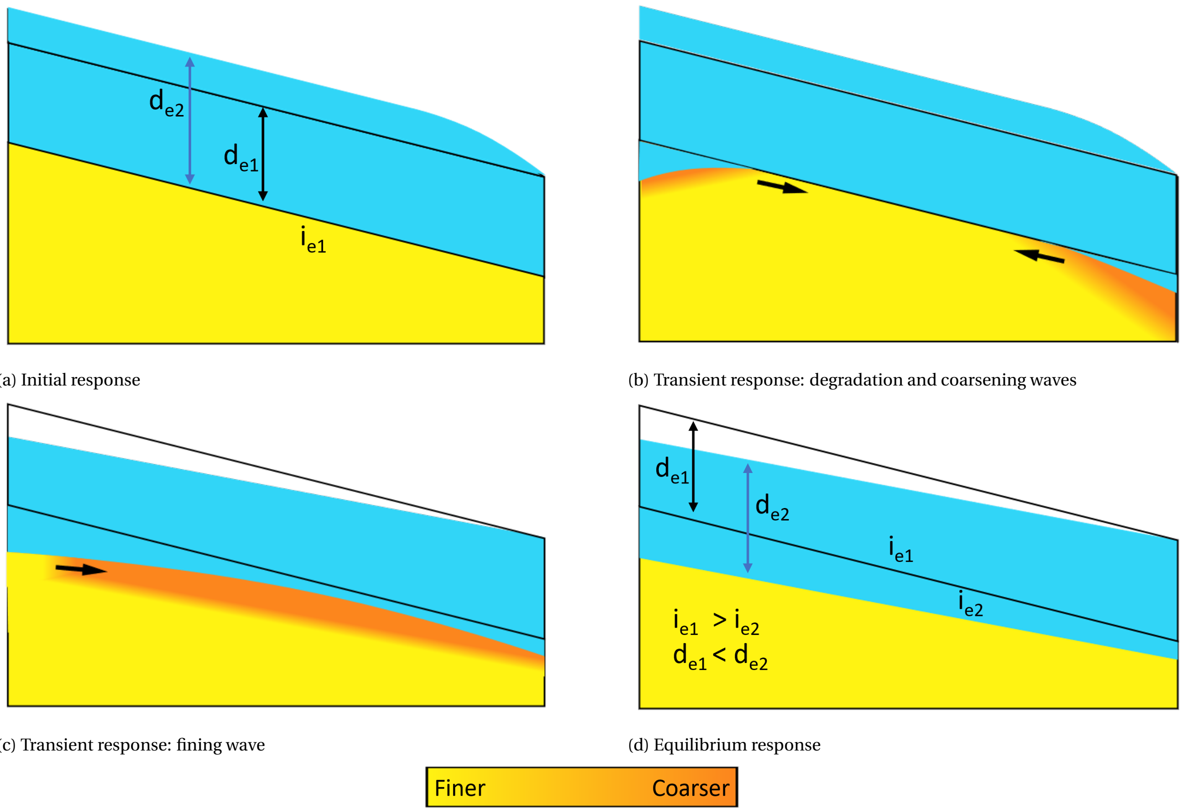

(a) (b)

Figure 6.2: Sand content of the river bed for various moments in time. With (a) showing S1: an increasing discharge and (b) showing S2: a decreasing discharge.

At the downstream end of the river the same behaviour is visible as upstream, degradation and bed coarsening (see figures 6.1a and 6.2a). The mechanisms for this behaviour are however slightly different. The increase in discharge causes an increase of the equilibrium depth of the river reach. Since the downstream water level is fixed an M2 backwater curve occurs, increasing flow velocities in downstream direction. This increase in flow velocity, similar to the upstream end of this river reach, causes an increase in sediment transport capacity, resulting in degradation. This increase in flow velocity has the secondary effect of increasing the mobility difference between sand and gravel, causing relatively more sand to be eroded compared to the gravel. This downstream behaviour is again illustrated in 6.3b.

Continuing the line of reasoning from the modelled results we would expect that in the new equilibrium for S1 the bed surface texture is coarser. This is however not the case. As discussed in section 3.2, the new equilibrium state of a river with bi-modal sediment and increasing discharge actually has the same bed surface texture as the initial state. This is because the sediment supply stays unchanged. In the new equilibrium the sediment transport capacity and therefore the flow velocity needs to be restored to its original values for a balance in sediment transport to occur. Since the flow velocity in the new equilibrium is equal to that of the initial state and bed surface texture is dependant on this flow velocity, the original bed surface texture is restored. This is accomplished by a secondary fining wave starting upstream, see also figure 6.3c.

This secondary fining wave does not appear in our modelling results. This brings to light a limitation of our model: since the upstream hydrodynamic boundary is constantly changing throughout the modelled period of time, no stable situation is ever reached. Instead we only observe the primary degradation/coarsening waves. This limitation holds for all of the modelled scenarios in this chapter and the focus of this chapter will therefore solely be on this primary wave. In chapter 7: Discussion, this limitation is further discussed.




