Rijkswaterstaat
Ministry of Infrastructure and the Environment

RWS INFORMATION -

River Waal: Preliminary hydraulic and morphological impact analysis of the Room for the Waal intervention

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Summary

The Room for the Waal project near Nijmegen-Lent is one of the biggest subprojects of the overarching Room for the River programme. The aim of this project is to decrease the water level in the river Waal during extreme discharges with up to 35 centimetres. With the measure being officially completed in late 2015, this study will give a preliminary impact analysis of the measure. This analysis is performed to give insight in the hydraulic and morphological impact of the side channel on the river Waal and to check if this is in line with the expected impact of the side channel. Note that as no significantly high discharges have occurred since its completion, the changes are expected to be minimal.

The expected changes are determined using background theory and literature of the design phase as well as other projects. The observed changes are determined using data provided by Rijkswaterstaat. For the morphology, biweekly bed level measurements are used and for the hydraulic part, ADCP measurements and water level measuring stations in the study area are used. Diver data, which could also provide valuable information on water levels in the river Waal, are not used due to time constraints. The period 2007 to 2017 is analysed, so that autonomous processes and other water management projects, which could affect the results, can be identified and excluded.

In the end, for the autonomous processes, erosion of approximately two centimetres per year was found in the river Waal near Nijmegen-Lent. Additionally, it was found that other water management projects, specifically the groyne reduction program downstream of Nijmegen, showed water level decreases of a number of centimetres. Using the autonomous processes and the results of other water management projects, the impact of the Room for the Waal measure is isolated. Water level changes at the Port of Nijmegen and the Pannerdense Kop correspond with the expectations of a few centimetres water level decrease. However, given that the changes were only on a small scale, they are not deemed significant, as noise in the data could have a similar impact. This means that, for now, no definitive statements can be made about the hydraulic impact of the side channel. Additionally, no significant morphological changes could be attributed to the Room for the Waal measure. Though morphological changes did take place in the study area, the continuous fluctuations of the river bed level made it that these changes could not be attributed to the side channel with any certainty.

In conclusion, no significant hydraulic and morphological changes were found that can be confidently attributed to the Room for the Waal measure. This means that more high discharge periods are needed before definitive statements can be made about the hydraulic and morphological impact of the side channel.

Index

1 Introduction

1.1 Background

As stated by Sinnhuber & Mutton (2016) in the Encyclopædia Britannica, the river Rhine is ‘culturally and historically one of the greatest rivers of the continent and among the most important arteries of industrial transport in the world’. Apart from its vital role in transportation, it also serves as a source of drinking water for over 20 million of the 50 million people who live in its watershed (Drinking water, 2017). While the river Rhine originates in the Alps, a large amount of its yearly discharge comes from non-Alpine tributaries (e.g. the Neckar, Main and Moselle). These tributaries are the main reason the river Rhine’s discharge is stable throughout the year, as the Alps shed their waters during early summer months and the non-Alpine tributaries–coming from the French and German mountains–convey high discharges during winter months (Cioc, 2002; Dooge, 2009).

Since the climate changes, it is expected that the river Rhine’s discharges will continue to change. Since 1950, the average precipitation in all seasons but the summer has increased significantly. According to climate scenarios proposed by the KNMI, the trend of increasing rainfall in spring, winter and fall will continue (KNMI, 2014). Additionally, the increase in temperature will result in less snow accumulation in the Alps during the winter and in a higher amount of evotranspiration during the summer–both of which will result in lower summer discharges. Overall, the river Rhine’s winter discharges will most likely increase, while summer discharges will decrease (Middelkoop, et al., 2001; Asselman, et al., 2000).

During high water periods in 1993 and 1995 it became clear that the river Rhine and river Meuse posed greater flood risks than was expected at the time and that the rivers were not equipped for future developments in the rivers’ discharges (Rense, n.d.). Partly triggered by these events, the Room for the River project officially started in 2007, which included over 30 subprojects in just as many locations. The main goal of this project is to reduce the water level in the rivers of the Netherlands. For the river Rhine, this means that the discharge the river has to be able to handle has increased from 15.000 m^3/s to 16.000 m^3/s. This translates to roughly 10.165 m^3/s in the river Waal, as the river Waal conveys about 2/3 of the river Rhine’s discharge (Jong, Paarlberg, & Barneveld, 2010).

In the past, increasing water levels were kept under control by increasing the height of dikes. Even though this kept the probability of flooding at an acceptable level, risks grew. Additionally, the steady increase in population density and economic value of land behind the dikes has made any type of flooding disastrous (Nederlands Interdisciplinair Demografisch Instituut, 2003; Rense, n.d.). In order to combat the increase in water levels and discharges in the coming years, a change of mentality had to take place. Instead of heightening dikes and constraining rivers, it was decided to give space back to the rivers, hence the name ‘Room for the River’. Examples of Room for the River measures are the relocation of dikes and the construction of high-water channels (Rijkswaterstaat, 2016a). One of the measures was carried out at Nijmegen-Lent–where the lack of sufficient floodplains made this location serve as a bottleneck (Figure 1). In order to decrease the water level during high discharges, the dike was relocated and a side channel was constructed to give extra room to the river (Rijkwaterstaat, n.d.).

Figure 1: River Waal near Nijmegen-Lent with the side channel on the right (Municipality of Nijmegen; i-Lent, 2016)

The Room for the Waal measure near Nijmegen-Lent was one of the biggest subprojects, with a budget of about 358 million euros–more than 15% of the Room for the River's budget. Apart from monetary costs, non-monetary costs were also high, with over 50 houses having to be relocated (Rijkswaterstaat, 2015b; Rijkswaterstaat, 2016b).

1.2 Problem context

The Room for the Waal project consisted primarily of a dike relocation near Lent, which aimed to lower the water levels by 27 centimetres during extreme discharges. The solution that was ultimately implemented met this goal without difficulty, as it achieved a water level decrease of up to 35 centimetres during extreme discharges. During extreme discharges, 25-33% of the river Waal’s discharge flows through the side channel. During low discharges, a maximum of 1,5% of the river’s discharge will flow through the side channel (Stammen, 2017; Jong, Paarlberg, & Barneveld, 2010). As shown in Figure 2, the proposed measure RPN (Ruimtelijk Plan Nijmegen) affects the water level in the main channel upstream, parallel and downstream of the side channel. Apart from hydraulic effects, construction of a side channel results in morphological changes in the river. These morphological changes include fluctuations in river bed elevation, which also affect the water level. The hypothesis is that water surface curves in the form of M2 (Figure 32) are visible in the section before the side channel and water surface curves in the form of M1 (Figure 32) parallel to the side channel. Figure 33 shows how erosion and sedimentation will likely have occurred in the study area. The (dynamic) equilibrium will, given the limited timespan, not have been reached.

The hydraulic and morphological effects a side channel has on the main channel can be estimated fairly well (Appendix A). However, it is important to get an idea of the actual impact the measure has had since its completion in late 2015 (Rijksoverheid, 2015). Both to justify the investments of the Dutch government as well as to give information about the changes that have taken place and that might take place in the future. Furthermore, as the Room for the River project is a whole new take on water safety, linking this measure to a water level decrease would also be the first step in calling the new method a success. Therefore, this study is done to give preliminary insights in the impact of the Room for the Waal project on the river Waal near Nijmegen-Lent and to check whether this is in line with the expectations.

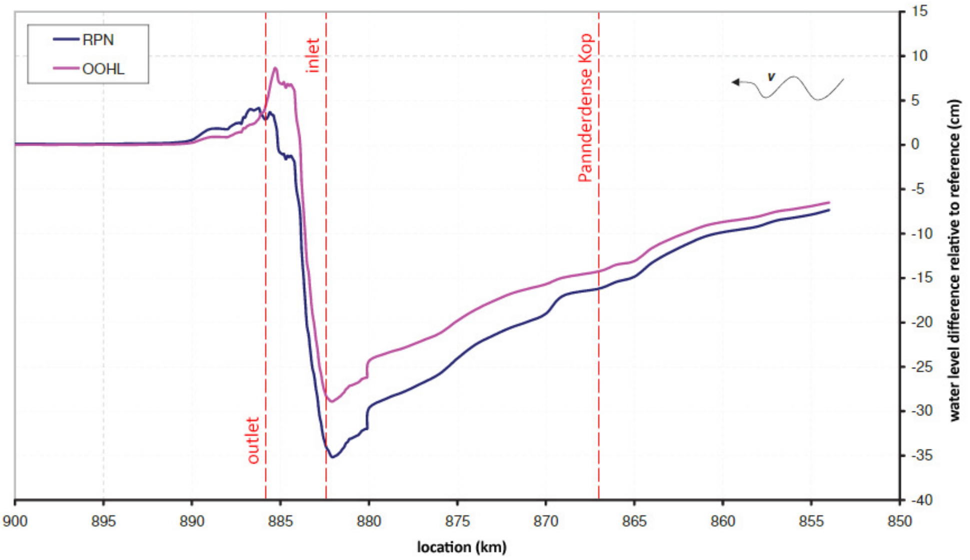

Figure 2: Expected water level change when compared to the pre Room for the Waal situation. The initial plan (OOHL) and the final Room for the Waal measure (RPN) are shown (Municipality of Nijmegen, 2007).

1.3 Research aim

The aim of this research is to determine the hydraulic and morphological effects on the main channel of the Room for the Waal measure and to check whether this is in line with the expected changes. Analysing the period 2007 to 2017 will allow us to make preliminary statements on how the Room for the Waal intervention affects the river Waal near Nijmegen-Lent.

1.4 Research questions

In order to determine the preliminary impact of the Room for the Waal measure, one main question will be answered: **Are the observed hydraulic and morphological effects of the Room for the Waal measure in line with the expected impact?**

To answer the main question, it will be divided in two main parts: hydraulics and morphology. This has resulted in the following research questions:

1. Are the observed hydraulic changes in line with the expected hydraulic changes?
2. Are the observed morphological changes in line with the expected morphological changes?

1.5 Methodology

To answer the research questions, both the expected and observed changes for the hydraulic and morphological parts will be determined. The changes will be divided into different categories: changes caused by the Room for the Waal project, changes caused by other water management projects and changes caused by autonomous processes. Expectations about these categories will be made using available literature and reports on the Room for the Waal project. The observed changes will be determined using bed level and water level measurements as well as discharge data of the river Rhine and the river Waal in the period 2007 to 2017. Uncertainties that might affect the observed changes are also stated and will be taken into account to the best extent possible. The expected and observed changes are compared and preliminary statements are made about the hydraulic and morphological impact of the Room for the Waal measure.

1.6 Available data

To accurately assess the changes that have taken place, a significant amount of bed level, water level and discharge data is needed. Together with Daniël van Putten, Emiel Kater and Susanne Quartel of Rijkswaterstaat, the following data were acquired for the period 2007-present:

Hydraulic data

- ADCP measurements – discharge [m^3/s]
  River discharges are acquired by measuring the velocity profile under the ADCP. The ship carrying the ADCP repeatedly sails between the river banks, which results in velocity profiles of the river section, which in turn are used to determine the discharge in the corresponding section. This approach is regularly used to determine discharges in both the river Waal and in the river Rhine (near Lobith).
- Fixed measurement stations – water level [m]
  There are a number of fixed measurement stations in the river Waal (Appendix B). These stations measure the water level on a ten-minute basis (hourly basis up to August 2010). The water levels at some of these stations are translated into discharges using Qf-relations composed by Rijkswaterstaat.
- *Diver measurements – water level [m] [not available]*
  Diver measurement instruments are located on a number of points in the study area, including at the inlet and downstream of the outlet of the side channel (Appendix B). Data are collected after high discharge periods, which would provide–as they are located on strategic locations–valuable information about water levels during high discharge periods.

Morphological data

- Yearly bed measurements
  Yearly bed level data of the river Waal are available. These data are gathered by Rijkswaterstaat using multi-beam echo and encompass the entire measurable river bed.
- Fortnightly bed measurements
  Fortnightly bed level data of the river Waal are also available. These data are gathered by a dredging contractor for Rijkswaterstaat and only encompass the fairway.

1.7 Reading guide

In this research paper the different methods for answering the research questions are treated in Chapter 2, after which the results are stated in Chapter 3. These results are used to make a comparison between the expected and observed changes in Chapter 4. In Chapter 5, the research project is discussed, after which, in Chapter 6, conclusions are drawn on the project and its findings. In Chapter 7, recommendations are made for future research.

2 Methods

In this chapter the different methods for answering the research questions are described. First, the methods to determine and analyse the hydraulic changes are stated, after which the methods for the morphological changes are described.

2.1 Hydraulic changes

The methods for the determination of the hydraulic changes are divided in expected changes and observed changes. These changes are subsequently divided in the different categories that play a role.

2.1.1 Expected changes

The expected changes are divided into other water management projects & autonomous processes and the Room for the Waal project.

Other water management projects & autonomous processes:
The expected impact of other water management projects and autonomous processes will be derived from available literature and input from Rijkswaterstaat.

Room for the Waal project:
For the Room for the Waal project, the changes are estimated by using Appendix A as a basis. It can be seen in Figure 4 that the construction of the side channel results in a different equilibrium depth on the area running from A to B, which results in changes in the water level. It should be noted that due to the limited length of the side channel, the equilibrium depth–or the maximum water level decrease that could potentially occur–will not be achieved. The water level on different points is calculated using a simple analytical method which uses the Belanger equation. It is also possible to model the side channel in software like WAQUA, as was done during the design phase of the project. However, these models are not directly available and are too time consuming to use. Therefore, it is decided that this method provides results that are sufficiently accurate for the aim of this research.

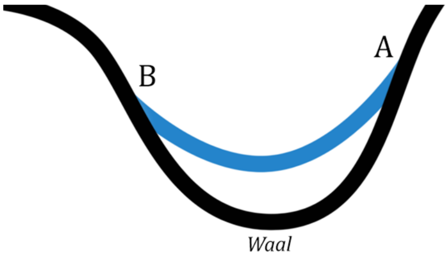

Figure 3: Top view of the side channel (blue) and the river Waal (black)

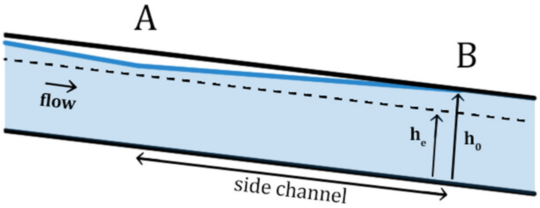

Figure 4: Equilibrium depths (h_0 and h_e) of the river Waal with the side channel running from A to B

Approach

To determine the expected change in water depth on a location along the side channel, the following approach is used. The initial equilibrium depth (upstream and downstream of the side channel) is given by h_0 and the equilibrium depth in the area where the side channel splits off from the main channel is given by h_e. In order to calculate these parameters, Equations 1 and 2 are used. Refer to Appendix C for the determination of additional parameters used in these equations.

$$h_0 = \left(\frac{Q_1}{w * C * \sqrt{i_b}}\right)^{\frac{2}{3}} \tag{1}$$

$$h_e = \left(\frac{Q_2}{w * C * \sqrt{i_b}}\right)^{\frac{2}{3}} \tag{2}$$

Where:
h_0 = equilibrium depth upstream and downstream of side channel [m]
h_e = equilibrium depth on side channel bifurcation [m]
Q_1 = discharge through the main channel directly downstream of point B [m^3/s]
Q_2 = discharge through the main channel between points A and B [m^3/s]
w = width of the main channel [m]
C = Chezy coefficient of the main channel [$m^{0.5}/s$]
i_b = slope of the river bed [m/m]

To calculate the water depth along the river, the Belanger method is. This results in a water depth change as follows:

$$L_{1/2} = \frac{0.24 * h_e}{i_b} * \left(\frac{h_0}{h_e}\right)^{\frac{2}{3}} \tag{3}$$

$$h_x = h_e + (h_0 - h_e)\left(\frac{1}{2}\right)^{-\frac{(x-x_0)}{L_{1/2}}} \tag{4}$$

$$h_{dif} = h_0 - h_x \tag{5}$$

Where:
x = distance from x to point B [m]
x_0 = distance from point B to point B (equals 0) [m]
h_{dif} = water depth change on location along the river [m]

Since it is not necessary to calculate the water level change for every discharge at Lobith, a limited number of discharges are considered. The side channel was designed to extract discharges of up to 1,5% of the river Waal during discharges at Lobith smaller than 4600 m^3/s. Since this will have a negligible impact on the water level, it is not necessary to calculate the water level decrease for all discharges up to 4600 m^3/s at Lobith. However, when this amount is exceeded, the impact of the side channel significantly increases. Therefore, for all of the discharges between 4600 and 6000 m^3/s at Lobith the expected water level decrease is calculated. Note that as the discharges in 2016 and 2017 have not exceeded 6000 m^3/s at Lobith, no predictions will be made about discharges exceeding 6000 m^3/s.

2.1.2 *Observed changes*

As with the expected changes, the observed changes are divided into other water management projects, autonomous processes and the Room for the Waal project.

Other water management projects:
The impact of other water management projects is studied using the fixed measuring point at the Port of Nijmegen. This location is, however, only usable for discharges up to 4600 m^3/s at Lobith, since the barrier does not flow over below this discharge, resulting in a negligible impact of the side channel. For discharges exceeding 4600 m^3/s at Lobith, measuring points downstream of the Port of Nijmegen are necessary. However, given the limited timeframe, data of locations downstream of the Port of Nijmegen are not available.

Therefore, results of the Port of Nijmegen of discharges below 4600 m^3/s at Lobith are used. This, however, gives only a broad indication of the expected water level decrease caused by other water management projects during discharges exceeding 4600 m^3/s at Lobith. Hourly water level and discharge data for each hydrologic year are plotted, which runs from November 1st to October 31th (IGG Bointon de Groot, 2016). A polynomial line of degree n=2 is fitted to different discharge classes in each year. Discharge classes of 1500-2000, 2000-3500 and 3500-4600 m^3/s are used, as these roughly indicate the different phases at which the main channel bed, areas above the groynes and flood plains convey water. To exclude the significant impact of the side channel during discharges exceeding 4600 m^3/s at Lobith, the highest discharge class does not top 4600 m^3/s. As the weir near Driel opens at around 1500 m^3/s at Lobith, it will likely impact the Qh-relation (de Bruijn & van Mazijk, 2003). Therefore, the lowest discharge class only uses data points exceeding 1500 m^3/s at Lobith.

Autonomous processes:
The impact of autonomous processes is determined by analysing the water levels at the Port of Nijmegen. Qh-relations are composed for each year using averaged daily water level and discharge data. To best calculate the erosion, the impact of the groyne reduction program is avoided as much as possible by using discharges where the groynes are not submerged. A discharge range of 1500-2500 m^3/s at Lobith is therefore used. A polynomial of degree n=2 is fitted through this dataset. The average difference between subsequent years is then calculated. This results in a quantitative statement on the yearly water level change in this discharge range, which is caused by yearly erosion of the river bed.

Room for the Waal project:
To determine the hydraulic impact of the Room for the Waal project, different methods are available. A Qh-relation can be composed using daily discharge data for each year since 2007. However, as the side channel was officially completed in late 2015, few high discharge data of the post Room for the Waal situation are available. Therefore, it is beneficial to use hourly water level and discharge data instead of averaged daily data points. To obtain an accurate polynomial fit (degree n=2) of the discharges exceeding 4600 m^3/s at Lobith, only data exceeding 4650 m^3/s at Lobith are used. A value of 4650 m^3/s is chosen to make sure that the barrier has flown over. The difference between each year's fit is determined for multiple discharges (Q_{Lobith} = 4650, 5000, 5200 m^3/s). Discharges of 4650 and 5000 m^3/s at Lobith show the moment at which the side channel starts to have a significant impact, while a discharge of 5200 m^3/s at Lobith is the highest discharge that has occurred since the completion of the measure. This method is used for two locations: the Port of Nijmegen and the Pannerdense Kop.

Uncertainties:
Using literature and reports of past projects, uncertainties that might affect the data or results are identified. The effects these uncertainties have, are studied and to what extent they can be taken into account.

2.2 Morphological changes

2.2.1 Expected changes

Other water management projects:
The morphological changes caused by other water management projects constructed downstream of the study area are assumed to be negligible, as they were only completed in the past couple of years. Therefore, long term upstream morphological effects are not likely to have occurred yet.