(a) Initial response

(b) Transient response: degradation and coarsening waves

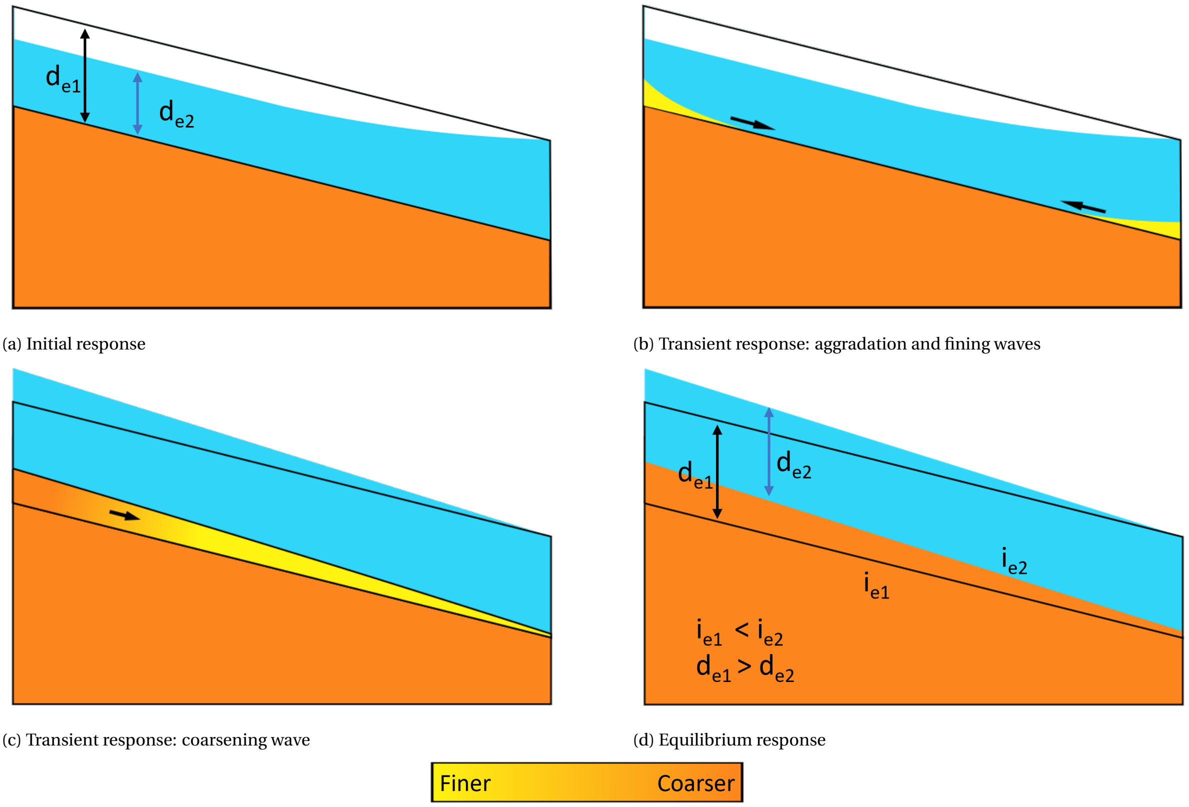
(c) Transient response: fining wave

(d) Equilibrium response

Figure 6.3: The initial, transient and equilibrium response of a river with bi-modal sediment to S1: an increasing discharge.

Now consider S2: a constantly decreasing discharge. For this scenario the opposite effect occurs. The decreasing discharge in this scenario causes a decrease in flow velocity, decreasing the sediment transport capacity. Since the sediment supply from upstream stays unchanged, this leads to aggradation of the river bed, as the supplied sediment is deposited. At the same time fining occurs, as the decreased flow velocity decreases the mobility difference between sand and gravel grains, causing relatively more sand to be deposited. (see figure 6.4b). At the downstream end of the river for scenario 2 we also observe bed aggradation and fining. This can be explained by the fact that the decreased discharge causes a decreased equilibrium depth, but due to a fixed water level downstream an M1 backwater curve occurs (figure 6.4a). This causes flow velocities to decrease downstream, causing aggradation and relatively more fine sediment to be deposited, causing fining of the river bed (see figure 6.4b).

Similar to S1, the model does not tell the whole story. After the primary aggradation/fining wave a secondary coarsening wave moves in downstream direction into the river reach, eventually bringing the river reach to a new equilibrium. This new equilibrium has a steeper bed slope and smaller water depth, while keeping the same bed surface texture as in the initial situation, as the sediment supply and therefore the required flow velocity to transport the sediment downstream does not change.




(a) Initial response

(b) Transient response: aggradation and fining waves

(c) Transient response: coarsening wave

(d) Equilibrium response

Figure 6.4: The initial, transient and equilibrium response of a river with bi-modal sediment to S2: a decreasing discharge.

Different from the unisize sediment case, the sedimentation waves from up and downstream seem to be moving into the reach at a similar velocity. Figures 6.5 shows that the sediment waves meet around the middle of the river reach. This can be explained by the difference in backwater length for the two different cases. Where the initial slope ($i_b$) of the unisize sediment case is $3.7e-5$, for the bi-modal sediment case it is $6.8e-5$. This is a difference of a factor $\frac{6.8}{3.7} = 1.8$. The length of a backwater curve can be approximated using the empirical fit of Bresse, which assumes subcritical flow and a rectangular uniform channel, as is the case for us:

$$L_{1/2} = 0.24 \frac{d_e}{i_b} \left( \frac{d_0}{d_e} \right)^{4/3} \tag{6.1}$$

Using our values, the steeper slope in the bi-modal case suggests that the backwater curve will be 1.8x shorter. Translating it to our model, this suggests a result in which the downstream sediment wave takes longer to move into the reach. As mentioned at the beginning of this paragraph, this is indeed the case.

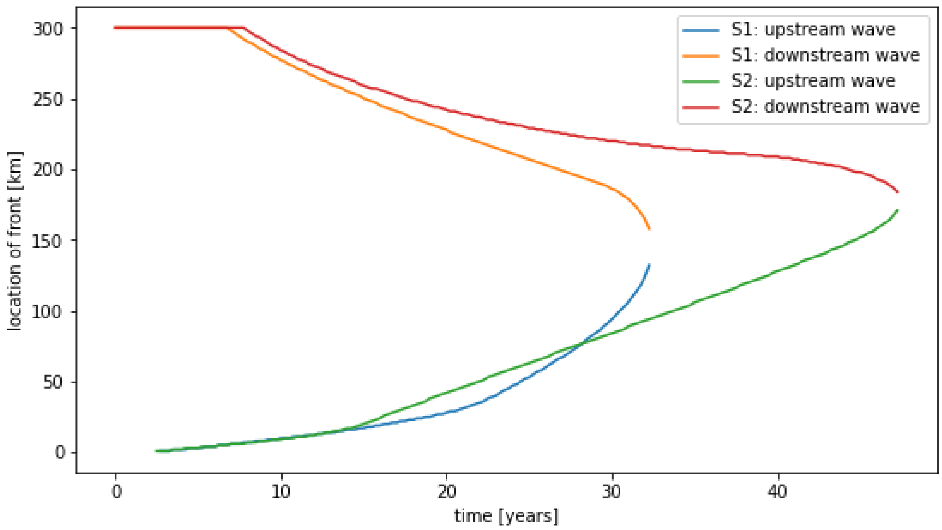



Figure 6.5: Location of the sedimentation wave front both up- and downstream for S1: an increasing discharge and S2: a decreasing discharge

## 6.2. The effect of changes in the hydrograph

Case BH deals with a river channel with bi-modal sediment size and a variable water discharge. In the initial situation, the mean discharge is 1500 $m^3/s$ with a variability of 50%, or 750 $m^3/s$. In this section the results are shown from the different scenario runs for this case. First the scenarios in which the variability is decreased or increased, but the mean discharge stays the same are discussed. Next it is investigated what the effects of an increased peak discharge are. Finally the effects of a decrease in base discharge is investigated.

### 6.2.1. Increased discharge variability

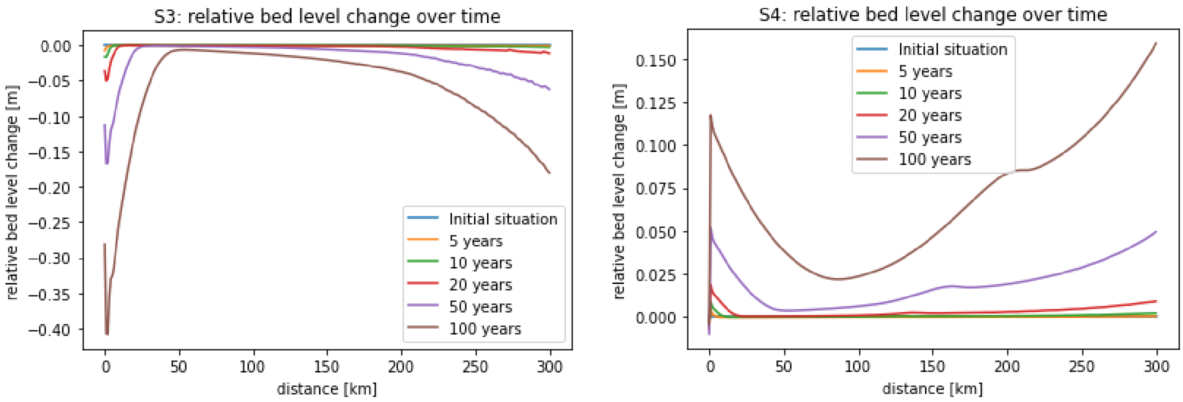
In this part the scenarios in which a change in discharge variability occurs are discussed. These scenarios, together with the base case, are shown in table 6.1 below.

| **Scenario** | **Qmean** $[m^3/s]$ | **Peak discharge** $[m^3/s]$ | **Base discharge** $[m^3/s]$ |
|---|---|---|---|
| Base Case | 1500 | 2250 | 750 |
| S3 | 1500 | **2500** | **500** |
| S4 | 1500 | **2000** | **1000** |

Table 6.1: Increased variability of discharge scenarios for case BH. The values changed from the base case are in bold.

Figure 6.6a and b respectively show the relative bed level change over time compared to the initial situation for the increased variability (S3) and the decreased variability (S4). From these figures we can see that an increased variability leads to a decrease in bed level and that a decrease of discharge variability leads to an increase in bed level. This bed level change is visible both up and downstream. Clear parallels can be made with the simple cases of scenario 1 and 2 explained in section 6.1. An increase of variability seems to have the same effect as in increase of discharge and a decrease of variability seems to have the same effect as a decrease in discharge. This can be explained as follows: The discharge that is formative for the river channel is the dominant discharge, which is to a larger extend affected by the peak discharge, and therefore higher than the mean discharge (see chapter 3). An increase in variability therefore results in an increased dominant discharge and in extension increased sediment transport, and thus degradation.