Autonomous processes & Room for the Waal project:
The expected impact of autonomous processes are derived from available literature and input from Rijkswaterstaat. Literature and reports on the Room for the Waal project are used to determine the locations where river bed level change is expected and to what extent changes are expected to have occurred. This includes quantitative statements on predicted erosion and sedimentation locations.

2.2.2 Observed changes

Other water management projects:
Water management projects downstream of the Port of Nijmegen are assumed negligible, as stated in Section 2.2.1. Though water management projects upstream may cause sedimentation build-ups or sedimentation pits that slowly move downstream into the study area, this is not in the scope of this research. To account for these river bedforms, sedimentation or erosion spikes that occurred near the inlet or outlet of the side channel are traced back to either determine their origin or show they migrated from upstream river bed sections.

Autonomous processes:
For the determination of the autonomous processes, both yearly and fortnightly river bed measurements are available. However, for the purpose of determining autonomous processes, the yearly bed level data are sufficient. Using the method of Rijkswaterstaat (i.e. using sections of 100 meters to study changes in the river bed), the average river bed levels over time are plotted. The 100 meter averages are aggregated to kilometre sections, which helps to filter out outliers in the data and keeps the amount of data manageable. In the end, this results in a quantitative statement on the yearly bed level erosion of the river bed near Nijmegen.

Room for the Waal project:
To determine the morphological changes that took place in the study area in the past decade, bed level averages of multiple sections are calculated and compared. This is done using ArcGIS for the sections shown in Figure 5. These sections span about 200 meters in length and half of the fairway in width (approximately 80 meters). The average length of bedforms generally ranges between 50 to 100 meters, based on visual inspection of the river bed, which means that a section of 200 meters in length covers multiple bedforms. This averages out a large part of the regular bed level dynamics. It should be noted that as certain areas are not measured (i.e. areas below bridges) and changes are primarily expected near the inlet and outlet of the side channel and after the solid layer, it is deemed unnecessary to cover the entire study area with these sections.

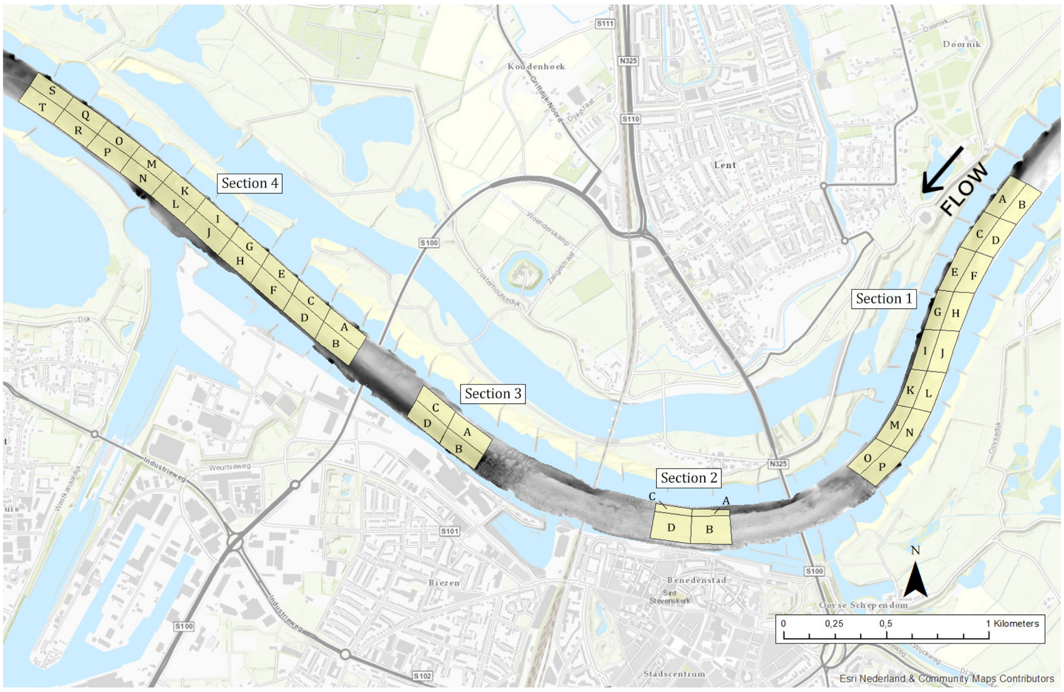

Figure 5: First bed level section grid for determination of morphological changes (Background map: ESRI, 2017)

It is possible that the sections as drawn in Figure 5 also average out changes that are due to the side channel. Therefore, a second grid is made with smaller sections at the areas that are most of interest (Figure 6).

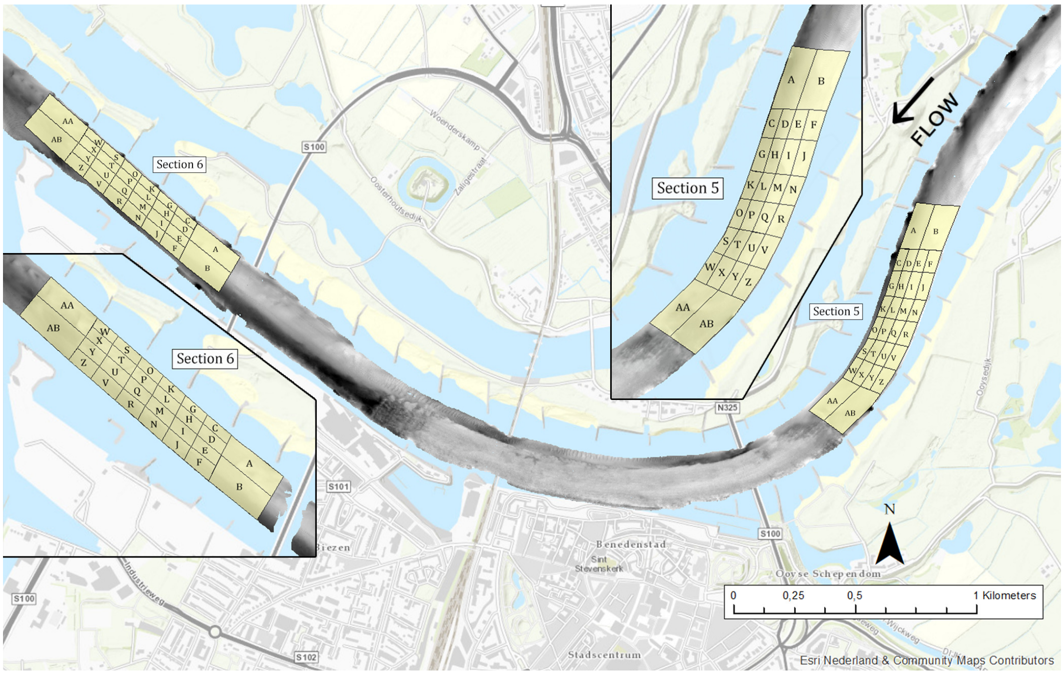

Figure 6: Second bed level section grid for determination of morphological changes (Background map: ESRI, 2017)

Uncertainties:

For uncertainties in the morphological part, the same approach is used as is done in the hydraulic part: literature and reports of past projects are used to determine what the uncertainties are and to what extent they can be taken into account.

3 Results

In this chapter, the results of the different parts of the research questions are described. First, the results of the hydraulic part are stated, after which the results of the morphological part are given.

3.1 Hydraulic changes

The results of the hydraulic part are divided in expected changes and observed changes. These changes are subsequently divided in the different categories that play a role.

3.1.1 Expected changes

The expected changes are, following the methods, divided into other water management projects, autonomous processes and the Room for the Waal project.

Other water management projects:
Projects downstream of Nijmegen mainly consist of groyne reductions and the construction of longitudinal dams. Projects 'Mid river Waal' and 'Waal Fort St. Andries' are expected to have the largest influence, as they are directly downstream of Nijmegen. As stated by Rijkswaterstaat (2015a), the height of groynes was reduced by about one meter in the period 2009 to 2015. This results in a maximum water level decrease of 6-12 centimetres during extreme discharges, which causes the groynes to be submerged for about 265 days a year, as opposed to the original submersion rate of 100 days per year. This means that the discharge at which most of the groynes flow over of 2000-2500 m^3/s in the river Waal (3000-3500 m^3/s at Lobith) decreases (Broekhoven, 2007).

The groyne reduction program was implemented in three phases from 2009 till 2015, which means that no clear distinction can be made between the before and after situation. However, there are years where more change is expected to be visible. It is shown in Appendix E that some years mark the start or end of groyne reduction phases. Additionally, some phases are closer to Nijmegen, which means they are likely to have an increased impact. This means that phase three is expected to have relatively little impact, as this phase primarily involves locations further downstream of Nijmegen. Following from this, the highest water level decreases are expected between the years 2009-2010, 2011-2012, 2012-2013 and 2015-2016.

Autonomous processes:
River bed level erosion of one to two centimetres per year is expected in the river Waal near Nijmegen (Blom, 2015). Since the river bed level directly affects the water level, a gradual water level decrease of one to two centimetres is also expected. It is assumed that for larger discharges, the impact of bed level erosion will be less than for lower discharges, as areas above the groynes and floodplains will also convey water during higher discharges. This reduces the impact of main channel bed level erosion. As it is hard to quantify the expected water level decrease due to erosion during high discharges and one to two centimetres is already a relatively wide range, the assumption is that water level changes during higher discharges also lie between one to two centimetres.

Room for the Waal project:
Using the calculations as described in Appendix C, the expected changes are determined for the inlet and the Port of Nijmegen, which is approximately two kilometres from the inlet.

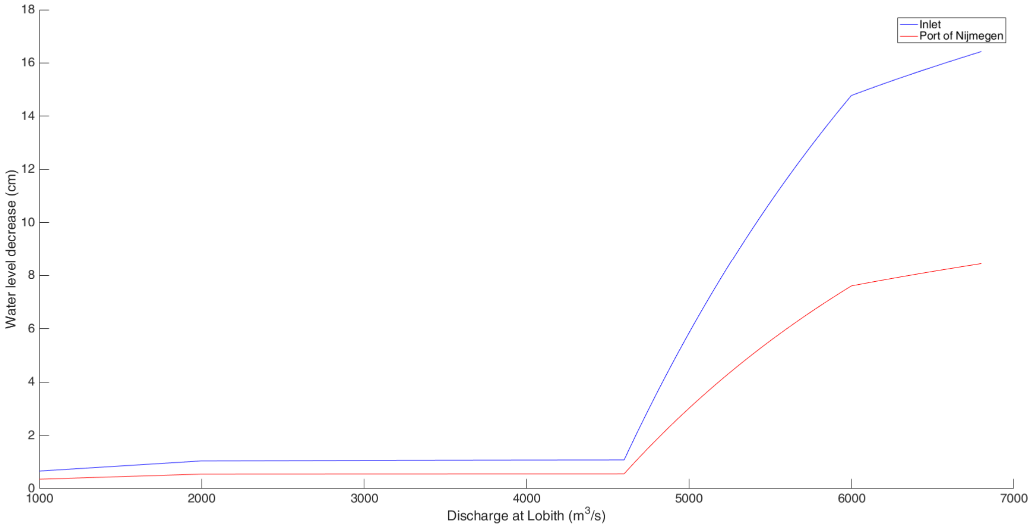

Figure 7: Expected water level decrease at the side channel inlet and the Port of Nijmegen

As can be seen in Figure 7, the water level decrease up to a discharge of 4600 m^3/s at Lobith is around one centimetre at the inlet. Larger discharges result in a water flow over the barrier, causing larger discharges to be conveyed by the side channel, resulting in a larger water level decrease. It is assumed that water level decreases at the Pannerdense Kop are similar to those at the Port of Nijmegen, given that the calculated halving length is approximately 20 kilometres, which is roughly the distance from Nijmegen to the Pannerdense Kop.

The expected results shown in Figure 7 do not entirely coincide with the expected changes as stated by Jong, Paarlberg, & Barneveld (2010), as they expect a water level decrease at the inlet of 22 centimetres during discharges of 6800 m^3/s at Lobith. It should be noted that the decrease of 22 centimetres is based on Delft3D calculations and though no predictions for this discharge were made with WAQUA, it is likely that WAQUA would have given a decrease of less than 22 centimeters (Table 10). Therefore, it is assumed that Figure 7 gives sufficiently accurate estimations, especially for the lower discharges that have occurred since the completion of the measure.

3.1.2 *Observed changes*

Other water management projects:

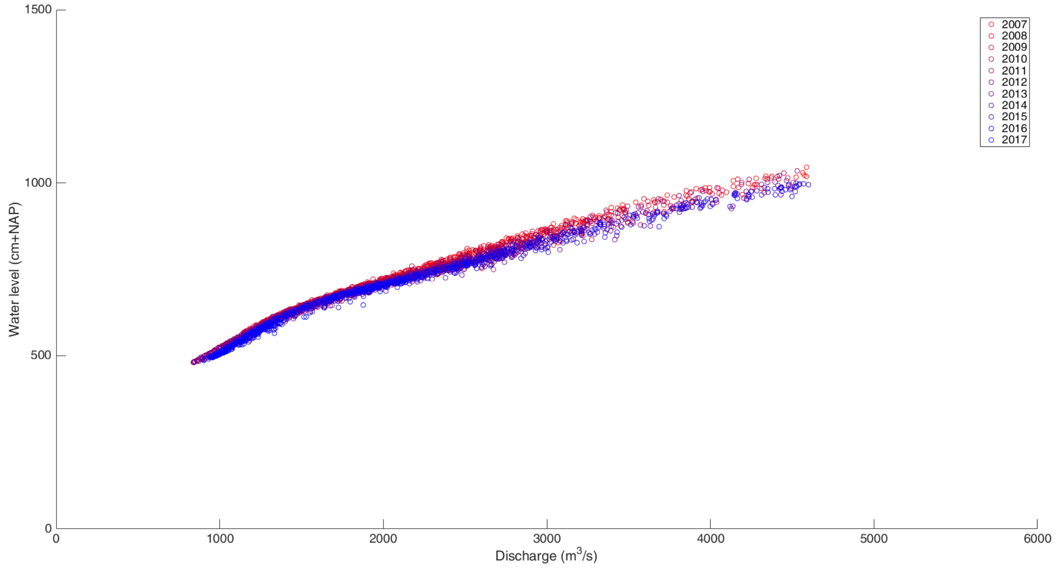

Figure 8: Daily water levels at the Port of Nijmegen with discharges at Lobith for each year

As can be seen in Figure 8, the change in curvature caused by the weir near Driel occurs near 1500 m^3/s at Lobith. Before the groyne reduction program, the groynes overflowed at discharges exceeding 2000-2500 m^3/s in the river Waal (Broekhoven, 2007). This translates to roughly 3000-3500 m^3/s at Lobith. However, given that groynes flow over during different discharges, it is plausible that no change in curvature due to the groynes is visible in Figure 8. An overall decrease in water level is, on the other hand, clearly visible. This is likely caused by erosion of the river bed. Since no clear effects of the groynes are immediately visible, a line is fitted through the three discharge classes for each hydrological year (Figure 9). Note: for the purpose of clarity, Figure 8 shows daily data points, the fits were however based on hourly data points.

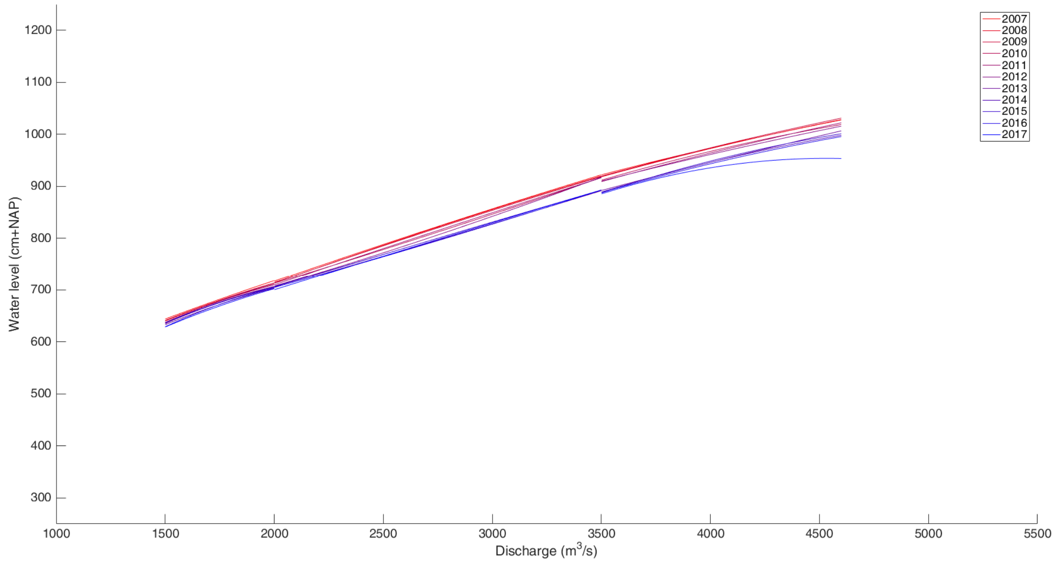

Figure 9: Fitted lines per discharge class and year for hourly water levels at the Port of Nijmegen and discharges at Lobith

Calculating the difference between subsequent years, based on the fitted lines, results in Table 1.

Table 1: Water level change per year at the Port of Nijmegen: negative values represent a decrease in water level

Years	**Average change in water level per discharge class at Lobith [cm]**			
	Overall	1500-2000 m^3/s	2000-3500 m^3/s	3500-4600 m^3/s
2007-2008	-1,9	-2,9	-1,8	-1,0
2008-2009	0,3	0,4	-1,1	1,6
2009-2010	-5,3	-2,0	-5,9	-8,0
2010-2011	-0,3	-0,4	1,3	-1,9
2011-2012	-3,6	-2,1	-5,8	-3,0
2012-2013	-9,9	-4,0	-11,5	-14,3
2013-2014	1,3	2,9	3,0	-2,1
2014-2015	0,9	0,8	-0,1	2,0
2015-2016	-3,9	-4,1	-3,3	-4,5
2016-2017	-5,1	-2,5	0,8	-13,7[1]

[1] Unrealistic water level decrease, likely caused by lack of data in the discharge class

In Table 1 an overall trend of decreasing water levels, most likely due to bed level erosion, is visible. Additionally, it is shown that in the years 2009-2010, 2011-2012, 2012-2013 and 2015-2016 a significant average decrease occurs. This is roughly in line with the phased planning of the groyne reductions and the Room for the Waal project (Appendix E). The year 2016-2017, however, shows unrealistic results, primarily in the highest discharge regime. This can be explained using Table 2, as this shows that 2017 has not had any discharges exceeding 3800 m^3/s at Lobith. The fit in this range is therefore only based on a few data points. Additionally, some years show slight water level increases, which might indicate sedimentation of the river bed. However, this can also be caused by noise in or lack of data, as especially in higher discharge classes few data points are present. Overall, when looking primarily at 2015-2016, the water level decrease of -4,5 centimetres during a discharge of 4600 m^3/s at Lobith seems plausible. This is because the goal of the program was a decrease of 6-12 centimetres during extreme discharges and Nijmegen is further upstream of the groyne reductions. The assumption is made that the groyne reductions have approximately half the effect on the water level at the Pannerdense Kop as they have on the water level at the Port of Nijmegen. The impact of erosion is expected to stay the same.

Autonomous processes:
In Figure 10 the fitted lines per year are shown for the range of 1500 to 2500 m^3/s at Lobith. The distance between subsequent year's curves is calculated for all integer discharges in the range 1500-2500 m^3/s. This is averaged to get the mean water level change between subsequent years. The mean change per year is also averaged to get an average yearly water level change in the period 2007-2017. This results in a yearly erosion level of 1,63 centimetres for the range 1500 to 2500 m^3/s at Lobith. However, this is an average over all the years in the period 2007 to 2017, which means every subsequent year does not necessarily show erosion over the previous year (Table 1).