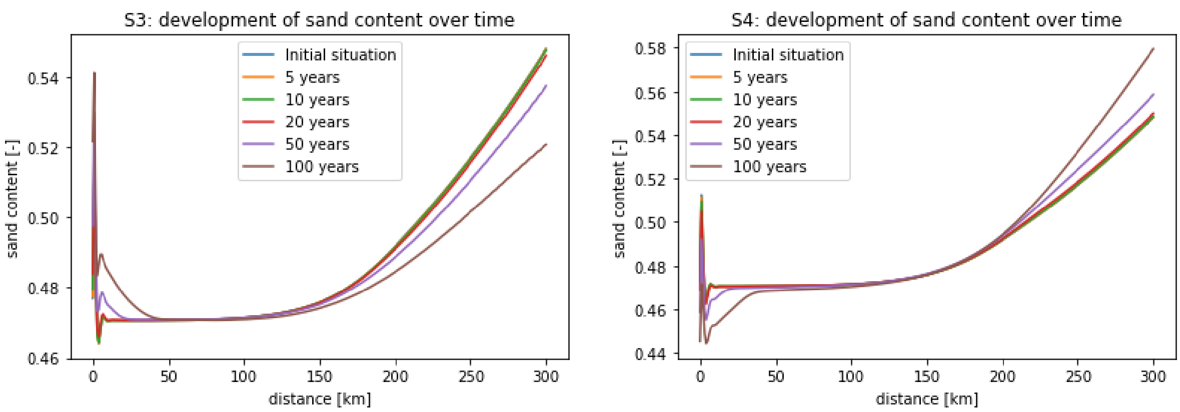
There are however also differences in the response of scenario 3 and 4 compared to the previous section. One clear difference is the sharp change in relative bed level change at the upstream end of the river reach. This is due to the presence of the Upstream boundary segment (UBS). The effect and behaviour of the UBS has been explained in the previous chapter, as a short recap: The UBS forms when the sediment supply rate does not match the sediment transport capacity, even though they have equivalent time-averaged values. This causes large variation in the bed level upstream in the short term.




(a) (b)

Figure 6.6: Relative bed level change compared to the initial situation for an increased variability (a) and a decreased variability (b) of discharge over a period of 100 years.

A clear difference between the previous case with a constant discharge and this case is the development of sand content over time: both the initial (equilibrium) state and the changes to this initial state look very different. Due to the effect of downstream fining, the further one goes downstream the finer the bed texture gets in the initial state, as can be seen by the increasing sand content in downstream direction in figures 6.7a and b. Figures 6.7a and b show the sand content of the river bed at different times during the simulation, for an increasing variability and a decreasing variability respectively.




(a) (b)

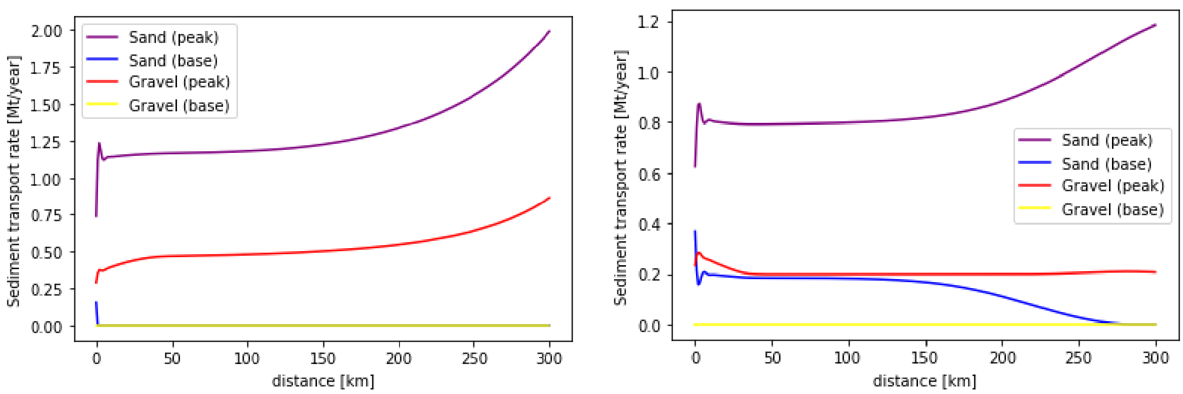
Figure 6.7: Sand content of the river bed for various moments in time. With (a) showing S3: an increasing discharge variability and (b) showing S4: a decreasing discharge variability.

First we look at the situation with an increasing water discharge variability (S3), see figure 6.7a. It shows that at the upstream end the sand content increases over time. This can be explained by taking into account that we are dealing with bi-modal sediment and variable discharge, meaning that during different parts of the year, the two different grain sizes have different mobilities. The effect of this is visible in figure 6.8a, which shows the sediment transport rates for both sand and gravel during peak and base flow in the year 100. In this figure we can see that during low flow periods not only gravel is immobile, but so is sand. This means that during these low flow periods sand is also deposited upstream, causing fining, since the sediment supply is finer than the bed sediment. However since over time the variability increases (and with it increasing dominant discharge) on average degradation occurs.

Now we look at S4: a decreasing discharge variability, see figure 6.7b. In this scenario the opposite development of the bed texture is visible: coarsening upstream and fining downstream. Here the opposite effect to S3 occurs. The decrease in variability causes a decrease in dominant discharge, resulting in aggradation. However due to the decrease of variability, flow increases during the low flow period. The effect of this is illustrated in figure 6.8b. During low flow periods sand is mobile, while gravel is not. Meaning the gravel is deposited at the upstream end, causing the bed to become coarser. During peak flow periods both sediments sizes are mobile, but due to the decreasing variability (and therefore decreasing dominant discharge) over time aggradation occurs.

When looking at the downstream end of the river reach for these scenarios, likeness to the scenarios in the previous section can be found. The response with an increased discharge variability (S3) seems to show similar behaviour with the response an increased discharge (S1): degradation and coarsening. This similarity stems from the fact that an increased discharge variability causes an increase in the dominant discharge (see also chapter 5.2.1). This increase of dominant discharge means an increase in the average equilibrium depth. As mentioned before in section 6.1, the resulting M2 backwater causes degradation and coarsening (see figure 6.3)b.

Likewise the response of S4, a decreasing discharge variability, can be linked to the response of the with a decreasing discharge (S2). The decreasing variability means a decrease in dominant discharge, decreasing the downstream equilibrium water depth, resulting in an M1 backwater which causes aggradation and fining (see figure 6.4b).




(a) (b)

Figure 6.8: Sediment transport rates in the year 100 for S3: an increasing discharge variability (a) and S4: a decreasing discharge variability (b).

## 6.2.2. Increased peak discharge

In this part we discuss the scenario in which the peak discharge increases, as shown in table 6.2 below.

| **Scenario** | **Qmean** $[m^3/s]$ | **Peak discharge** $[m^3/s]$ | **Base discharge** $[m^3/s]$ |
|---|---|---|---|
| Base Case | 1500 | 2250 | 750 |
| S5 | | **3000** | 750 |

Table 6.2: Increased peak discharge scenario for case BH. The value changed from the base case is in bold.

Figure 6.9 shows the relative bed level change over time compared to the initial situation for an increased peak discharge of 3000 $m^3/s$. This figures shows that with an increased peak discharge the whole river reach will start degrading. This degradation is initially visible both up- and downstream. Over time this degradation moves further into the river reach: a degradation wave moves from both up and downstream. This behaviour is similar to that of scenario 3: an increased discharge variability. This is due to the fact that both this change (increasing peak discharge) and the change that occurs in scenario 3 (an increased discharge variability) have an increased dominant discharge as effect. This dominant discharge is the discharge that is formative for the river bed. Another similarity with scenario 3 is the presence of the UBS upstream.

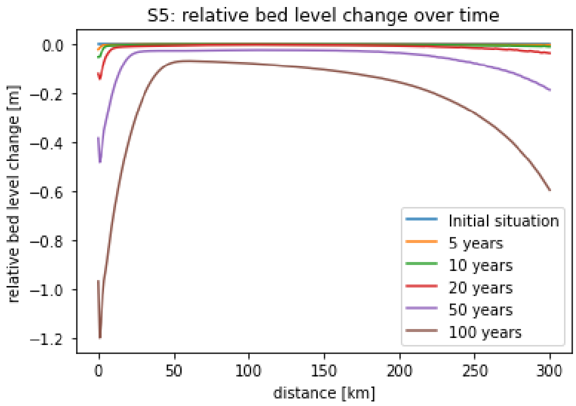



Figure 6.9: Relative bed level change compared to the intial situation for S5: an increasing peak discharge.

The main difference between this scenario and scenario 3 is visible when looking at the development of the bed texture (see figure 6.10). Where in scenario 3 a decrease in sand content is only visible at the downstream end, in this scenario the sand content seems to be decreasing along almost the entire reach. At the upstream end an increase of sand content does occur and moves slowly into the river reach. This difference can be explained when taking into account that the fining that was visible for scenario 3 was due to the decreasing base discharge. In this scenario, S5, no such decrease occurs, and sand stays longer mobile almost throughout the entire year. Only during the periods with the lowest flow does sand become immobile and is deposited. This is also visible in figure 6.11, where the blue line, which shows sand transport rates during base flow, shows a small degree of transport.

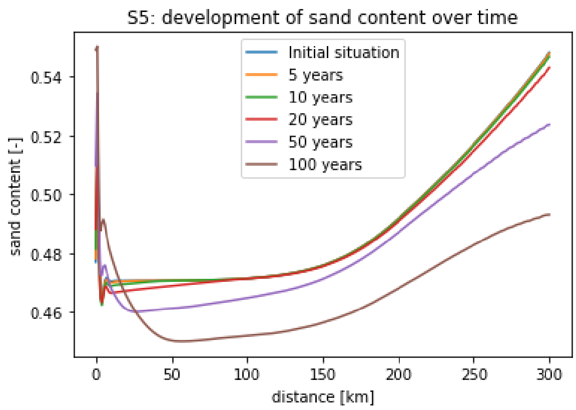



Figure 6.10: Sand content of the river bed for various moments in time for S5: an increasing peak discharge.

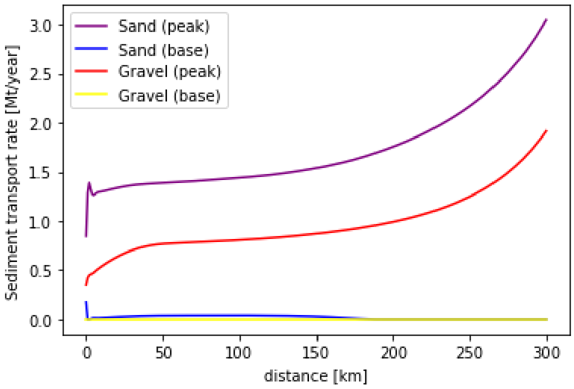



Figure 6.11: Sediment transport rates in the year 100 for S5: an increased peak discharge

### 6.2.3. Decreased base discharge

In this part the scenario in which the base water discharge decreases is discussed. This scenario, together with the base case, is shown in table 6.3.

| **Scenario** | **Qmean** $[m^3/s]$ | **Peak discharge** $[m^3/s]$ | **Base discharge** $[m^3/s]$ |
|---|---|---|---|
| Base Case | 1500 | 2250 | 750 |
| 6 | | 2250 | **500** |

Table 6.3: Increased peak discharge scenarios for case BH. The value changed from the base case is in bold.