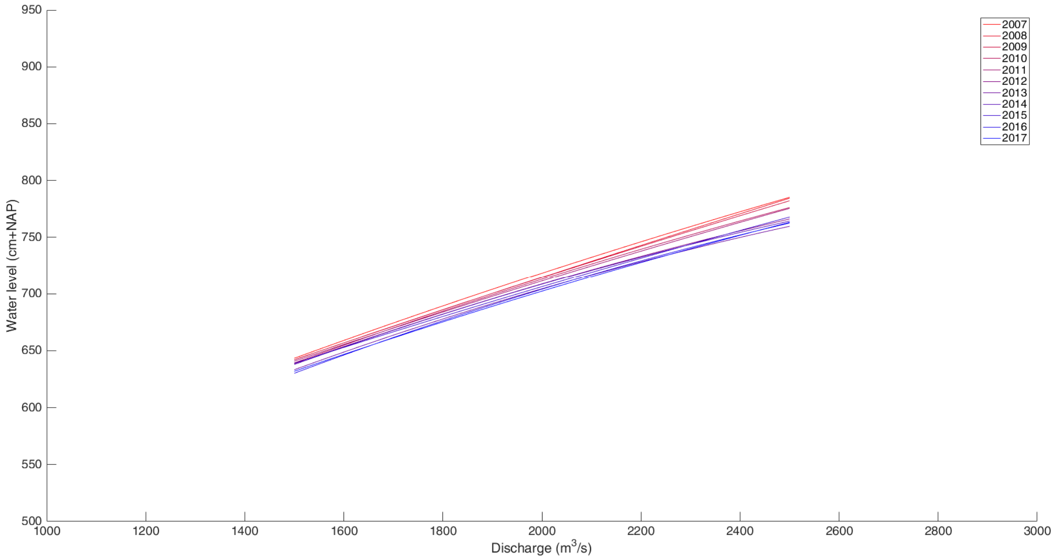

Figure 10: Fitted lines per year for water levels at the Port of Nijmegen and discharges at Lobith

Room for the Waal project:
In Table 2 the different years with their respective maximum discharges are given, which shows whether years have had discharges in the range of 4650-5200 m^3/s at Lobith. More information about each year's high discharge periods is given in Appendix F.

Table 2: Individual years and their maximum discharges

Year	Maximum discharge [m^3/s]	Discharges in range of 4650-5200 m^3/s at Lobith
2007	6174	+
2008	5526	+
2009	4452	-
2010	5518	+
2011	8388	+
2012	6750	+
2013	6746	+
2014	4525	-
2015	4600	-
2016	5253	+
2017	3767	-

Table 2 shows that the closest year to 2016 with a sufficiently high discharge period is 2013. Additionally, 2010 is the closest year that had a high discharge period similar to the high discharge period of 2016. Therefore, 2010, 2013 and 2016 are used to compare the pre and post Room for the Waal situation. For the Qh-relations of 2010, 2013 and 2016 at the Port of Nijmegen and the Pannerdense Kop and the fitted lines, refer to Appendix G.

Polynomial lines of degree n=2 are fitted for the years 2010, 2013 and 2016. The differences between the lines are subsequently calculated, which results in Table 3 and Table 4.

Table 3: Water level change per discharge at the Port of Nijmegen: negative values represent a decrease in water level

Years	**Change in water level at the Port of Nijmegen for discharges at Lobith [cm]**		
	4650 m^3/s	5000 m^3/s	5200 m^3/s
2010-2013	-12,8	-18,0	-17,7
2013-2016	-12,2	-7,1	-8,0
2010-2016	-25,0	-25,1	-25,7

Table 4: Water level change per discharge at the Pannerdense Kop: negative values represent a decrease in water level

Years	**Change in water level at the Pannerdense Kop for discharges at Lobith [cm]**		
	4650 m^3/s	5000 m^3/s	5200 m^3/s
2010-2013	-5,0	-7,4	-7,3
2013-2016	-6,9	-6,1	-5,9
2010-2016	-11,8	-13,4	-13,3

Uncertainties:
There are a number of uncertainties that might affect the results and therefore the reliability of conclusions. Therefore, the main uncertainties that might play a role and to what extent they are accounted for are described in this section.

- Changed discharge distribution at the Pannerdense Kop

As the water level decreases significantly during discharges higher than 4600 m^3/s at Lobith, the water level at the Pannerdense Kop also decreases. This might cause a change in discharge distribution at this location, resulting in more water being conveyed by the river Waal than before. This can, in turn, increase the water level again. One method for determining whether the discharge distribution changes is to examine ADCP measurements in the before and after situation during high discharges. When the same discharge at Lobith is measured, while discharges through the river Waal differ, the discharge distribution has most likely changed. This is, however, only of interest for discharges exceeding 4600 m^3/s at Lobith, as lower discharges have a negligible effect on the water level near the Pannerdense Kop. Since only one ADCP measurement was performed during discharges higher than 4600 m^3/s since the completion of the Room for the Waal measure, no statements can be made about a change in discharge distribution caused by the side channel.

- Reliability of Qf-relation

The reliability of the Qf-relation, which is used for the determination of the discharges at Lobith and in the river Waal, is questionable. When comparing the calculated (DONAR) discharges to the actual (ADCP) measurements, both low and high discharges are off a significant amount of the time. Since the calculated discharges are used to make predictions for shipping, the consequences of wrongly estimated discharges can be catastrophic. This is especially the case if the calculated discharges exceed the actual discharges. In Figure 11, the percentage error for different discharge classes is shown. If the percentage error exceeds zero, the calculated discharge exceeds the actual discharge. Given that the percentage error means and standard deviations of most discharge classes are below zero, it can be said that actual discharges exceed the calculated discharges most of the time. It should be noted that in lower discharge classes the percentage error does exceed zero. This can be a problem, as these are the discharges where accurate discharge calculations are needed the most. For this study, however, higher discharges are used. It is shown that for higher discharges, the actual discharges generally exceed the calculated discharges. This means that if the calculated discharges show that the barrier flows over, it can be said with reasonable certainty that the barrier actually flows over.

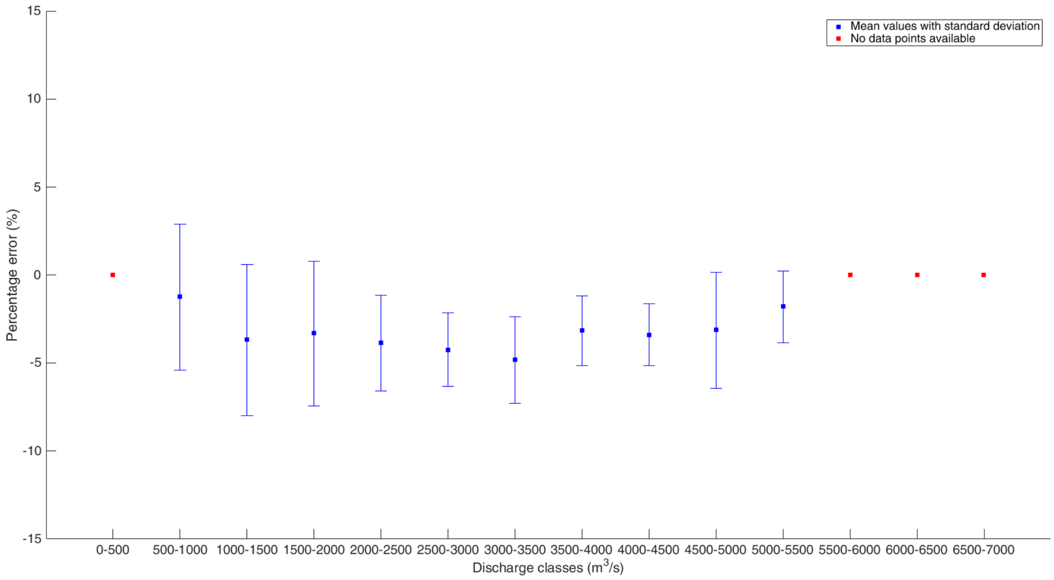

Figure 11: Percentage error with mean and standard deviation per discharge class at Lobith (492 data points)

- Hysteresis

During high discharges, hysteresis can occur. This means that discharges at the start of a high discharge wave result in different water levels than at the end of the discharge wave. The result is a Qh-relation that seems to loop when a high discharge wave occurs. As this phenomenon happens in reality and is not caused by a measurement error, water levels can differ significantly for equal discharges. This is taken into account by making fits through all the data points, both when water levels are rising and when they are falling. This results in an average water level for the given discharges.

3.2 Morphological changes

3.2.1 Expected changes

Other water management projects:
Other projects downstream of Nijmegen-Lent are deemed negligible. Projects upstream of Nijmegen are taken into account by analysing sections both upstream and downstream of the areas of interest.

Autonomous processes:
As stated in 3.1.1, the river Waal gradually erodes over time. Though the exact bed level decrease varies per section, it can be said that the section of the river near Nijmegen erodes with one to two centimetres per year.

Room for the Waal project:
It is expected that, based on Appendix A, sedimentation likely occurs near the inlet of the side channel. Additionally, erosion likely occurs near the confluence. This is in line with predictions made by Jong, Paarlberg, & Barneveld (2010), as shown in Figure 12. These predictions were made using Delft3D, taking into account the dredging strategy as implemented by Rijkswaterstaat. This means that not all bed level changes are visible, as some sediment build-ups were removed by the dredging strategy. Following from Figure 12, given a time span since completion of about 1,4 years, sedimentation at the inlet and erosion at the confluence of +0,25 and -0,25 meter respectively is expected after a high discharge period. Additionally, as stated by Jong, Paarlberg, & Barneveld (2010), sedimentation most likely occurs near the end of the solid or fixed layer (nautical km 885,5), as no dredging is allowed here (Figure 13).

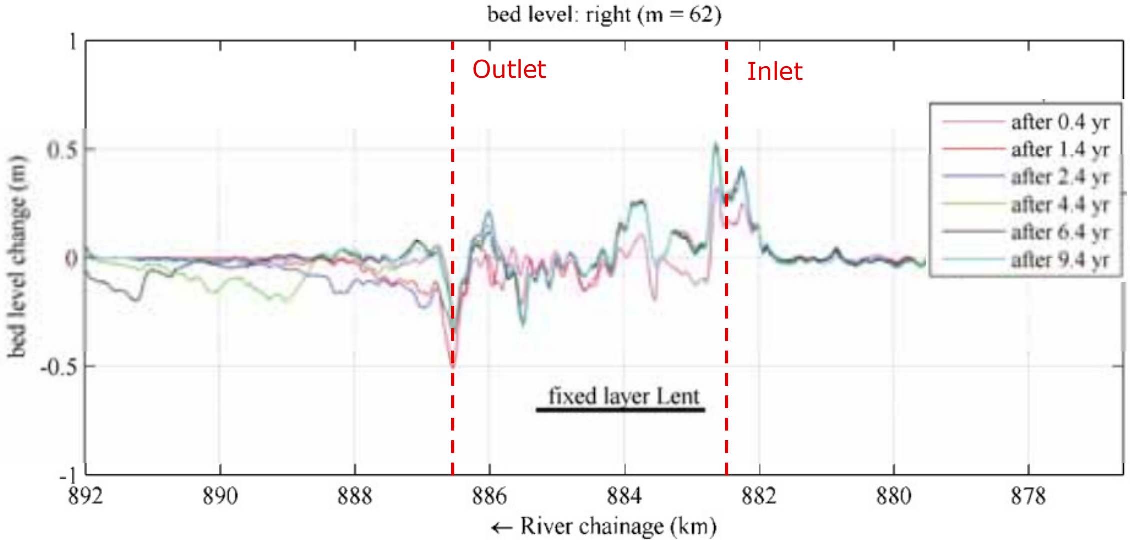

Figure 12: Expected bed level change on right side of river Waal after high discharge (Jong, Paarlberg, & Barneveld, 2010)

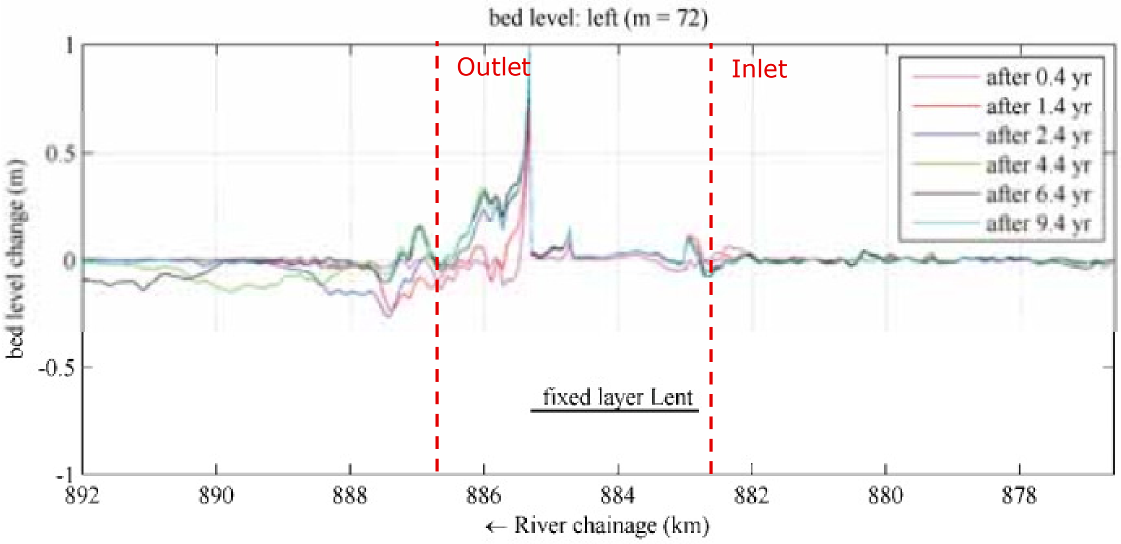

Figure 13: Expected bed level change on left side of river Waal after high discharge (Jong, Paarlberg, & Barneveld, 2010)

Since the Room for the Waal measure was completed just over a year ago and no significantly high discharges have occurred since then, it is unlikely an (dynamic) equilibrium has developed. Therefore, the changes associated with an (dynamic) equilibrium are unlikely to have taken place. However, it is possible that the early stages of the equilibrium are visible, which are shown by a slightly elevated bed level upstream of the side channel.

3.2.2 *Observed changes*

Other water management projects:
Other projects downstream of Nijmegen-Lent are deemed negligible. Projects upstream of Nijmegen are taken into account by analysing sections upstream of the areas of interest.

Autonomous processes:
In Figure 14 the average river bed levels per year, ranging from 1999 to 2016, are shown, excluding 2008 and 2010 due to a lack of data. It is shown that the slope of the river Waal is clearly visible as well as erosion of the river bed level. Though some sections show irregularities (e.g. km 925 to km 935), the area of interest in Figure 15, ranging from km 870 to km 890, shows results that are in line with the theory (i.e. a bed level decrease of some centimetres).

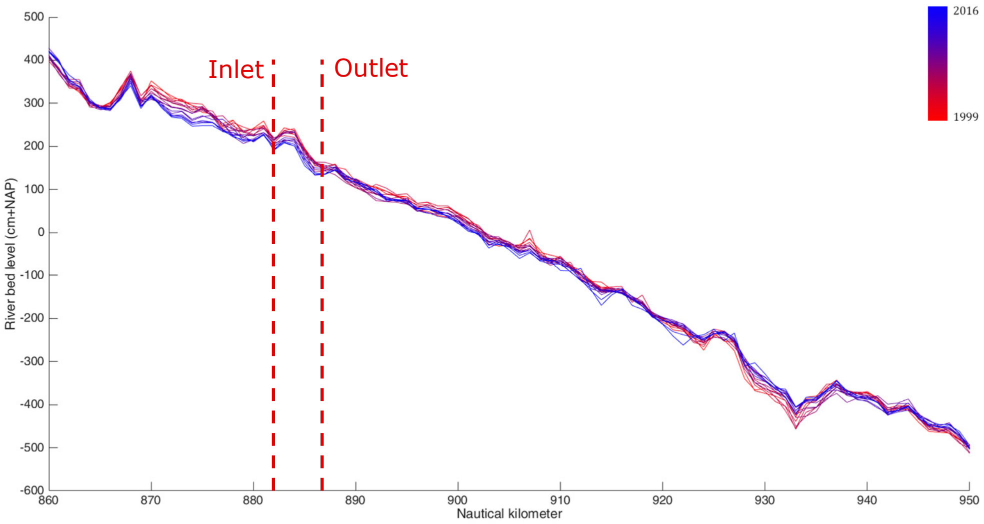

Figure 14: Average bed level measurements of the river Waal for the period 1999 to 2016

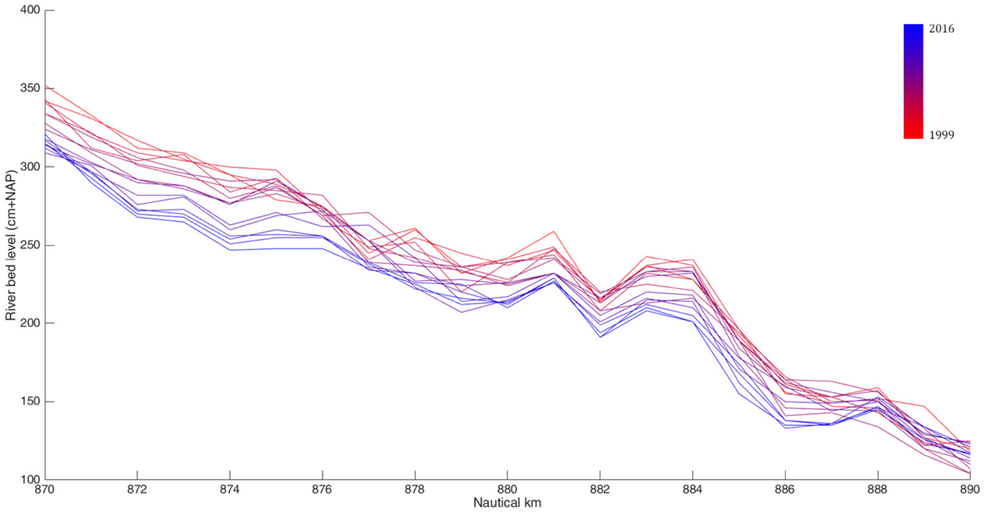

Figure 15: Average bed level measurements of the study area for the period 1999 to 2016

Averaging the erosion per kilometre for each year results in an average bed level decrease of 1,83 cm per year, which is roughly in line with the one to two centimetres as stated by Blom (2015). Additionally, it does not differ significantly from the erosion as found in Section 3.1.2.

Room for the Waal project:
In this section, the changes in river bed level of the most relevant subsections are given (i.e. inlet, outlet and after the solid layer). In Appendix D more subsections are evaluated, including the long term effects, to get a more complete picture of the changes that have taken place. Note that x and y-axes boundaries may change given different subsections.

Inlet

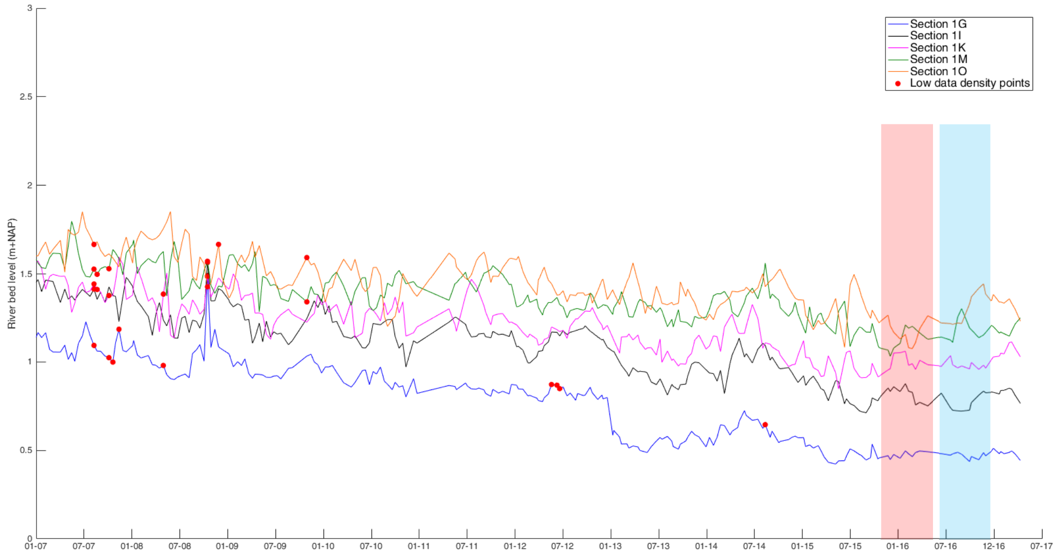

Figure 16: Changes in average bed level over time – subsections 1G, 1I, 1K, 1M, 1O

There are a number of observations that can be made from Figure 16. Firstly, it can be seen that the bed level of the river Waal fluctuates significantly over time, albeit with a slight downward trend. Secondly, sedimentation is visible in the second half-year of 2016 (blue area), though a 'small' sedimentation spike is also visible in the first half-year of 2016 (red area). This spike is, however, not visible in subsection 1G. Moreover, the spike in section 1I seems to differ from those in subsections 1K, 1M and 1O, which implies that this is a different sedimentation build-up. Therefore, it is possible that this spike originates at the inlet.