Figure 6.12 shows the relative bed level change over time compared to the initial situation for a decreased base discharge of 500 $m^3/s$. This figure shows big differences in bed level change for different parts of the river reach. At the upstream end degradation occurs. This degradation moves slowly into the river reach. downstream of the degrading area aggradation occurs. The area over which aggradation occurs seems to be increasing and moving downstream over time. Where after 20 years the aggrading area runs from about 10 to 80 km, after 100 years this area runs from 25 km to 250 km. At the downstream end of the river reach we again see degradation. The area over which this degradation occurs seems to be slowly decreasing over time. Where after 20 years degradation is visible between 200 and 300 km, after 100 years this only seems to be the case between 250 and 300 km. The area between 200 and 250 km still has a total relative bed level decrease, but has actually been increasing after 50 years.

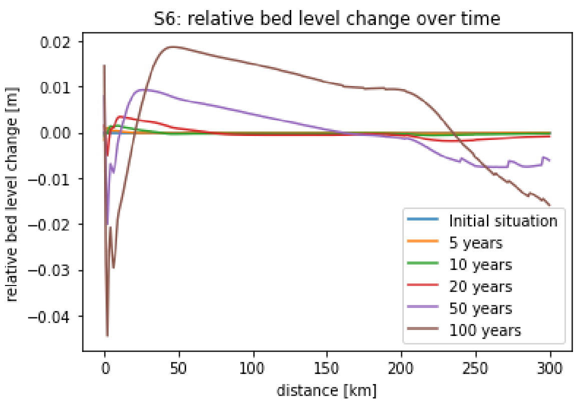
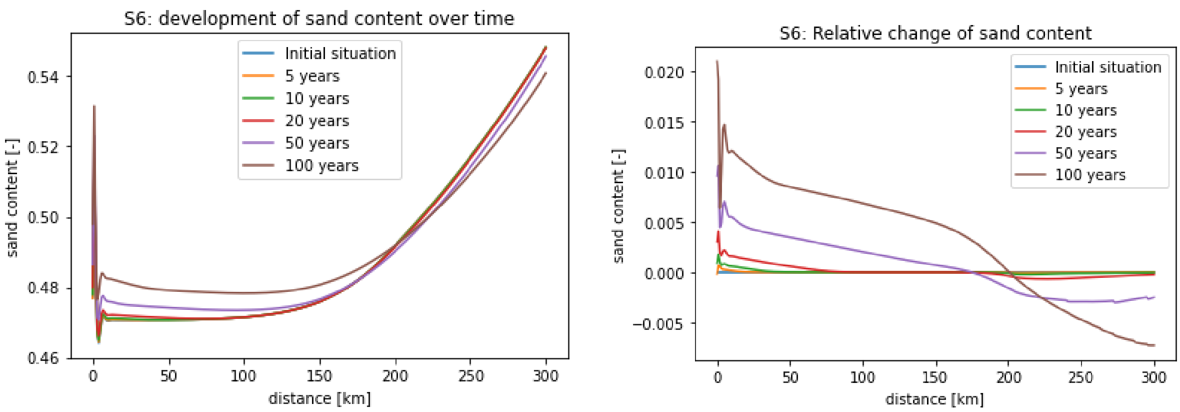



Figure 6.12: Relative bed level change compared to the intial situation for S6: a decreasing base discharge.

Now we consider how the development of the bed texture ties into this. Figure 6.13a shows that upstream the sand content increases, while further downstream, around 200 km, the bed becomes coarser. The changes are more clearly visible in figure 6.13b, which shows the relative change compared to the initial situation. When comparing this to figure 6.12, the aggrading parts seem to coincide with the parts of the river that becomes finer, while degradation and coarsening seem to be linked. This can be easily explained using the theory of response. The decrease in base discharge causes a decreased sediment transport capacity. This combined with the fixed upstream sediment supply means deposition of sediment upstream, causing aggradation. Since the sediment supply is finer than the bed sand content, fining occurs.

The results at the downstream end of the river brings us back to the results of the same scenario with unisize sediment. It was explained here that due to the decreasing base discharge the sediment will become less mobile during low flow periods, meaning a larger and larger part gets deposited upstream, to such an extend that no sediment is transported to the downstream end of the river reach. During higher flow periods however sediment is still being transported, causing degradation downstream. Since sand is more mobile than gravel, coarsening of the bed occurs.




(a) (b)

Figure 6.13: Sand content of the river bed for various moments in time for S6: a decreasing base discharge. With (a) the actual sand content and (b) relative to the initial sand content.

# 7 Discussion

## 7.1. The hydrograph

For this research discharge scenarios for the Rhine were taken from (Hegnauer et al., 2014), which uses the KNMI'14 climate scenarios (KNMI, 2015). These KNMI'14 scenarios combine the IPCC'14 report (IPCC Panel, 2014) with KNMI's own models to come to climate predictions relevant to the Netherlands. Recently however the IPCC has come out with its new report (Gray, 2007) and the KNMI will follow with its own climate scenarios, likely in 2023. The new IPCC report expects climate change to be more extreme than previously predicted. Global temperature is expected to rise by a larger degree, sea levels will rise faster and to higher levels and extreme weather events are becoming more likely and more extreme. Since the new KNMI report is not yet published no concrete statements can be made about the validity of the hydrograph changes of the Rhine. The trend of increased variability of the hydrograph in the Rhine likely still holds, as the trends between the old and new IPCC report has not changed. The magnitude of these changes might however change.

In modelling the effects of a changing hydrograph on the river bed a decision has been made to create the hydrograph as sinusoidal with a period of 1 year. This hydrograph has a peak, base and mean discharge that are relatively close to the average long term recorded discharges in the Lower Rhine. In reality however a hydrograph is far more irregular; it will never look like a perfect sinusoid. Higher frequency perturbations will be visible throughout the year, causing local peaks and troughs in the hydrograph. At the same time it is very unlikely that low and high discharge periods are of equal lengths throughout a year: the high discharge periods may as well be only a very short period of the year. It was however decided to use this sinusoidal hydrograph in this research, which has both advantages and disadvantages. The first advantage is that peak- and base discharge are linked to specific parts of the year, peak discharge to the first half and base discharge to the second half. It is therefore easy to recognise the effects of these different discharges in the modelling results. Any changes made to peak discharge, base discharge, or both are therefore easy to analyse. Secondly, the use of a sinusoidal hydrograph can prevent the model from becoming ill-posed. Ill-posedness is a drawback of the active layer model used in this research (Hirano, 1971): under certain circumstances negligible perturbations in the initial or boundary conditions can produce significant differences in the solution (Chavarrías et al., 2018). One such a perturbations is a sudden change of discharge (upstream hydrodynamic boundary). The use of a sinusoidal hydrograph ensures a smooth transition between discharges, reducing the risk of this happening.

A disadvantage of this method is that the terms of peak and base discharge loose its relevance. While indeed these indicated values are reached, it only does so for a very short period of time (1 timestep for each peak per year). Due to the sinusoidal nature of the hydrograph we see increasing discharge in both flow periods (between base discharge and peak discharge) and decreasing discharge in both periods (between peak discharge and base discharge), basically allowing us to sub-divide the yearly hydrograph into four parts. While this is (partially) taken into account by looking at quarterly results of the model, it creates an unclear separation between peak- and base discharge. Using a hydrograph with a more clear separation between base- and peak discharge periods could give a more clear distinction in their modelled effects.

Another consideration is how changes over time to the hydrograph have been applied. It was decided to have the discharge (variations) change linearly over time, with the new hydrograph (or constant discharge in the case of the simplified model) being reached after 100 years. This method allows for better comparison of changes to the river bed over this 100 year period, as each year sees the same change in discharge. This development over time of the discharge is however an assumption. In a real world situation the discharge could develop in a multitude of ways, for example due to non-linearity in weather changes, changes to discharge distributions over bifurcations (specifically at Pannerdensche Kop) and human intervention. What this means is that even though our model gives a decent representation of a theoretical river, care needs to be taken when applying its results to real life situations. If at any point in the future conditions in or around the river change, the predictions according to this model need to be re-evaluated.

Another limitation of the linear change of discharge (variation) over time is that our model does not give us the equilibrium response, no stable solution is ever reached. Instead we constantly find ourselves in the transient phase of river response. Knowing to what new equilibrium a river will evolve could give us a clearer view of the mechanism in play. Secondly, when solely looking at the modelled transient response it may give the impression that bed surface texture is changing in the long term, while this is not the case. Despite these disadvantages we still have a model that gives as an insight on rivers with constantly evolving discharges, which are relevant given the ever ongoing changes to rivers caused by climate change.

## 7.2. Modelling choices

In order to model the effects of a changing hydrograph on the river bed level and surface texture of a river, a model was created in ELV. Multiple assumptions and simplifications were made in this model. This section goes into what the advantages and disadvantages of these assumptions and simplifications are and how or if these affect the usability of the results.

First of all it was assumed that the river has a rectangular cross-section, and that there are no flood plains. It was assumed that all increase in flow was taken by the main channel. The presence of floodplains can mostly have an effect in scenarios where we see an increase in discharge. Floodplains catch part of the discharge during high flow periods, decreasing the flow velocity and thereby decreasing the magnitude of degradation. Considering that in reality the Lower Rhine does have floodplains, the actual changes to the river bed, especially in regards to degradation, may not be as large as modelled.

It was also assumed that the width of the channel is constant and fixed along the river reach. It is reasonable to assume fixed banks, seeing that the Lower Rhine is a highly regulated river and has been so for a long time. This also ensures that any changes to the river due to changes in discharge are for the account of the river bed. As mentioned it is also assumed that the channel has a single width along its entire reach. In reality this is however not the case. The width of a river varies throughout its reach, meaning that at different points of the river, the magnitude of (bed level) change can be different. Not to mention the presence of river bends, infrastructure, hard bed surfaces, etc. Local difference that can have large (local) effect on the bed level change and sediment distribution.

## 7.3. Boundary conditions

The focus of this research is on the effects of the upstream hydrodynamic boundary; the discharge. Here we will look at the other two boundary conditions: the downstream hydrodynamic boundary and the upstream morphodynamic boundary.

Due to the region of interests location in the Rhine delta, the water level in the reach is effected by the sea level. For the downstream hydrodynamic boundary it was assumed that there is no sea level rise, a fixed downstream water level, eventhough sea levels are likely to rise in the future (Gray, 2007). An advantage of this assumption is that any change that is visible to the river bed can be attributed to discharge changes. In reality however sea level rise will most likely have an affect on the river bed, possibly (partially) compensating degradation that may occur due to the increase in discharge variability, since the increased sea level is likely to cause aggradation of the river bed, due to decreased downstream flow velocities.

Also the upstream morphodynamic boundary, the upstream sediment supply, has been kept at a constant. In reality however this is unlikely: the variables that drive change in the river reach also affect the river reach above and below that reach and thereby causes changes to the supplied sediment. An increased variability of water discharge is likely to not only cause erosion in the modelled reach, but also upstream of this reach, meaning an increase in sediment supply from upstream into the modelled reach. This can possibly have dampening effects on the degradation that has been observed in the modelling.