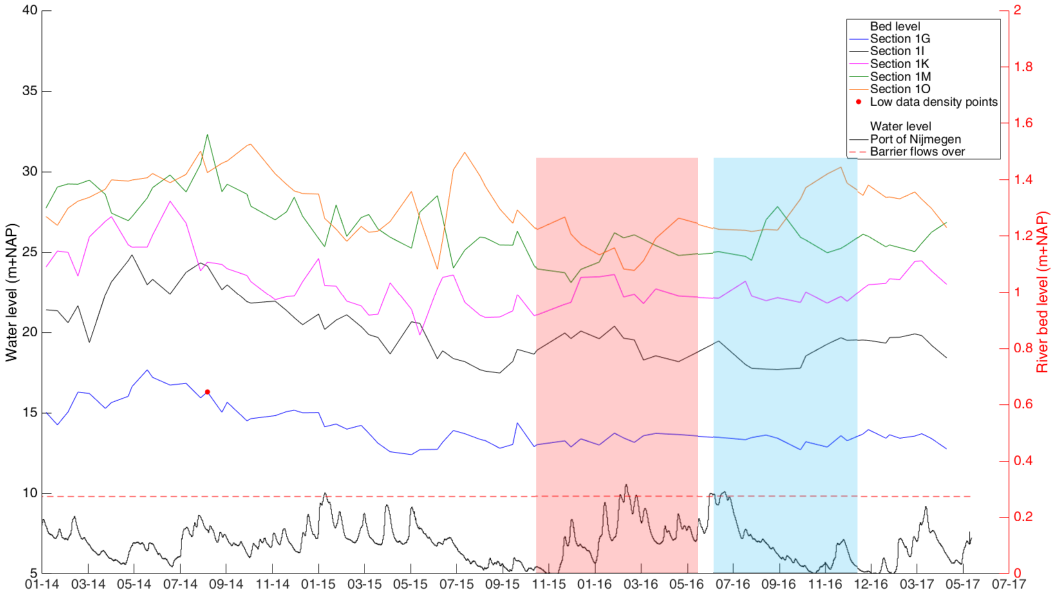

Figure 17: Changes in average bed level and water levels over time – subsections 1G, 1I, 1K, 1M, 1O

The sedimentation in the second half-year of 2016 seems to coincide with a decrease in water level at the Port of Nijmegen, while the small sedimentation spike in the first half-year seems to accompany the rise in water level (Figure 17). However, the sedimentation spike in early 2016 started in section 1K while the barrier had not flown over yet. Therefore, it is unlikely that this spike was caused by the side channel. This will be analysed further in Section 4.1.

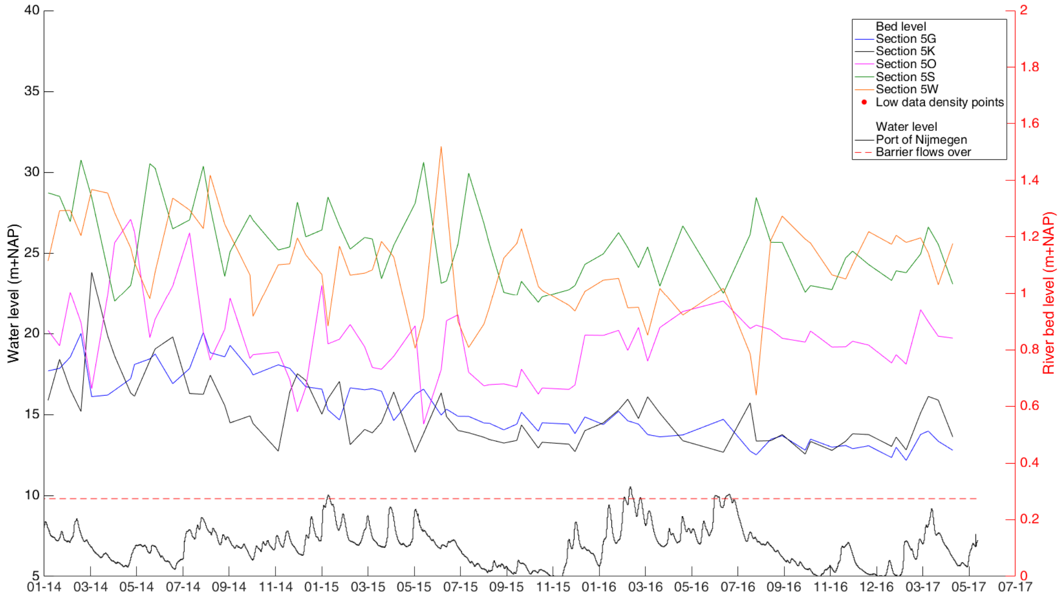

Figure 18: Changes in average bed level - subsections 5G, 5K, 5O, 5S, 5W

In Figure 18 similar trends as in Figure 17 are visible, though occasionally with higher or lower extreme values. However, no significant sedimentation build-ups or erosion pits are visible that were not visible in Figure 17.

Outlet

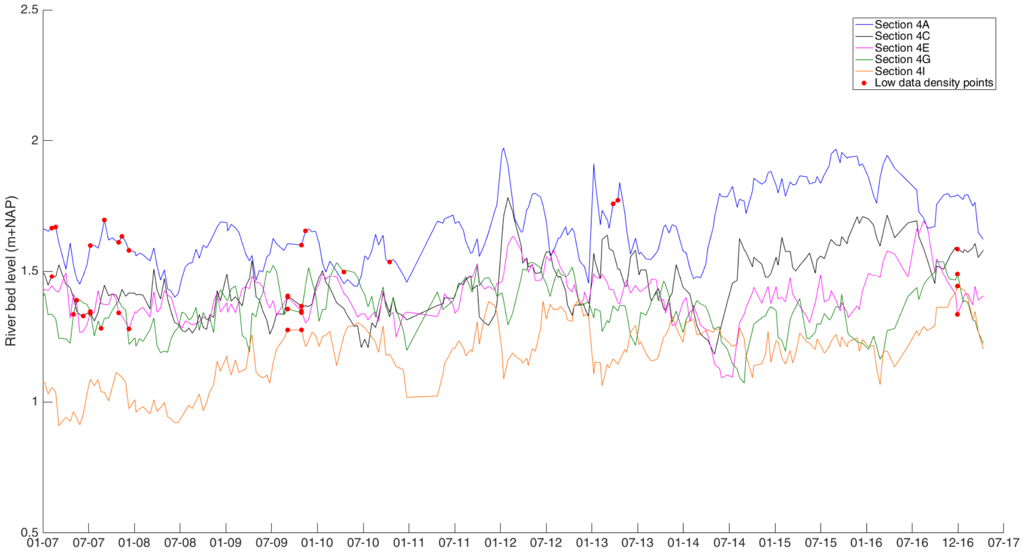

Figure 19: Changes in average bed level over time – subsections 4A, 4C, 4E, 4G, 4I

In Figure 19 the downward trend as seen in Figure 16 cannot be distinguished, while the fluctuations in average bed level are still significant in these subsections. As seen in Figure 20, erosion is visible in primarily early 2016 (red area), while sedimentation occurs in late 2016 (blue area). The sedimentation build-up in late 2016, however, does not seem to start at the outlet. Additionally, a sedimentation build-up at the outlet would be inconsistent with the predictions, as erosion is expected at the outlet.

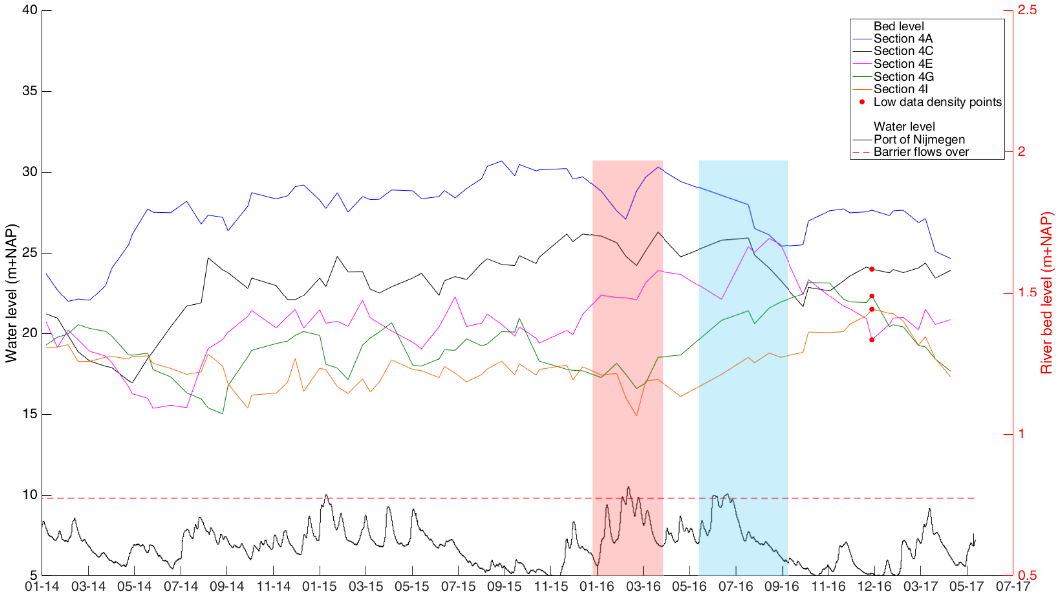

Figure 20: Changes in average bed level and water levels over time – subsections 4A, 4C, 4E, 4G, 4I

It should be noted that erosion occurs simultaneously in all sections in early 2016. This would imply that it is not caused by the side channel nor that it is a ‘regular’ river bank or erosion pit that moves downstream, as it does not appear to be moving downstream. Therefore, it might be caused by other processes that were not taken into account. It is also possible that, due to the limited temporal resolution of the bed level measurements, the bed form does not seem to be moving, while in reality it is. The erosion pit in early 2016 is studied more extensively in Section 4.1.

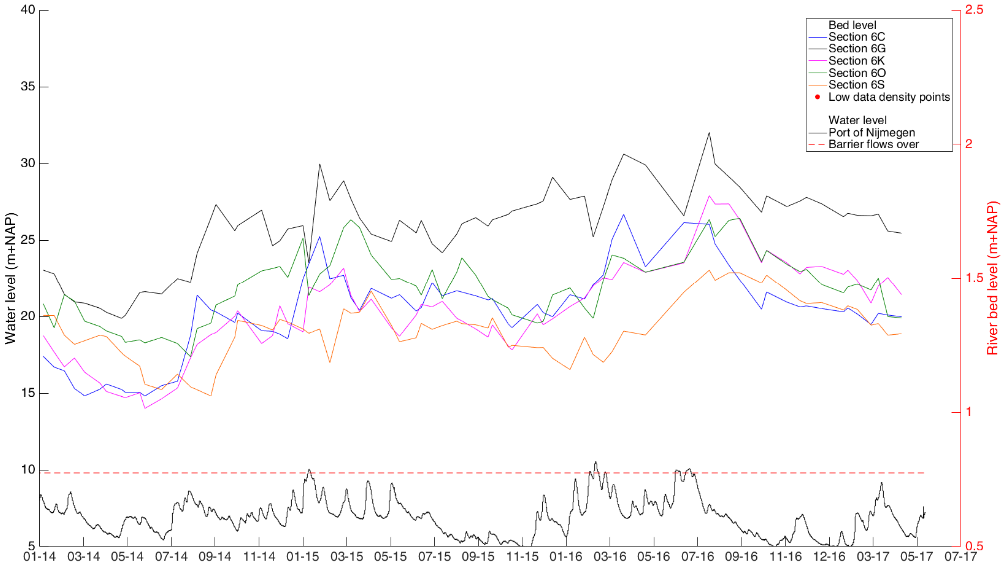

Figure 21: Changes in average bed level and water levels over time – subsections 6C, 6G, 6K, 6O, 6S

In Figure 21 a similar pattern as in Figure 20 is visible: erosion in early 2016 and sedimentation after the high discharge wave in early 2016. These sedimentation build-ups are, however, also visible in section 6C, which is upstream of the outlet, which implies that they are not caused by the side channel. It is interesting to note that section 6G has a continuously higher bed level than 6C, which is counterintuitive, given that 6G is downstream of 6C.

End of the solid layer

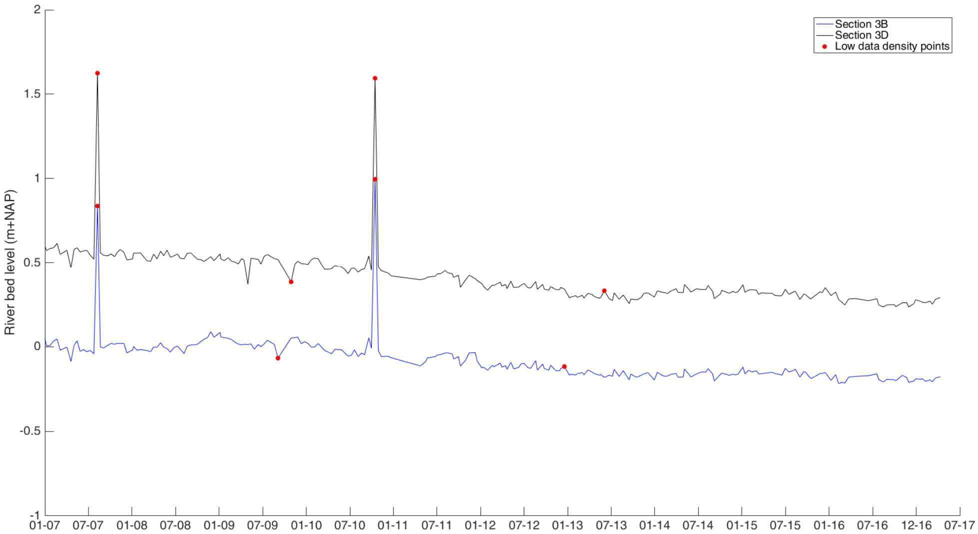

Figure 22: Changes in average bed level over time – subsections 3B, 3D

As seen in Figure 22, the erosion pit at the end of the solid layer maintains a relatively stable bed level, apart from a slight downward trend. Both sections have two distinctive outliers, which are both low data density points (coverage <95%). Therefore, it is highly likely that these outliers are caused by unrepresentative data points, rather than significant changes in bed level. There are, however, no significant changes visible in the period 2015-2017 (Figure 23). Results of more subsections are given in Appendix D.

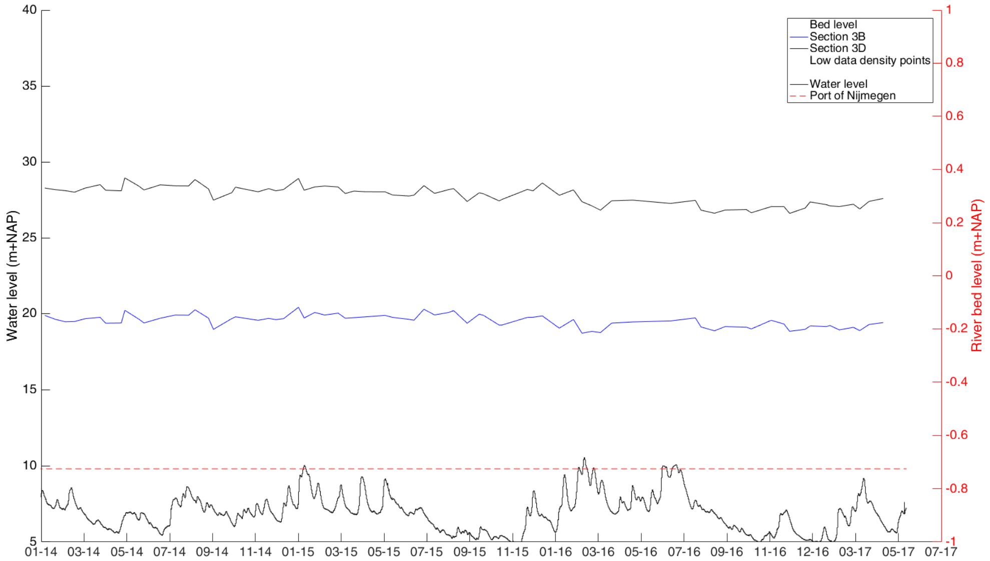

Figure 23: Changes in average bed level over time – subsections 3B, 3D

Uncertainties:
There are a number of uncertainties that might affect the results and therefore the reliability of the conclusions that are drawn. Therefore, the main uncertainties that might play a role and to what extent they are accounted for are described in this section.

- Passing river bedforms

As high water periods affect the whole river, sedimentation build-ups or erosion pits in the areas of interest not necessarily originate in these areas. It is possible that they develop further upstream and slowly move downstream into the areas of interest. To get a better idea whether changes actually originated in the areas of interest, two options are available: the sections further upstream can be studied to determine if similar patterns arise or the original bed level measurements can be studied to find the origin of the changes. These approaches are used in Section 4.1 for a comparison of the expected and observed changes.

- Dredging

Via Rijkswaterstaat, MGD (Minst Gepeilde Diepte) data are obtained. MGD data show the locations of the smallest depth in the river Waal for certain dates. Though this data do not show actual dredging operations in the study area, it does mean that locations in the MGD dataset are more likely to have been dredged.

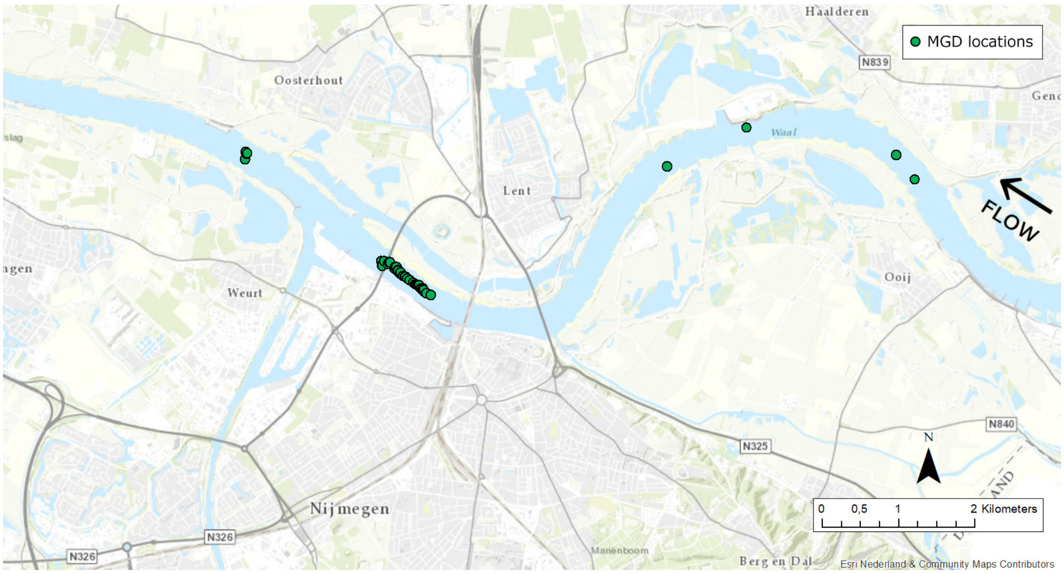

Figure 24: MGD locations for the period 2015 to 2017

As seen in Figure 24, the MGD locations are not near the inlet or the outlet of the side channel. There are MGD locations on the right side of the river after the solid layer. However, only predictions regarding changes in bed level are made about the left side of the river in this area. In conclusion, the MGD data do not suggest that dredging operations took place in the areas of interest.

4 Comparison

In this chapter, the expected and observed changes are compared for both the hydraulic and morphological parts. In the hydraulic part, the expected changes are compared to the observed changes, taking into account autonomous processes and other water management. In the morphological comparison, the actual bed level measurements are studied to make more substantiated statements on the origin and scale of river bedforms. It is then determined if and to what extent they are in line with the expected morphological changes.

4.1 Hydraulic changes

The expected water level decrease, based on Figure 7, is shown in Table 5. The water level change caused by erosion and the groyne reduction program, based on Table 1, is shown in Table 6. The water level change at high discharges, caused by erosion, the groyne reduction program and the side channel is shown in Tables 7 and 8.