# 8 Conclusions & Recommendations

The objective of this thesis was to assess the effects of a changing hydrograph, considering climate change, on the bed level and surface texture of a river. This was done by creating two models of a river reach with either unisize or a bi-modal sediment distribution, inspired by the Lower Rhine. This chapter answers the research questions defined for this research in section 1.2. After that some recommendations for further research are made.

## 8.1. Conclusions

### What are the expected changes to the hydrograph of the Lower Rhine, considering the KNMI'14 climate scenarios, up to the year 2100?

The discharge of the river Rhine is controlled by rainfall in the Rhine basin and snow- and glacier ice-melt originating in the Alps and other mountain headwater regions in Central Europe (Stahl et al., 2017). To answer this question 5 different climate scenarios were analysed (Sperna Weiland et al., 2015). These climate scenario resulted in 5 different discharge projections for the Rhine at Lobith, up to the year 2085. These projections were used to make predictions for the year 2100. It showed that in all scenarios an increasing of discharge was visible for the high flow period, the winter (+22% - +49%). For the low flow period, summer, in all but one scenario a decrease of discharge is predicted (-11% to -40%). The exception scenario is the scenario with the least climate change. a small increase of +1% is visible in the dry season.

### How does the bed level of a river reach with unisize sediment react to changes in the river hydrograph?

In order to answer this research question a simplified model of a river reach was made using ELV with unisize sediment and the results from this model were analysed. It was found that an increase in hydrograph variability causes degradation along the entire river reach, eventually resulting in a new equilibrium with a steeper bed slope and a lower water depth. The opposite effect, aggradation along the entire river reach, can be observed when decreasing the hydrograph variability. Especially changes to the peak discharges, the discharges above the mean discharge, affect the river bed. This is due to the non-linearity of sediment transport.

When looking at the initial and transient response of the river bed on changes to the river bed, a clear distinction can be made between the upstream and downstream effects. At the upstream end of the river reach large local bed level changes occur, which move slowly downstream. This behaviour is driven by the mismatch between sediment supply and sediment transport capacity. At the downstream end of the river reach a far more gradual change is visible. This bed level change is due to the formation of a backwater curve caused by a change in equilibrium depth, combined with a fixed downstream water level. This behaviour quickly spreads through the river reach upstream, but is limited in its magnitude.

One last case that is of interest is when the base water discharge becomes significantly smaller. In this situation it is possible for sediment to become immobile during these low flow periods, meaning a larger part of the sediment supply is deposited upstream, this may result in degradation downstream when looking at the yearly average, instead of the expected aggradation.

**How do the bed level and surface texture of a river reach with bi-modal sediment react to changes in the river hydrograph?**
In order to answer this research question a model was made using Elv and the results of this model were analysed. This model used a constantly evolving discharge boundary, and therefore focused on the initial and transient response of such a change. It was found that the transient response of an increase in discharge variability is degradation along the entire river reach, with fining of the bed texture occuring upstream and coarsening downstream. A decrease in discharge variability has the opposite effect on the river bed: aggradation with coarsening upstream and fining downstream.

This research also looked in more detail on the effect of base discharges vs peak discharges. It was found that the peak discharges are to a larger degree formative for the river bed. This is due to the non-linearity of sediment transport: higher discharge have a relatively larger effect than low discharges on sediment transport capacity. An increase in discharge variability, and with that an increase in peak discharge, therefore has the effect of increasing sediment transport rates, causing degradation.

At the downstream end this degradation is due to the formation of a backwater curve, caused by an increase in equilibrium depth, combined with a fixed downstream water level. Due to this degradation the downstream bed slope increases. This steeper bed slope increases the mobility difference between sand and gravel grains, causing the bed to become coarser. At the upstream end the degradation can be attributed to a mismatch between sediment supply and sediment transport capacity. This degradation causes the bed slope upstream to decrease, decreasing the mobility difference between sand and gravel grains, resulting in a fining of the river bed. When decreasing the discharge variability the opposite effect can be observed.

## 8.2. Recommendations

This research shows that when making predictions for bed level and surface texture changes due to changes in the discharge variability, just looking at a formative, dominant discharge is not enough. Even though it can give a reasonable approach for the equilibrium response, it is clearer what happens in the initial and transient response when the variability is taken into account. Since rivers are constantly evolving and rarely reach their equilibrium state, it could be worthwhile in further research to take this variability of discharge into account.

An important limitation of this research was the choice of hydrograph. The hydrograph and the development of the hydrograph in this research are artificial. It is defined as sinusoidal, with a linear development over time up to an assumed total discharge change. Although this gives us information on expected trends, it does not give a realistic view of what will happen. If in further research it is relevant to quantify the changes to the river bed the Lower Rhine, it is advised to use the actual hydrograph predictions, which were defined in (Hegnauer et al., 2015). As discussed in the previous chapter, the use of a sinusoidal hydrograph is not without issues. It is therefore also advised to consider other option, for example a hydrograph with just 2 discharge values throughout the year. This could give a more distinct effect of base and peak discharge.

Furthermore we should consider the other boundary conditions: the downstream hydrodynamic boundary and the upstream morphodynamic boundary. In this research both have been assumed as a constant. This gives however a distorted image of reality, where these boundary conditions affect not only the river bed, but to an extend each other. Most notably is the upstream morphodynamic boundary, the sediment supply, which could be affected by changes in water discharge. It is therefore advised to look into the effects of these other boundary conditions.

Finally we should consider the validity of the results of this research. The current model gives an interesting look at general developments. It would however be interesting to validate this by using historical discharge and bed data, to see if this method holds up.

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