Table 5: Expected water level change per discharge at Lobith for the Port of Nijmegen and the Pannerdense Kop: negative values represent a decrease in water level

Discharge at Lobith [m^3/s]	Water level change [cm]
4000	-0,6
4600	-0,6
5000	-3,0
5200	-4,1

Table 6: Water level change due to autonomous processes and other water management projects for the appropriate timeframes. Discharges at Lobith and water level changes at the Port of Nijmegen: negative values represent a decrease in water level

Years	Average change for discharge class 3500-4600 m^3/s [cm]
	Port of Nijmegen
2010-2013	-19,2
2013-2016	-4,6
2010-2016	-23,8

The water level change caused by erosion and the groyne reduction program differs at the Pannerdense Kop. It is assumed that, though the erosion level is roughly the same, the impact of the groyne reduction program is approximately half the effect of that at the Port of Nijmegen. The comparison of the hydraulic changes is done in multiple stages. In the first stage, the changes due to autonomous processes and other water management projects (Table 6) are subtracted from the observed changes at the Port of Nijmegen (Table 7), which results in the changes due to the Room for the Waal project at the Port of Nijmegen (Table 9). In the second stage, the acquired results are studied and compared to the expected water level changes caused by the Room for the Waal project (Table 5). Finally, in the third stage, the observed changes at the Port of Nijmegen (Table 7) are compared to the observed changes at the Pannerdense Kop (Table 8). This is done to determine whether the results as found in the second stage correspond with the water levels at the Pannerdense Kop, taking into account a different impact of the groyne reduction program.

Table 7: Water level change due to autonomous processes, other water management projects and the Room for the Waal project for the appropriate timeframes. Discharges at Lobith and water level changes at the Port of Nijmegen: negative values represent a decrease in water level

Years	**Changes in water level at the Port of Nijmegen for discharges at Lobith [cm]**		
	4650 m^3/s	5000 m^3/s	5200 m^3/s
2010-2013	-12,8	-18,0	-17,7
2013-2016	-12,2	-7,1	-8,0
2010-2016	-25,0	-25,1	-25,7

Table 8: Water level change due to autonomous processes, other water management projects and the Room for the Waal project for the appropriate timeframes. Discharges at Lobith and water level changes at the Pannerdense Kop: negative values represent a decrease in water level

Years	**Changes in water level at the Pannerdense Kop for discharges at Lobith [cm]**		
	4650 m^3/s	5000 m^3/s	5200 m^3/s
2010-2013	-5,0	-7,4	-7,3
2013-2016	-6,9	-6,1	-5,9
2010-2016	-11,8	-13,4	-13,3

Table 9: Water level change due to the Room for the Waal project for the appropriate timeframes. Discharges at Lobith and water level changes at the Port of Nijmegen: negative values represent a decrease in water level

Years	**Changes in water level at the Port of Nijmegen for discharges at Lobith: Room for the Waal project [cm]**		
	4650 m^3/s	5000 m^3/s	5200 m^3/s
2010-2013	6,4	1,2	1,5
2013-2016	-7,6	-2,5	-3,4
2010-2016	-1,2	-1,3	-1,9

A couple of things stand out when reviewing the changes due to the Room for the Waal project at the Port of Nijmegen (Table 9). Firstly, in the period 2010-2013 the changes due to autonomous processes and other water management projects (Table 6) are larger than the observed changes at the Port of Nijmegen (Table 7), which results in a positive change caused by the Room for the Waal project, even though the Room for the Waal project had not been completed at the time (Table 9). This, however, can be explained by the fact that the groynes have less impact during higher discharges than during the calculated lower discharges. This causes a positive water level change due to the Room for the Waal measure, as opposed to zero water level change. In the period 2013-2016, however, a credible decrease of 2,5 to 3,4 centimetres occurs in discharges ranging from 5000 to 5200 m^3/s at Lobith. This is relatively consistent with the expected decrease of 3,0 to 4,1 centimetres. The decrease during 4650 m^3/s at Lobith is less credible, as this is unrealistically high. When reviewing Figure 25 in combination with Appendix F, it can be seen that there is another high discharge period in 2016 that exceeds 4600 m^3/s. Since the discharges in this period are only slightly higher than 4650 m^3/s, they impact the fit in this initial stage significantly, which most likely accounts for the unrealistic results in this stage.

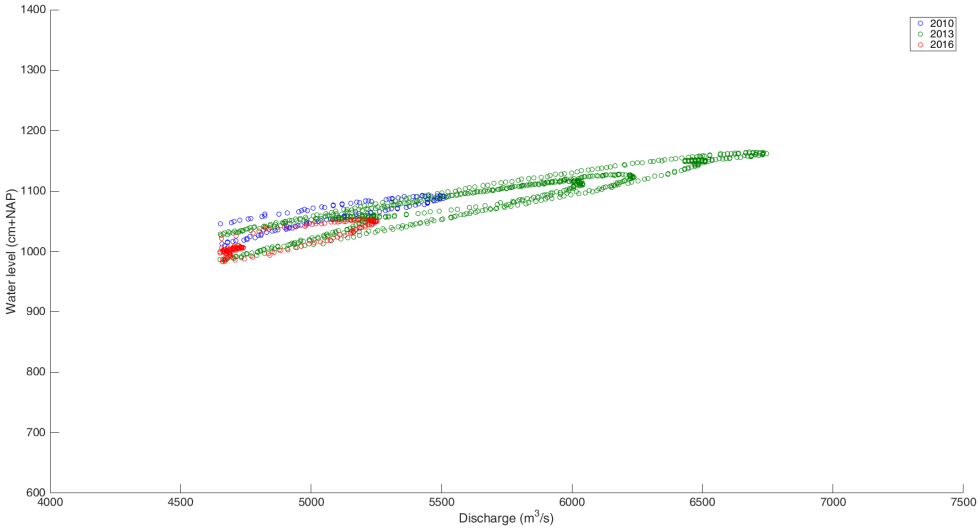

Figure 25: Qh scatterplot of water levels at the Port of Nijmegen and discharges at Lobith for the years 2010, 2013 and 2016. Only discharges exceeding 4600 m^3/s at Lobith are plotted.

When analysing Table 8, it is shown that the water level decreases in period 2010-2013 are less than half of those at the Port of Nijmegen. Though it is justifiable that the decreases, due to the distance to the groyne reduction program, are less than those at the Port of Nijmegen, the differences are implausibly high. When comparing Table 7 and Table 8 for the period 2013-2016, it shows that for discharges 5000 and 5200 m^3/s at Lobith, the water level at the Pannerdense Kop decreases a few centimetres less than at the Port of Nijmegen. This is in line with the expectations regarding the groyne reduction program. In conclusion, the data do not exclude the Room for the Waal project as being part of the cause for the water level decrease. However, as noise in the data might significantly affect the relatively small changes, the fits are based on a limited amount of data points, no sufficiently high discharges have taken place since the completion of the measure and Diver measurements at the inlet were not available, the visible changes cannot be guaranteed to be caused by the project.

4.2 Morphological changes

The morphological comparison is performed for the inlet and outlet of the side channel and for the area after the side channel, as these are deemed the most relevant subsections for this study.

Inlet

As mentioned in Section 3.2, a small sedimentation spike is visible parallel with a high discharge period in early 2016. However, the sedimentation spike starts before water flows over the barrier. To exclude the side channel from causing this sedimentation build-up, as it is possible the barrier flows over during lower discharges than was expected, the original bed level measurements are studied using Figures 26 and 27.

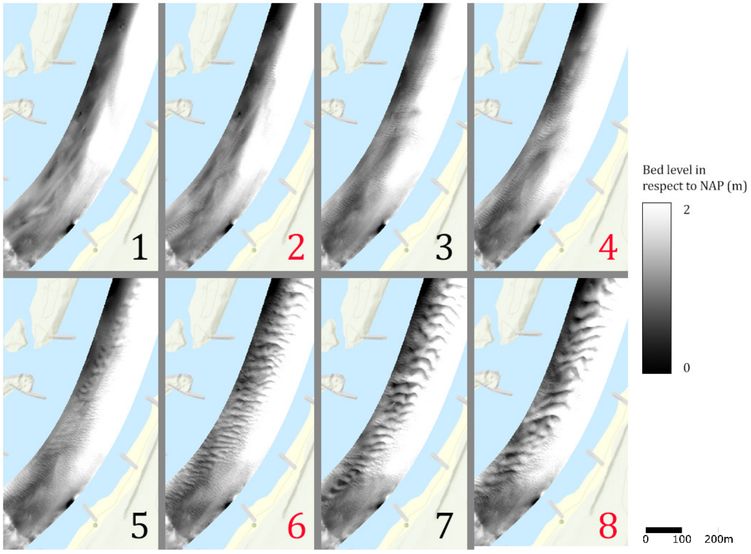

Figure 26: Evolution of the bed level near the inlet in early 2016

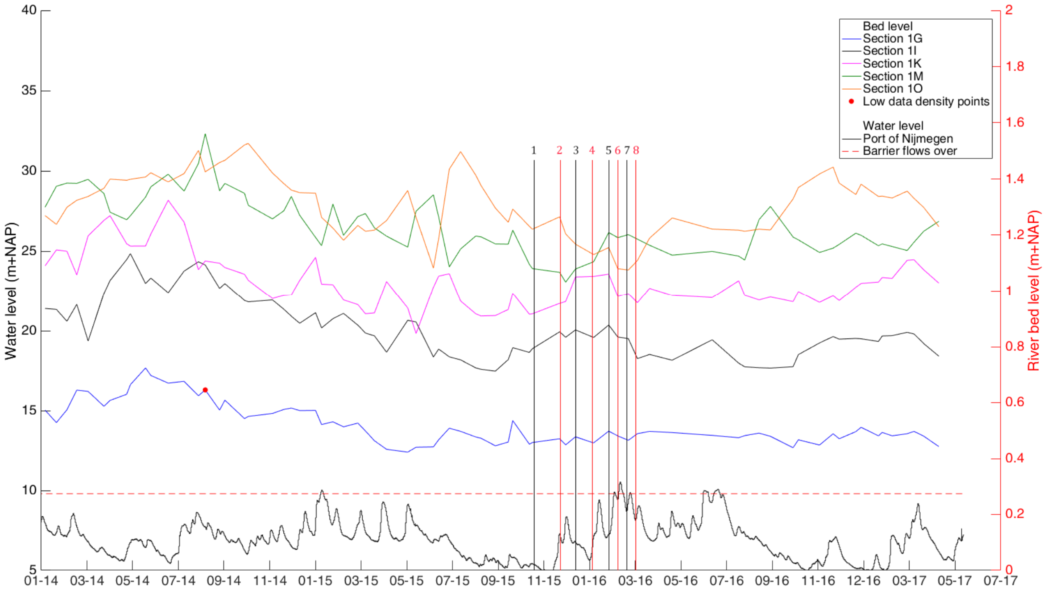

Figure 27: Used timepoints for early 2016 (distinction between black and red lines for the purpose of clarity)

Figure 26 does not indicate that bed level forms originate at the inlet in early 2016. However, given the possibly small scale of sedimentation build-ups, it is also possible that they are not visible in Figure 26 while in reality they do exist. This means that no definitive statements can be made about whether the sedimentation build-up in early 2016 is due to the side channel. For late 2016, the sedimentation build-up does not seem to be visible in section 1G, which means it is possible it originates at the inlet. For that reason, the original bed level measurements are also studied for this timeframe. A sedimentation build-up seems to move downstream, passing each section at roughly the same time the sedimentation spikes are visible (Figure 28: red circles). However, as there is no indication that it starts at the inlet, it is unlikely that it was caused by the side channel.

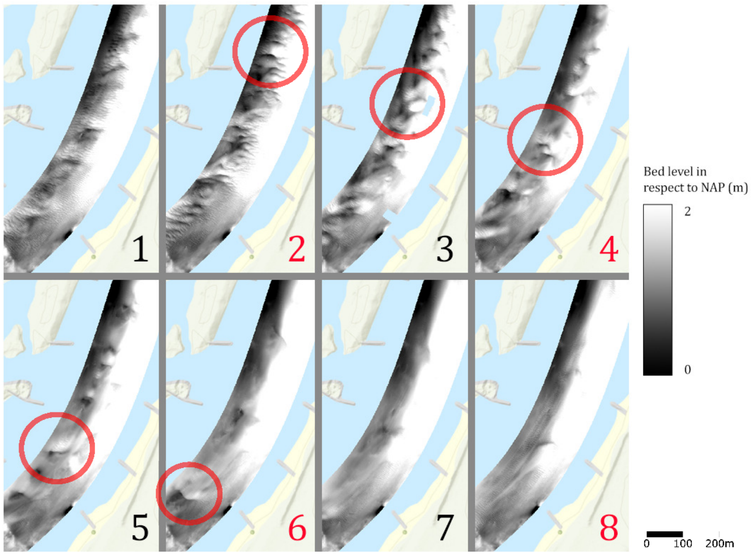

Figure 28: Evolution of the bed level near the inlet in late 2016

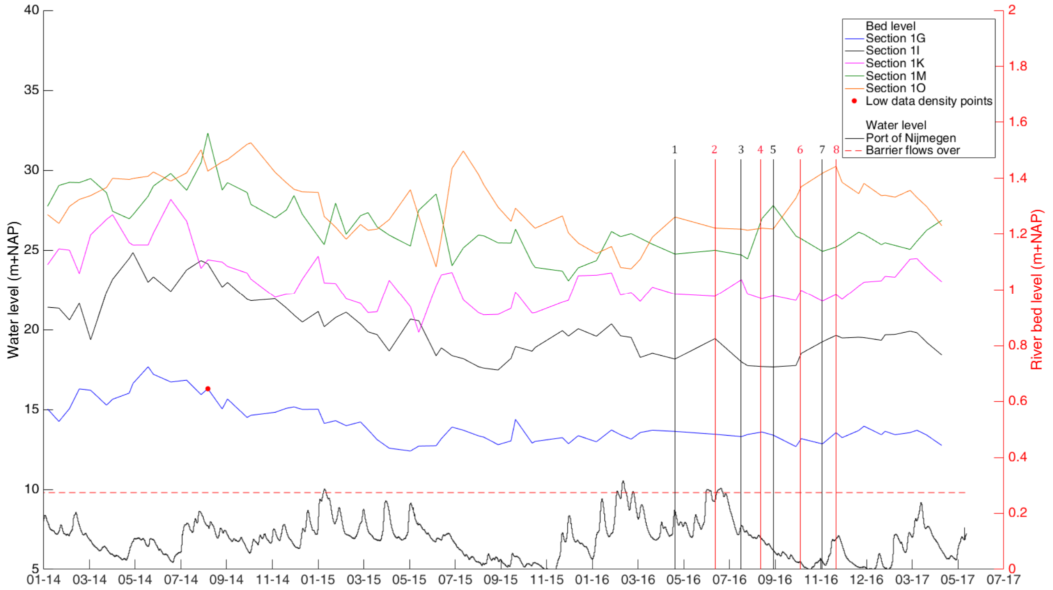

Figure 29: Used timepoints for late 2016 (distinction between black and red lines for the purpose of clarity)

Outlet

Figure 30, in combination with Figure 31, shows no significant erosion pit at the outlet of the side channel, though this could be caused by the fact that they are too small to be visible in Figure 30. Given that the erosion during timepoint 3 is not visible in Figure 30, no definitive statements can be made about whether it originates at the outlet, it originates further upstream or that it is caused by other processes. Additionally, no other significant sedimentation build-ups or erosion pits are visible in Figure 30 that can be attributed to the side channel.

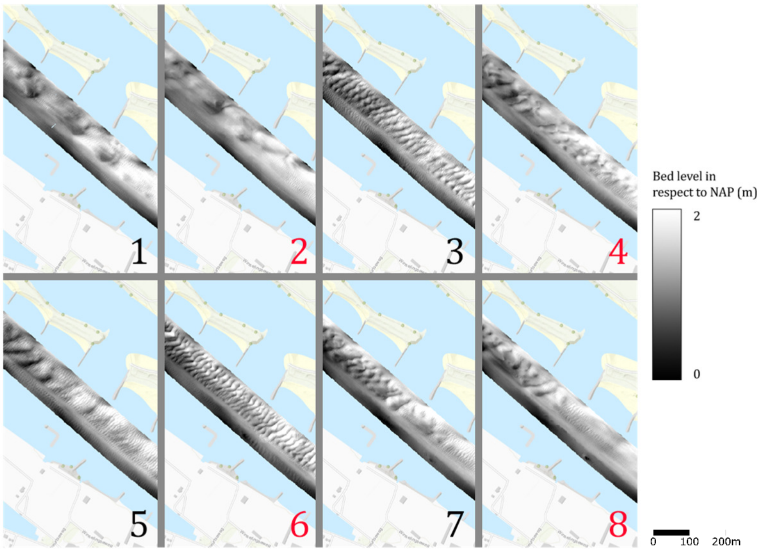

Figure 30: Evolution of the bed level near the outlet

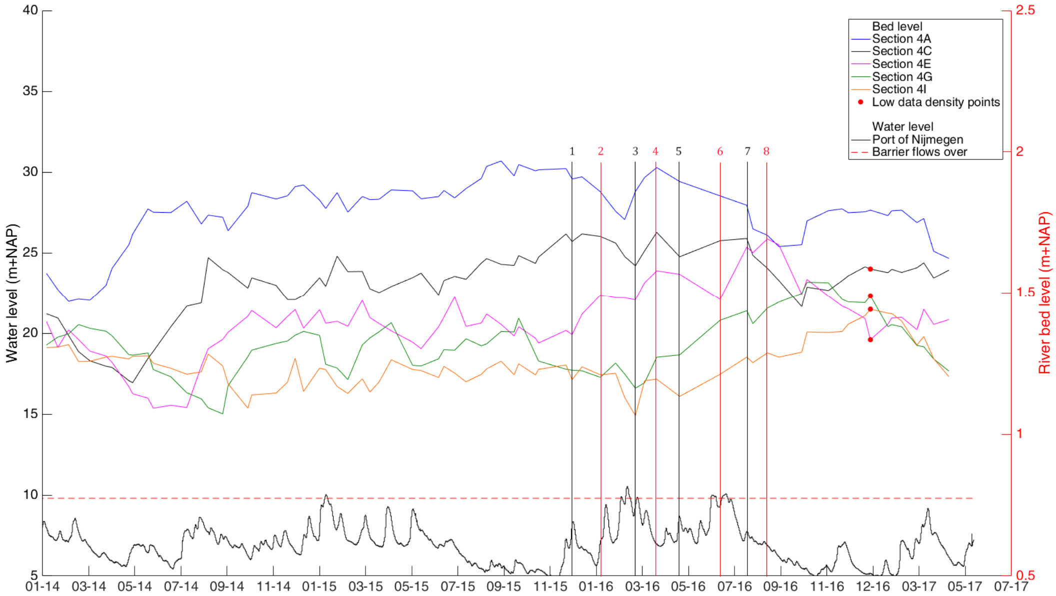

Figure 31: Used timepoints (distinction between black and red lines for the purpose of clarity)

End of the solid layer

It is clear in Figure 22 that the expected changes at the end of the solid layer are not visible in the bed level measurements. The bed level stays relatively constant with only a few outliers. Though a small erosion trend is visible over the years, no significant sedimentation is visible after the completion of the Room for the Waal measure.

5 Discussion

During the course of this research project, certain assumptions or choices were made that might have affected the accuracy of the results and subsequently the conclusions that were drawn. Additionally, due to time constraints, choices were made regarding the data that were used. These points are discussed in this chapter. First, the availability of data during the research project is discussed. Secondly, the choices regarding the analysis of data are discussed.

Due to time constraints, it was deemed infeasible to use water level data which were obtained by Diver measurement instruments. Since these instruments lie on strategic locations in the study area, including at the inlet and downstream of the outlet, a significant amount of potentially valuable information was not used. Since these measurements were not available, only water levels at the Port of Nijmegen and the Pannerdense Kop were used, which were expected to show less significant changes. For the morphological part, the data that were used to study changes in bed level were obtained by a dredging contractor for Rijkswaterstaat. These data are gathered once every two weeks to show that the river bed is in line with the contract between the contractor and Rijkswaterstaat. This affected the study in two ways: Firstly, only the fairway was measured. This means that changes that occurred outside the fairway were not visible and therefore not taken into account. It is possible that changes in the areas of interest occurred outside the fairway, which means that the conclusions that were drawn are not a good representation of the actual situation. Secondly, as the measurements are done to verify whether the contract is adhered to, they are usually performed after dredging operations, as opposed to before. This means that if sedimentation build-ups occurred in the time between surveys, it is possible they were removed before the survey was performed. For the dredging operations themselves, it should be noted that although the MGD locations (Section 3.2.2) were known, they do not show actual data of dredging operations. Additionally, no concrete information was known about dumping sites. If the dredging and dumping sites are in the areas of interest, information about these locations would have greatly increased the reliability and accuracy of the results and of the conclusions.

For the hydraulic part, it was not possible to accurately determine a change in discharge distribution at the Pannerdense Kop since the completion of the Room for the Waal measure. The decrease in water level at the Pannerdense Kop might have resulted in a higher discharge being conveyed by the river Waal, effectively increasing the water level again. This would dampen the changes and subsequently the impact that is attributed to the side channel. Therefore, the water level changes that were measured and attributed to the Room for the Waal measure, might have been higher if the discharge distribution was constant. In conclusion, it is possible that the water level change that was caused by the Room for the Waal project is higher than was found in this study. Another point is the time that it takes for water to flow from Lobith to the Port of Nijmegen and the Pannerdense Kop, which was not taken into account. However, it can affect the Qh-relations that were composed. Given that it takes up to a few hours for the water flow to reach the Port of Nijmegen and less for the Pannerdense Kop, it is assumed that it has not affected the results significantly. For the morphological part, the first bed level section grid that was used to measure changes in the bed level consisted of sections that averaged out most regular bedforms and banks. This way, the results were less affected by regular bed level dynamics. However, as bed level forms and banks come in different shapes and sizes, this was no guarantee. This is partially shown by the significant fluctuations in almost all bed level plots. Additionally, it is possible that changes in the bed level caused by the side channel are only minimal. These changes would have been averaged out by the relatively large sections sizes. For this reason, a second section grid was composed.

Though this grid allowed smaller bed level changes to be visible, it also showed more fluctuations, as regular bed level dynamics were also more visible. In conclusion, it is possible bed level changes caused by the side channel have not been identified as such, either because they were averaged out or because they were regarded as regular bed level dynamics. Though it is hard to entirely resolve this, the use of multiple bed level grids with varying sections sizes was deemed the best method to solve this. Furthermore, during this study the assumption was made that if a river bed form occurred near the inlet and not further upstream, it was likely caused by the side channel, given a discharge higher than 4600 m^3/s at Lobith. However, there are additional processes that might play a role. These processes include the impact of helicoidal flow, the impact of the solid layer or the fact that the inlet lies between two bends. Therefore, assuming that only the side channel plays a role is a significant simplification, as other processes might have affected the results.

6 Conclusion

To determine the preliminary impact of the Room for the Waal measure, the hydraulic and morphological changes in the river Waal of the past decade were studied. The hydraulic and morphological changes were determined by studying the autonomous processes, other water management projects and the Room for the Waal measure itself. Expectations for these categories were formed and it was checked if they were in line with the observed changes. The observed autonomous processes in the water level were in line with the expectations, as an average yearly water level decrease of 1,5 to 2,0 centimetres was found. Other water management projects that affected the situation near Nijmegen mainly consisted of the groyne reduction program. It was concluded that the changes in water level that were found, were in line with the phased execution of this program in the years 2009 to 2015. To determine the impact of the Room for the Waal measure, the autonomous processes and other water management projects were filtered out. The water level changes that were subsequently found were roughly in line with the expected impact of the Room for the Waal measure, which was a few centimetres on the Port of Nijmegen and the Pannerdense Kop. Since a change in discharge distribution at the Pannerdense Kop, due to the Room for the Waal measure, was not taken into account, the actual water level change is possibly higher than was found. It should be noted that, as noise in the data is a given, relatively few high discharge data were available and the water level changes were minimal, there is no certainty that the changes that were found were actually caused by the side channel. In conclusion, though changes are visible that are in line with the design of the Room for the Waal measure, additional information about high discharge periods and associated water levels is needed to make more substantiated statements about the hydraulic impact of the side channel.

For the morphological impact of the side channel on the river bed near Nijmegen-Lent, much of the same applies. Significant fluctuations were visible during the entire period of 2007 to 2017, which means that the river bed of the river Waal is constantly changing. However, an erosion trend of approximately two centimetres per year was visible, corroborating the one to two centimetres as stated by Blom (2015). On the other hand, no significant sedimentation build-ups or erosion pits were found that could be confidently attributed to the Room for the Waal measure. Though bedforms did show at the inlet and outlet of the side channel, they mainly seemed to migrate from upstream river bed sections or were not significant enough to make definite statements about. In conclusion, no sedimentation build-ups or erosion pits were found that could be confidently attributed to the side channel. Therefore, the same applies as with the hydraulic impact of the side channel: The situation near Nijmegen-Lent needs to be reassessed after additional high discharge periods have occurred to make more substantiated statements about the impact of the side channel.

7 Recommendations

As stated in Chapter 5, due to time constraints certain choices regarding data usage and analysis had to be made during the course of this research project. This means that some data that were not available or only became available in the later stages of the project were disregarded. Additionally, as the Room for the Waal project was only completed in late 2015, not much high discharge data of the post Room for the Waal situation were available. This allows for the following recommendations regarding future research to be made, so that future research will give a more accurate picture of the hydraulic and morphological impact of the Room for the Waal measure.

In Chapter 5 it was discussed that Diver measurements would provide valuable information on water levels during high discharges. Since these data became available at the end of this research project, it is available for future research. This is highly recommended, as the locations where Divers are located are expected to show significantly larger water level changes than at the Port of Nijmegen or at the Pannerdense Kop. Furthermore, a change in the discharge distribution at the Pannerdense Kop might have a significant effect on the water levels at Nijmegen (Chapter 5). Since only a minimal amount of ADCP measurements exceeding 4600 m^3/s at Lobith since the completion of the measure were available during the research project, the discharge distribution could not be updated. However, as time goes by, more high discharge and ADCP data become available. Therefore, it is highly recommended that when more data are available, a discharge distribution at the Pannerdense Kop is measured for the post Room for the Waal situation.

For the morphological analysis, acquiring information about current dredging and dumping locations would increase the accuracy of this research. This information would allow dredging and dumping operations to be excluded from the list of possible explanations for river bedforms (or the lack of them). Therefore, it is greatly recommended to obtain this information, possibly by acquiring the dredger’s timesheets. Additionally, though it is not cost-effective and practical and therefore unlikely to happen, bed level measurements with an increased temporal resolution (e.g. every week) and measuring range (i.e. entire width of the river bed) would allow bedforms to be followed more accurately.

In conclusion, the foremost recommendation is to perform this study, or a similar study, again when a significantly high discharge period has occurred (e.g. discharges exceeding 6000 m^3/s at Lobith). This way, more morphological activity due to the side channel is likely to be visible and water level changes will be significantly larger. In addition, this allows for more ADCP measurements to be performed, which can be used to update the discharge distribution at the Pannerdense Kop.

8 Acknowledgements

This research was carried out at Rijkswaterstaat Oost-Nederland, Arnhem. It was part of a bachelor thesis for the study Civil Engineering at the University of Twente in Enschede.

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Finally, I would like to thank all at Rijkswaterstaat Oost-Nederland for their hospitality and eagerness to help, even if they were not directly part of this project.

This research project has not only given me insights in river hydraulics and morphology, but also on what working in this field of study, outside of an educational environment, is like. It has shown me that the problems you encounter in a work environment differ substantially from the problems you deal with in an educational environment. In conclusion, this research project has been a very valuable experience, which has provided me with a better understanding on a wide range of topics.

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Appendix A Theoretical background

To get a better understanding of what the intended effects of the Room for the Waal measure are, it is important to get a better understanding of a side channel's hydraulic and morphological effects on the main channel. The understanding of these principles can also help to predict the effects of other water management projects in the river Waal for the situation in Nijmegen-Lent. Additionally, the impact other measures have (i.e. solid layer) will also be described, as this will too help to predict hydraulic and morphological changes in the channel.

A.1 Side channel: hydraulic and morphological effects

If a side channel is constructed, certain hydraulic changes in the water flow occur. In order to estimate the changes in water level, water surface curves can be used (Figure 32). Side channels not only cause changes in the water level in the area where the channel is constructed, but also further upstream–though it should be noted that the largest hydraulic changes occur at the inlet. The construction of a side channel will have both short term and long term effects, which are important to understand. Though it is unlikely that the long term effects of the side channel near Nijmegen-Lent have already occurred, having knowledge of these effects is vital for understanding future developments.

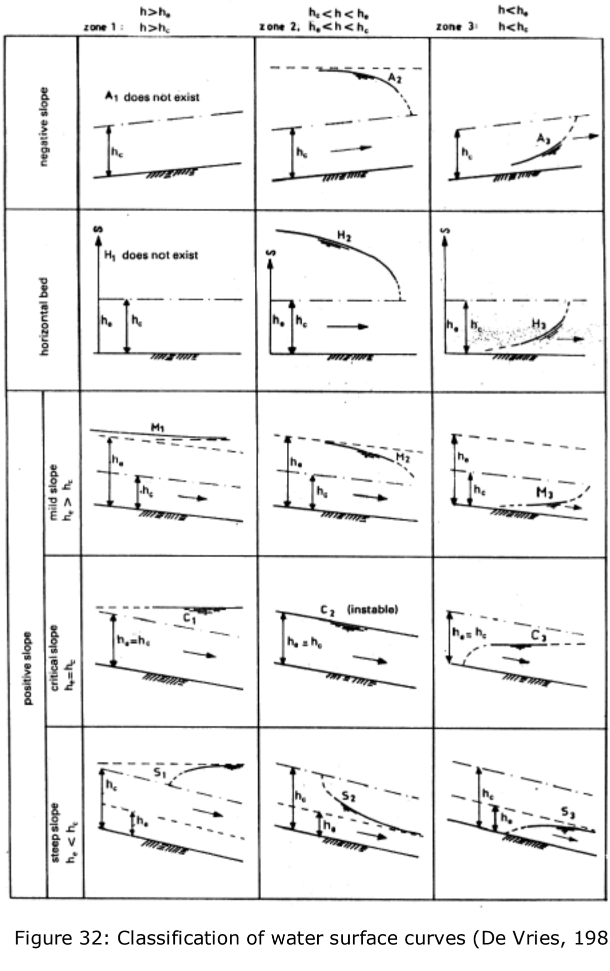


Figure 32: Classification of water surface curves (De Vries, 1985)

A.1.1 *Short term effects*

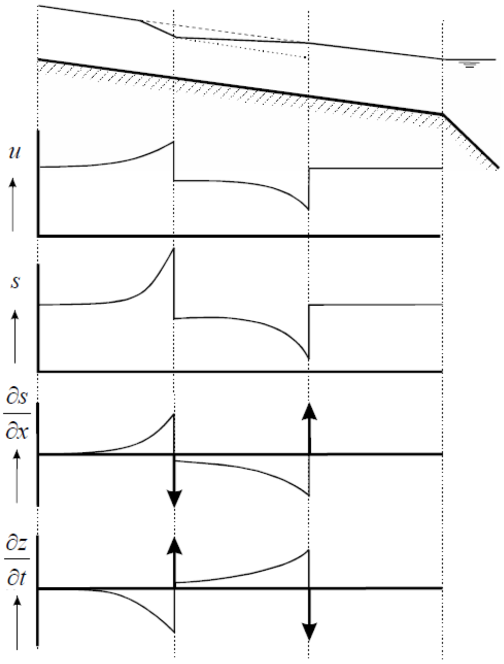


Figure 33: Water surface curves and bed level changes (Ribberink, 2011)

The extra space caused by the side channel will result in lower water levels in the main channel, as part of the discharge will be transported through the side channel. The decreased water level causes an upstream water surface curvature–if a mild slope is assumed, which is a safe assumption in the Netherlands–in the form of M2 (Figure 32 and Figure 33). The decreasing water level upstream of the side channel will cause an increase in flow velocity, as the discharge does not change. The increase in velocity increases the amount of sediment that is transported, which causes erosion of the river bed upstream (Ministerie van Verkeer en Waterstaat, Expertise Netwerk Waterkeren, 2007). At the point where water flows into the side channel, the extra space significantly reduces the flow's velocity. This change in velocity causes a decrease in sediment transport capacity of the water, which in turn results in sedimentation in the main channel. As the water flow approaches the confluence, the decreasing speed–resulting from the increasing water level (Figure 32: M1)– causes slight sedimentation. At the confluence of the two channels, however, all of the water is forced back into the main channel, which causes a significant increase in velocity. This in turn results in a peak in erosion (Ribberink, 2011).

A.1.2 *Long term effects*

If the situation stays constant (i.e. water will always be flowing through the side channel and discharges are constant), the bed level goes to an equilibrium. Though a true equilibrium (Figure 34) will never occur due to fluctuating discharges and other uncertainties, it might be approached. In an equilibrium, sediment transport, velocity and water height are constant. The downstream river bed slope is equal to the slope before the construction of the side channel, whereas the slope of the section that lies parallel to the side channel is larger (Figure 34). This is caused by a decrease in discharge through the main channel during this stage, in which still the same amount of sediment has to be transported. This results in a higher river bed level upstream, where the maximum discharge is transported through the main channel (Ribberink, 2011). The higher bed level upstream can, in theory, cause higher water levels than was the case without the side channel. Apart from the fact that this equilibrium can never be reached due to variable discharges and other variable parameters, it is also expected that sedimentation will occur in the side channel (Hoeven, 2002; Schuurman, 2012).

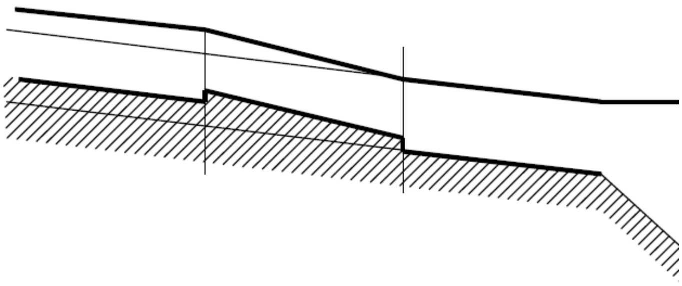


Figure 34: Equilibrium situation of the river bed (Ribberink, 2011)

As stated by Bolla Pittaluga et al. (2014), though a true equilibrium as seen in Figure 34 is unlikely, a dynamic equilibrium can be reached. In this dynamic equilibrium the 'perturbations intermittently induced by flood events' are suppressed by 'normal' low discharges (Bolla Pittaluga, Luchi, & Seminara, 2014). This means that disturbances caused by, for example, floods are corrected by normal discharges. This shows that, even in (dynamic) equilibrium, the river is constantly changing.

A.2 Solid layer: hydraulic and morphological effects

To get an idea of the effect a solid layer has on the river hydraulics and morphology, it is important to first get an idea on why a solid layer is constructed. Therefore, this chapter is divided in two main parts: the situation before a solid layer is applied and what happens in the river after a solid layer is constructed.

A.2.1 Situation before solid layer

As water flows through a river bend or meander, its inertia will try to keep it flowing in a straight line (Figure 35: I). Since this is not possible, water will 'accumulate' in the outer region of the bend, causing a rise in hydrostatic pressure (Figure 35: II). Additionally, as the centrifugal force is not uniform in the vertical cross section, the resulting force will cause circulations in the cross section (Figure 35: III, IV, V) (van Reen, 2002). Combined with the longitudinal (primary) flow, these circulations will result in helicoidal (secondary) flow (Benoit, 2012). This flow results in a force directing inward, resulting in sediment being transported to the inner region of the bend. As time progresses, an equilibrium will be reached–though as discharges vary, so does the equilibrium (Figure 35: VI) (van Reen, 2002). It should be noted that–as the helicoidal flow circulations take some time and distance to develop–effects of these processes are predominantly visible in the downstream part of the bend.

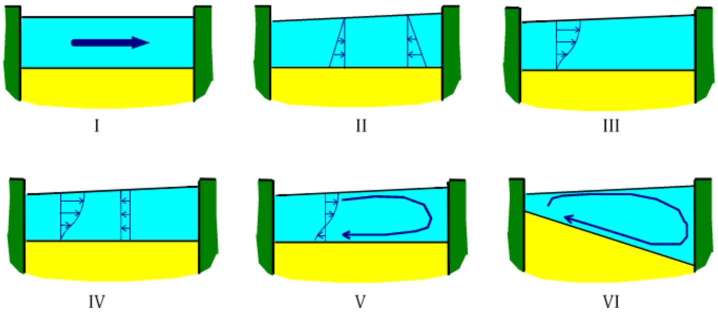


Figure 35: Transverse gradient river cross section (van Reen, 2002)

A.2.2 *Situation after solid layer*

After application of a solid layer–which consists of soil that is too heavy to be transported by the water flow or by the propeller jet of ships (Scholtens, 1996)–no erosion can occur in the area where this layer is applied. As stated by van Reen (2002), the application of a solid layer will reduce the hydraulic profile (Figure 36), which in turn will increase flow velocity.

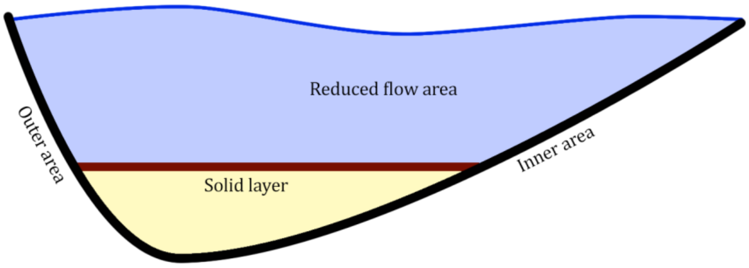


Figure 36: Hydraulic profile of the river with application of a solid layer

With the solid layer unable to erode, the inner area of the bend is subject to erosion. This is amplified by the fact that the roughness of the solid layer is greater than that of the natural bed level (Chezy values of ±30 $m^{0.5}/s$ and ±45 $m^{0.5}/s$ respectively as stated by Wolters, 1998)–causing a further increase in flow velocity and erosion in the inner area of the bend. At the end of the solid layer, the water flow in the outer area of the bend has a low concentration of sediment due to the lack of erodible soil. This means that downstream of the solid layer the bed level will start to erode, resulting in an erosion pit. On the other hand, as the water flowing in the inner area of the bend does transport sediment and the erosion pit draws water from the inner area, the resulting reduced speed in the inner bend causes sediment to be deposited in this area (van Reen, 2002) as seen in Figure 37.

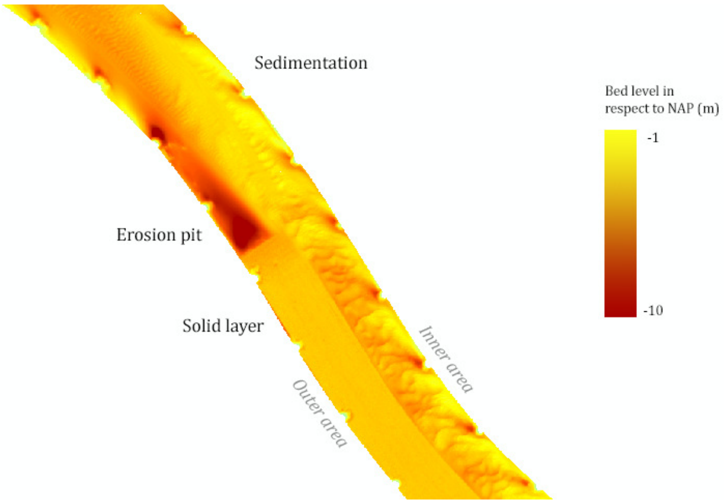
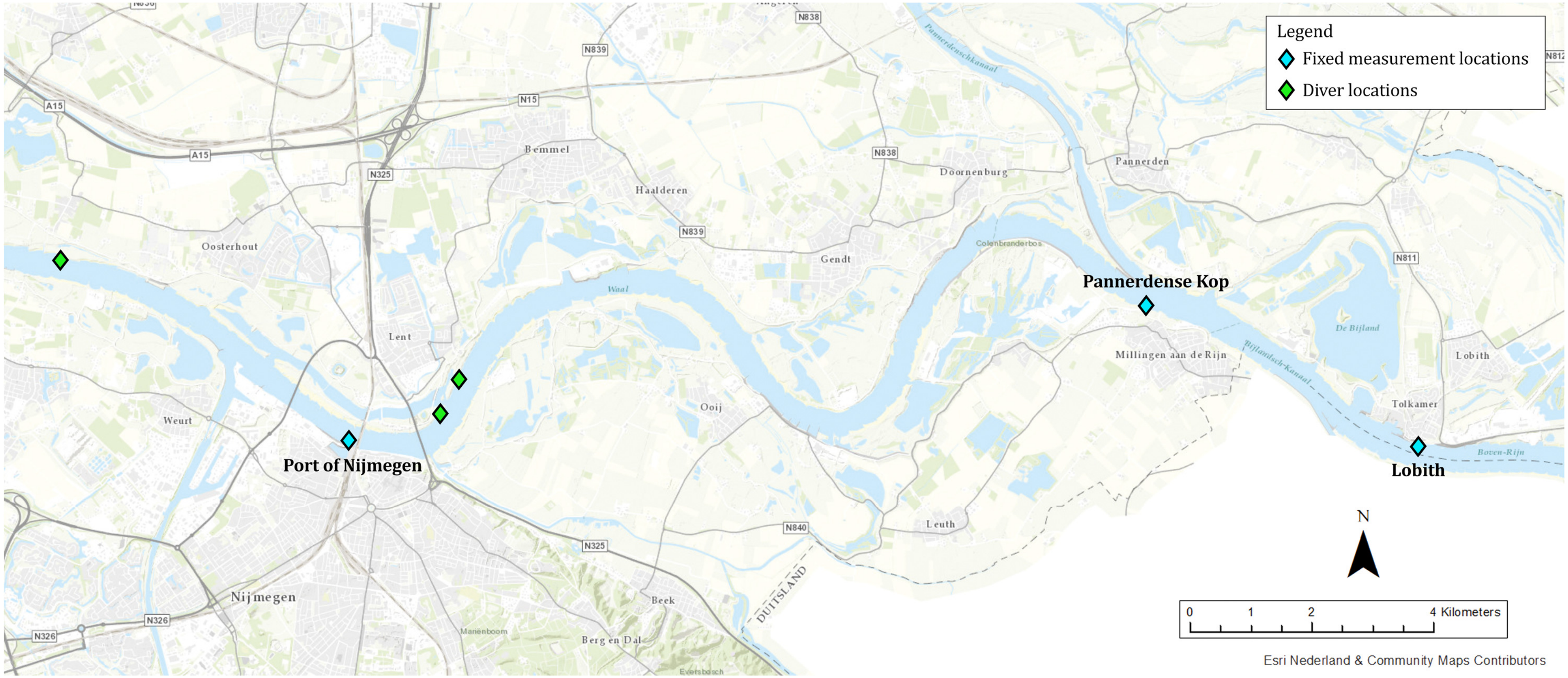


Figure 37: Erosion and sedimentation at solid layer near Sint Andries, GD (ESRI, 2017)

Appendix B Map of study area



Esri Nederland & Community Maps Contributors

Figure 38: Diver and fixed measurement locations in the area from Lobith to downstream of the outlet

Appendix C Calculation of the expected hydraulic changes

C.1 Discharge distribution at the Pannerdense Kop

To determine the discharges through the river Waal given discharges at Lobith, discharge distributions at the Pannerdense Kop are composed. These distributions are made using data obtained through ADCP measurements. To use these data for determining the discharge distribution at the Pannerdense Kop, same-day discharge measurements in the river Waal and river Rhine are compared. This has resulted in the distribution as shown in Figure 39, where the black line indicates the fitted polynomial line of degree n=2 and the red lines depict the discharge averages over -250 m^3/s to +250 m^3/s given a certain discharge Q (e.g. 1000 m^3/s, 2000 m^3/s).

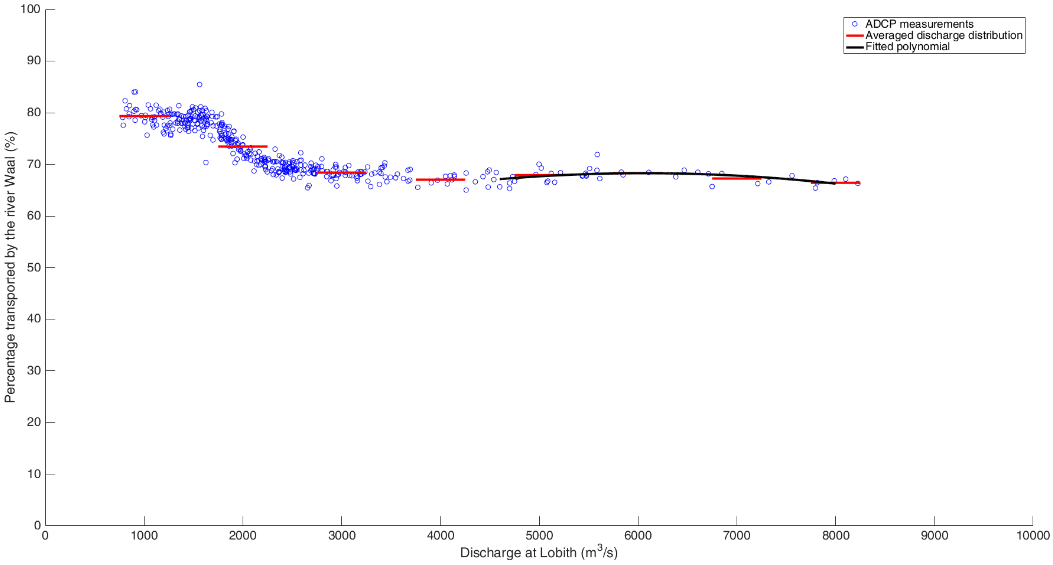


Figure 39: Discharge distribution the Pannerdense Kop

C.2 Width of the channel, slope of the river bed and Chezy coefficient

The width of the river Waal is roughly 260 meters at Nijmegen-Lent, excluding the distance between groynes and the river bank. The average bed slope of the river Waal is about 10,4 cm/km (=$1*10^{-4}$ m/m) (Berendsen, 1996). The Chezy coefficient differs, as the alluvial river bed has a Chezy coefficient of about 45 $m^{0.5}/s$ and the solid layer has a Chezy coefficient of about 30 $m^{0.5}/s$ during regular discharges (Wolters, 1998). Therefore, the actual value is expected to lie somewhere between these boundaries.

To get a better idea of the Chezy value in this section, Equation (1) can be rewritten in such a way that the Chezy coefficient is calculated:

$$C = \frac{Q_1}{h_0^{\frac{3}{2}} * w * \sqrt{i_b}} \qquad (6)$$

Where:
$Q_1 = Q_{Waal} = p*Q_{Lobith}$[1] m^3/s
$h_0 = h_{water\ level}$[2] $- z_{river\ bed}$[3]
$w = 260$ m
$i_b = 1*10^{-4}$ m/m

---

[1] Based on Figure 39, given Q_{Lobith} = 1000, 2000.. 6000

[2] Based on water surface curve data (nautical km 887) of Rijkswaterstaat

[3] Based on averaged yearly bed level measurements (nautical km 887) of Rijkswaterstaat

Completing Equation 6 results in Chezy coefficients of approximately 42,5 to 54,5 $m^{0.5}/s$ for discharges of 1000 to 6000 m^3/s at Lobith. As the Chezy coefficient differs significantly with varying discharges, it is beneficial to use different Chezy coefficients when determining the water level change at varying discharges. Therefore, a line is fitted through these data points. Using this fitted line, Chezy coefficients corresponding to discharges outside of the fixed discharge classes can be interpolated (e.g. 5045 m^3/s at Lobith).

C.3 Discharge distribution at the bifurcation

As stated by Jong, Paarlberg, & Barneveld (2010), the barrier that seperates the side channel from the main channel will flow over when discharges at Lobith exceed 4600 m^3/s. The following characteristics of the impact of the side channel are known, which are based on Jong, Paarlberg, & Barneveld (2010) unless stated otherwise. Note: calculations were made using both WAQUA and Delft3D, which gave different results. Data are based on WAQUA calculations, unless stated otherwise.

Table 10: Impact of the side channel as determined by Jong, Paarlberg, & Barneveld (2010)

Discharge [m^3/s]			**Consistency river Waal discharges [%]**	**Side channel [%]**	**Water level decrease [cm]**
Lobith	Waal[1]	Waal[2]			
1000	-	795	-	1,0	-
2000	1460	1470	99	1,5	1
4000	2820	2680	95	1,5	1
4600	-	3095	-	1,5	-
6000	4200	4100	98	20	1
6843	4516	4650	97	24 29 (Delft3D)	<22[3] 22 (Delft3D)
8000	5500	-	-	26	-
10000	6585	-	-	29	-
16000	10140 10165 (Delft3D)	-	-	36	37 (Delft3D)

[1] Based on Jong, Paarlberg, & Barneveld (2010) | [2] Based on the discharge distribution at the Pannerdense Kop (Figure 39)

[3] Assumption based on side channel distributions of WAQUA and Delft3D and water level decrease of Delft 3D

No river Waal discharge was given for 4600-5999 m^3/s at Lobith by Jong, Paarlberg, & Barneveld (2010). To still be able to make statements about the discharge through the side channel in this discharge range, Figure 39 was used to determine the discharge through the river Waal given Q_{Lobith} = 4600 m^3/s.

This was then used to make statements about the discharge through the side channel during discharges of 4600-5999 m^3/s at Lobith, as the extraction levels were known. For discharges of 6000-16.000 m^3/s at Lobith, modelled discharges of Jong, Paarlberg, & Barneveld (2010) were used, along with their fitted line. This has resulted in Figure 40, which can be used to make predictions about discharges that were not modelled in WAQUA or Delft3D.

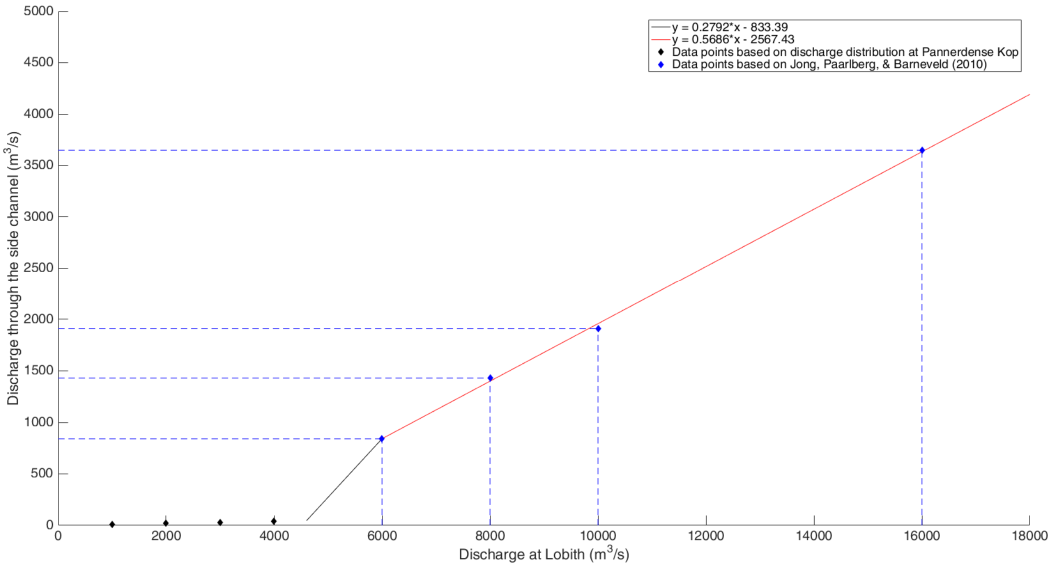


Figure 40: Modelled discharges through the side channel given discharges at Lobith

C.4 Sensitivity analysis

To determine the sensitivity of the expected water level decrease to the used parameters, a sensitivity analysis is performed. This will be done for the parameters b, i_b and the Chezy coefficient. The water level decreases at the inlet will be calculated given a discharge of 6000 m^3/s at Lobith. This will be done for varying values of the abovementioned parameters.

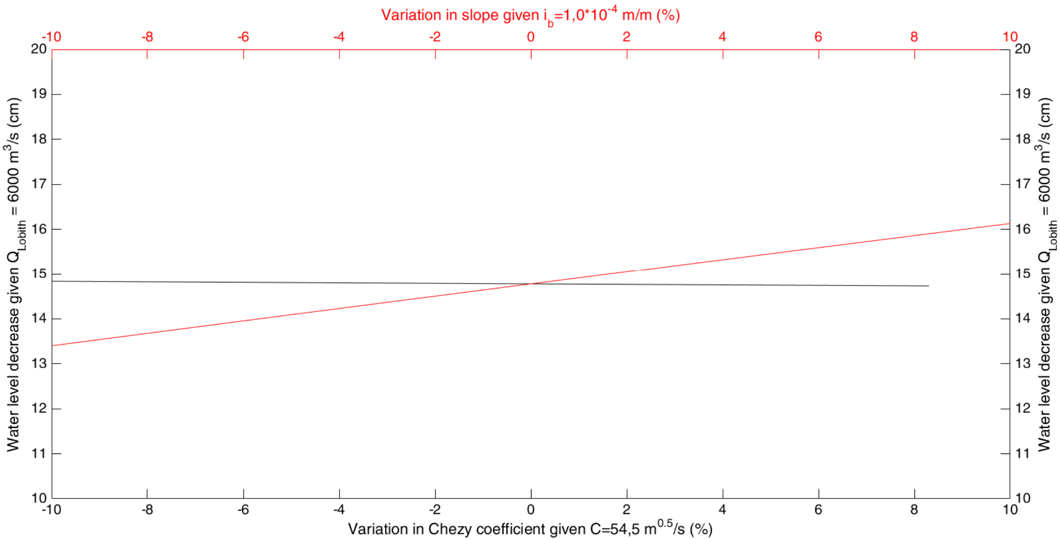


Figure 41: Sensitivity of the slope vs the Chezy coefficient given Q_{Lobith} = 6000 m^3/s

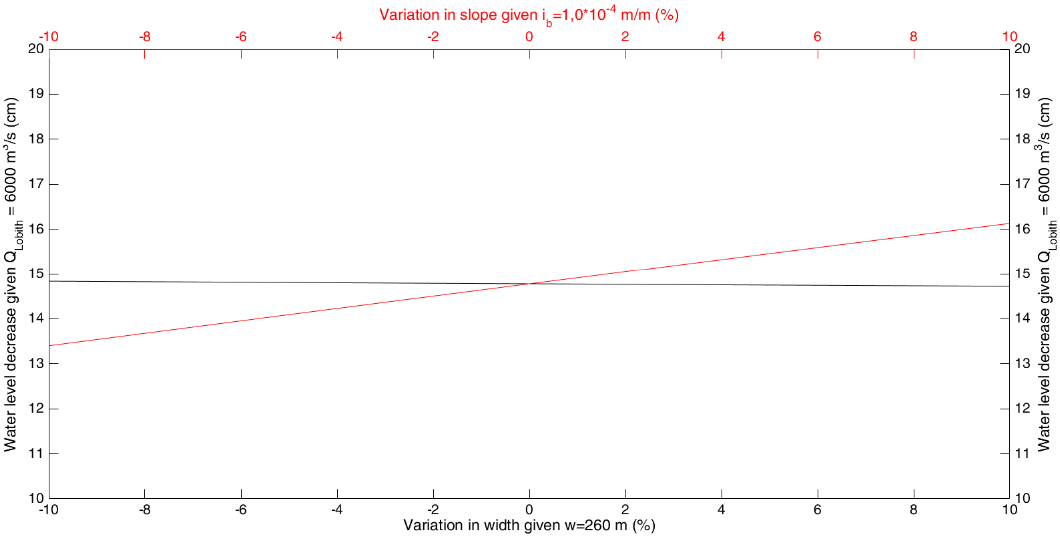


Figure 42: Sensitivity of the slope vs the width of the main channel given Q_{Lobith} = 6000 m^3/s

Though it is clear that fluctuations in river bed slope affect the expected water level decrease significantly more than variations in the Chezy coefficient or width of the main channel, it is decided no further improvement of the accuracy of the slope is done. Mainly due to the fact that the value for the river bed slope is already quite accurate (refer to trend in Figure 14) and as these are expected changes, the acquired results will serve merely as reference for the scale of changes that can be expected.

Appendix D Additional morphological changes

D.1 Solid layer

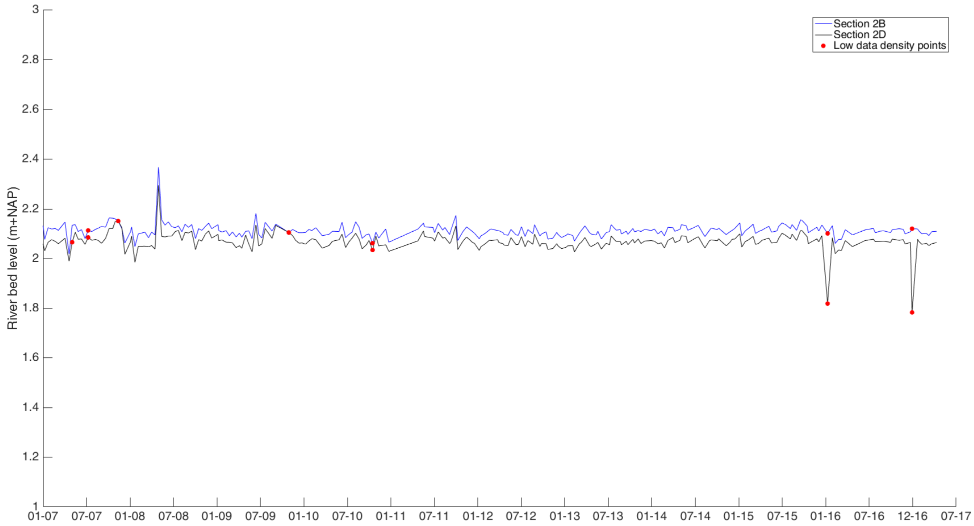


Figure 43: Changes in average bed level over time – subsections 2B, 2D

As seen in Figure 43, the solid layer constructed in this area has the expected effect. Only small variations in the bed level occur, with few outliers–of which most are probably due to low data density.

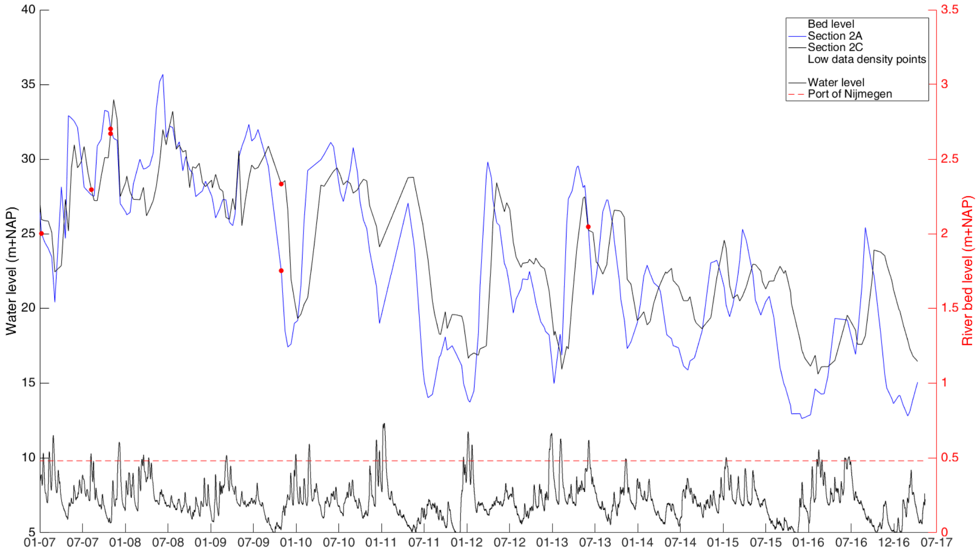


Figure 44: Changes in average bed level over time – subsections 2A, 2C

When evaluating subsections 2A and 2C, a couple of things can be seen. Firstly, the bed level fluctuates significantly as no solid layer is present in this area, though this is also caused by smaller subsection areas. Secondly, subsection 2C appears to follow subsection 2A quite closely with a delay of a couple of months. Given that the subsections are 200 meters in length, the delay of a couple of months roughly matches the one kilometre per year river bed migration speed as stated by Jong, Paarlberg, & Barneveld (2010).

As seen in Figure 44, sedimentation of the sections next to the solid layer seems to follow high discharge periods. When studying the original bed level measurements, sediment seems to build up near the bridge (most likely near the column) (Figure 45: right side). This sediment build-up is then slowly transported parallel to the solid layer, where it slowly spreads and dampens.

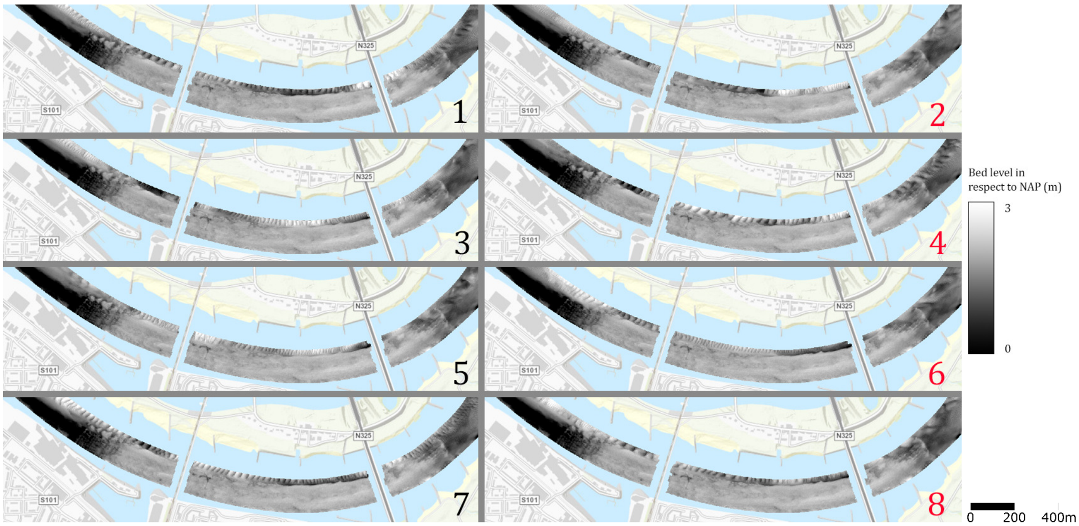


Figure 45: Evolution of the sediment build-up over time

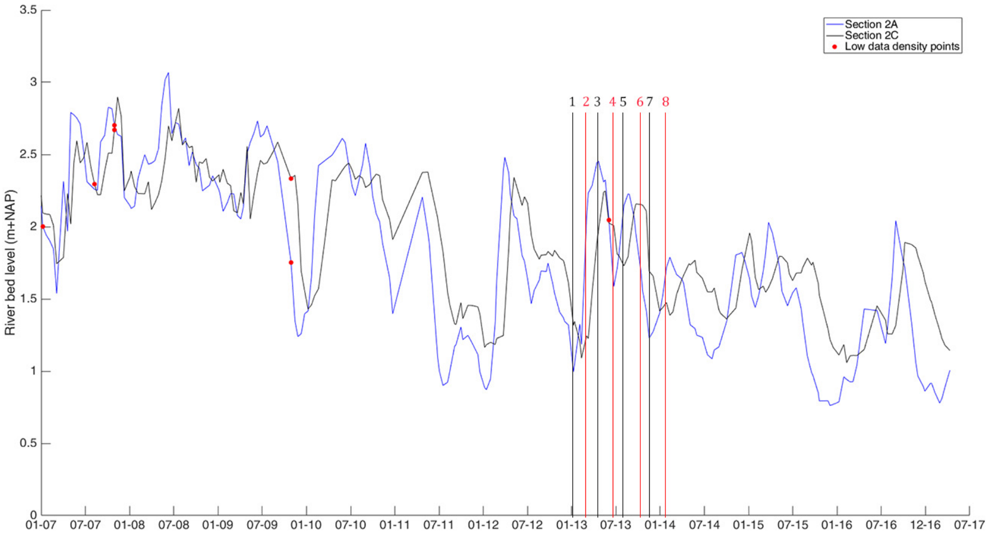


Figure 46: Used timepoints (distinction between black and red lines for the purpose of clarity)

D.2 Long term effects

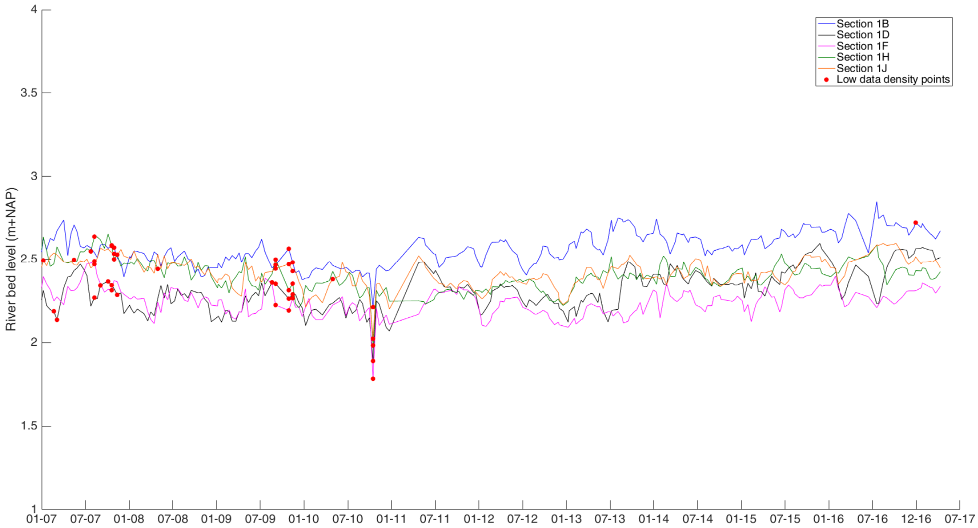


Figure 47: Changes in average bed level over time - subsections 1B, 1D, 1F, 1H, 1J

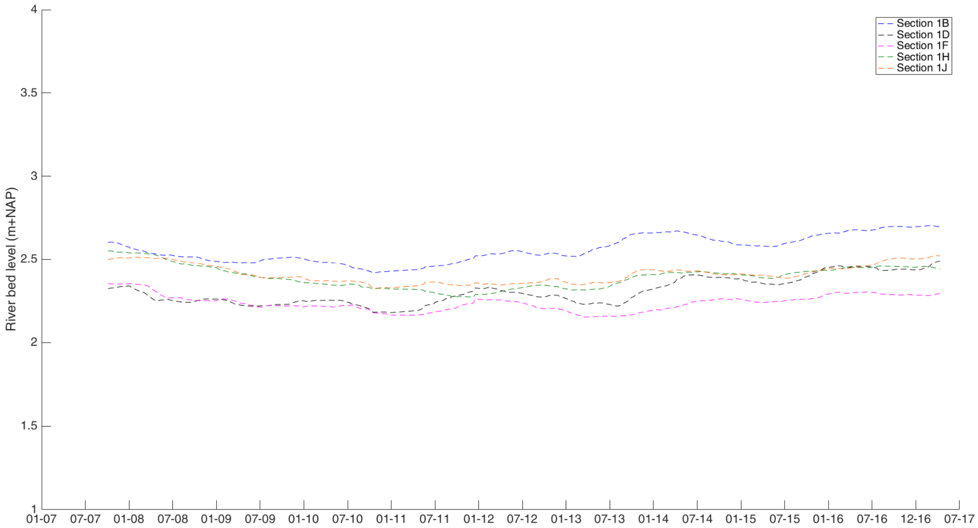


Figure 48: Moving average per subsection (20 data points)

In Figure 47 and Figure 48 the changes in bed level for subsections upstream of the inlet are shown. In these sections long term effects, if they had developed, would be visible. Since Figure 47 shows significant fluctuations and the different sections overlap quite often, Figure 48 shows the moving average over 20 data points. This will give a clearer picture of both the individual subsections and trends that occur per subsection. Till 2012, the sections seem to follow a slight downward pattern. However, after 2012 the trend seems to be that of sedimentation, where the bed level slowly increases. No significant changes, which can be associated with the Room for the Waal project, are visible though.

D.3 Left side of the river Waal

Though it is not expected that changes of the same scale will occur on the left side of the main channel, it is important to analyse these sections as well.

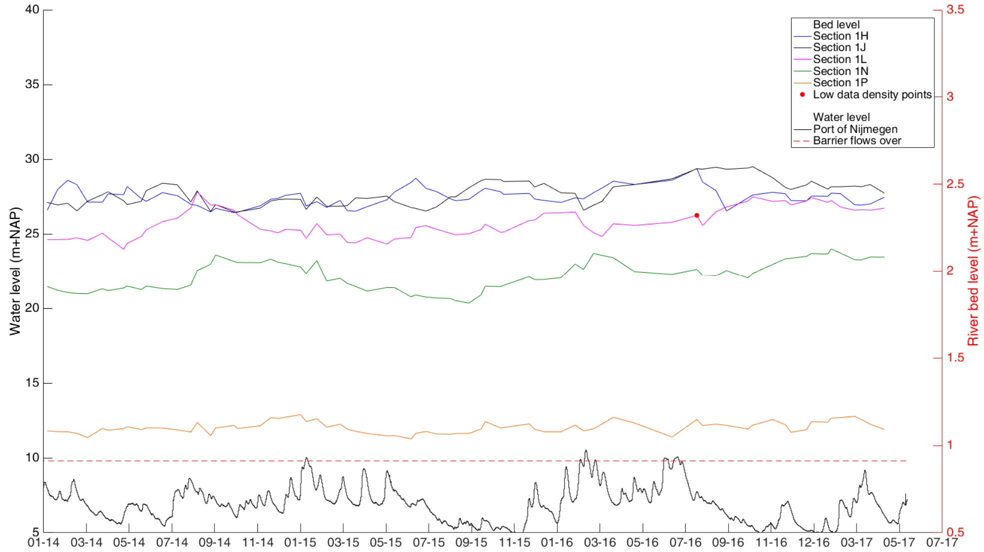


Figure 49: Changes in average bed level over time - subsections 1H, 1J, 1L, 1N, 1P

Though sedimentation does seem to occur parallel with the high discharge period in early 2016, it happens both upstream and downstream of the inlet. This would imply that the sediment build-up is not caused by the inlet but by build-ups further upstream. Another interesting thing to note is the large bed level difference between sections 1H, 1J, 1L, 1N and 1P. As can be seen in Figure 26, it is also clearly visible in the original bed level measurements. This can most likely be attributed to the fact that this section is near the transition of the previous bend, which roughly runs from nautical km 876 to 882.

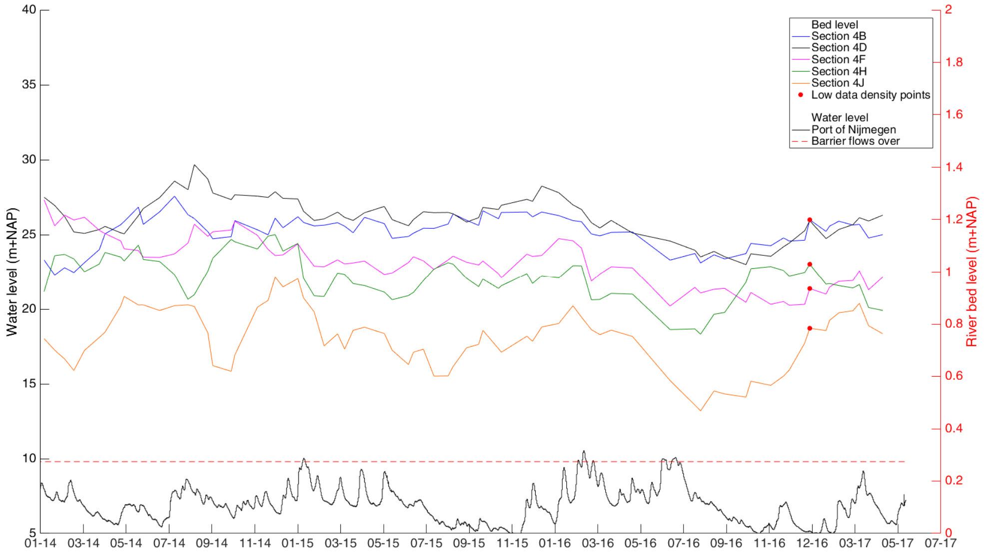


Figure 50: Changes in average bed level over time - subsections 4B, 4D, 4F, 4H, 4J

As with Figure 49, Figure 50 shows some erosion during the high discharge wave of early 2016. However, this is visible in all the sections and not exclusively in the section at or downstream of the inlet. During the high discharge wave of late 2016, a sedimentation build-up occurs in sections 4B and 4F, while it is not visible in sections 4D, 4H and 4J.

As it is possible this build-up is averaged out by the sections in the first grid, sections of the second grid are also analysed.

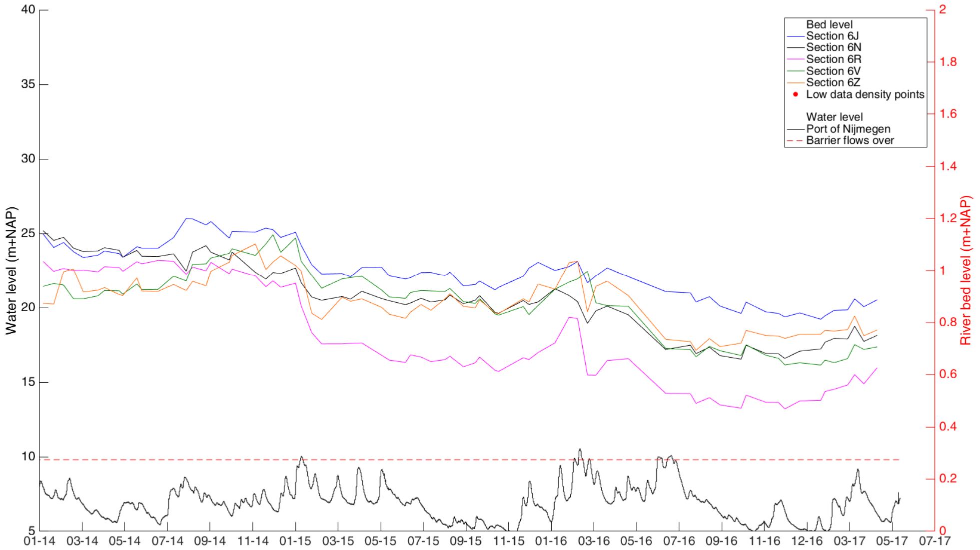


Figure 51: Changes in average bed level over time - subsections 6J, 6N, 6R, 6V, 6Z

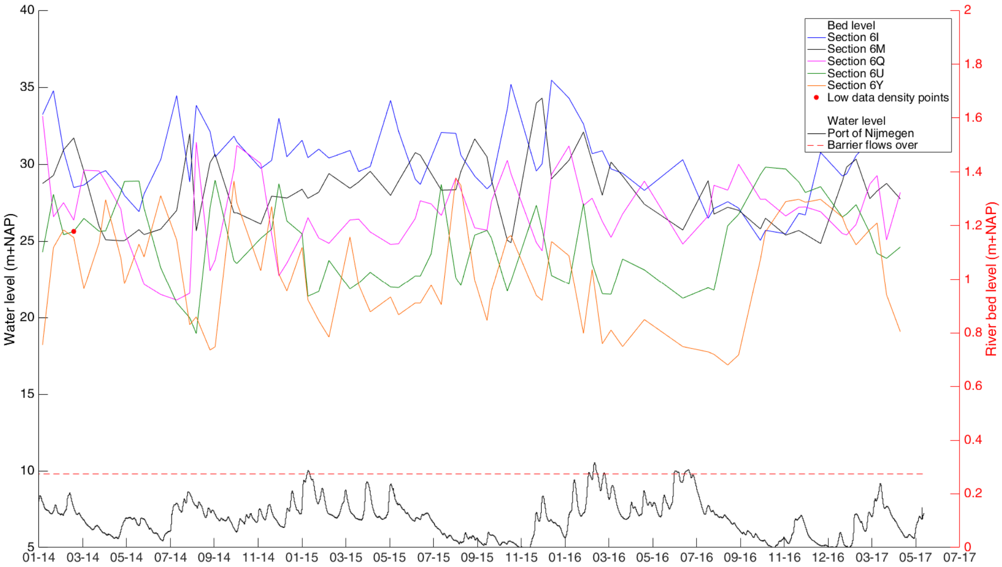


Figure 52: Changes in average bed level over time – subsections 6I, 6M, 6Q, 6U, 6Y

Neither in Figure 51 nor in Figure 52 changes are visible that are exclusively visible at or downstream of the outlet. Though some sedimentation does seem to occur in late 2016 in sections 6M and 6Q, a sediment build-up is also visible in 6I, albeit much earlier. Therefore, no significant changes on the right side of the main channel can be said to have been caused by the Room for the Waal project.

Appendix E Groyne reduction planning

Table 11: Phased groyne reduction planning

Stage	Location[1]	Number of groynes[2]	Combination with longitudinal dam[2]
1	Nijmegen – Winssen	70	-
2	Nijmegen – Tiel	120	-
3	Tiel – Gorinchem Wamel – Ophemert	350 250	- X
4	Completion water safety projects		

[1] Based on Rijkswaterstaat (2015a) | [2] Based on Rijkswaterstaat (2011)

Figure 53: Phased planning water safety program (Rijkswaterstaat, 2015a)

Appendix F High discharge periods per year

Table 12: High discharge periods per year

Year	No. of periods exceeding 4600 m^3/s at Lobith	Timespan	No. of days[1]	Maximum discharge in timespan	Accurate fit in range 4650 – 5200 m^3/s at Lobith
2007	2	22/01/2007-10/03/2007	13	6174	+
		14/08/2007	1	4618	-
2008	1	09/12/2007-16/12/2007	8	5526	+
2009	0				-
2010	2	03/01/2010-04/01/2010	1	4649	-
		28/02/2010-05/03/2010	6	5518	+
2011	1	11/12/2010-23/01/2011	24	8388	+
2012	1	05/01/2012-28/01/2012	16	6750	+
2013	2	19/12/2012-12/02/2013	27	6746	+
		03/06/2013-11/06/2013	9	6041	+
2014	0				-
2015	1	14/01/2015	1	4601	-
2016	2	11/02/2016-15/02/2016	5	5253	+
		02/06/2016-23/06/2016	10	4741	-
2017	0				-

[1] May differ from the timespan, as not all days within the timespan will have discharges exceeding 4600 m^3/s at Lobith

Appendix G Qh-relations comparison pre and post Room for the Waal

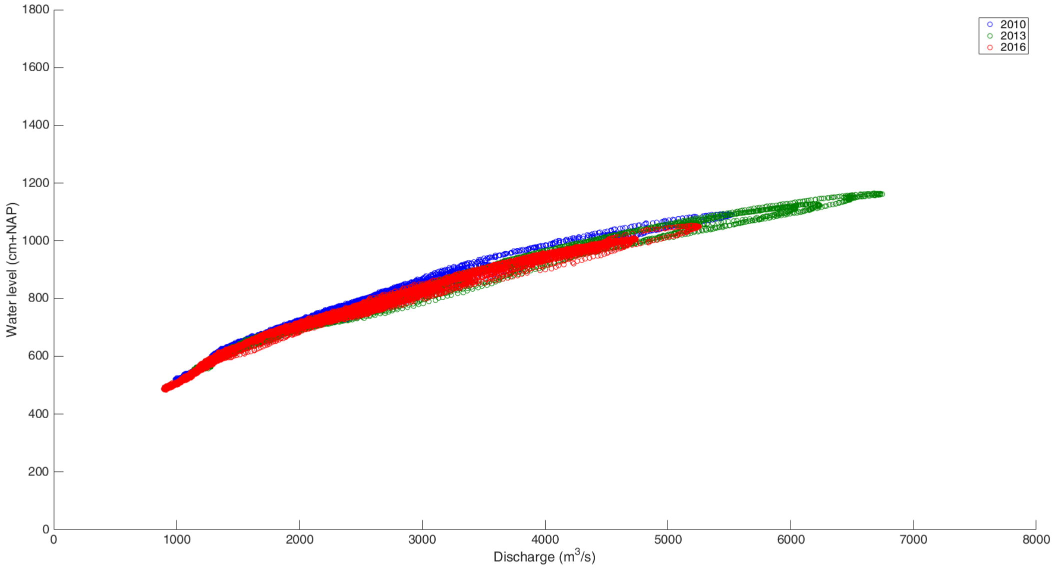


Figure 54: Hourly water levels at the Port of Nijmegen and discharges at Lobith for the years 2010, 2013 and 2016

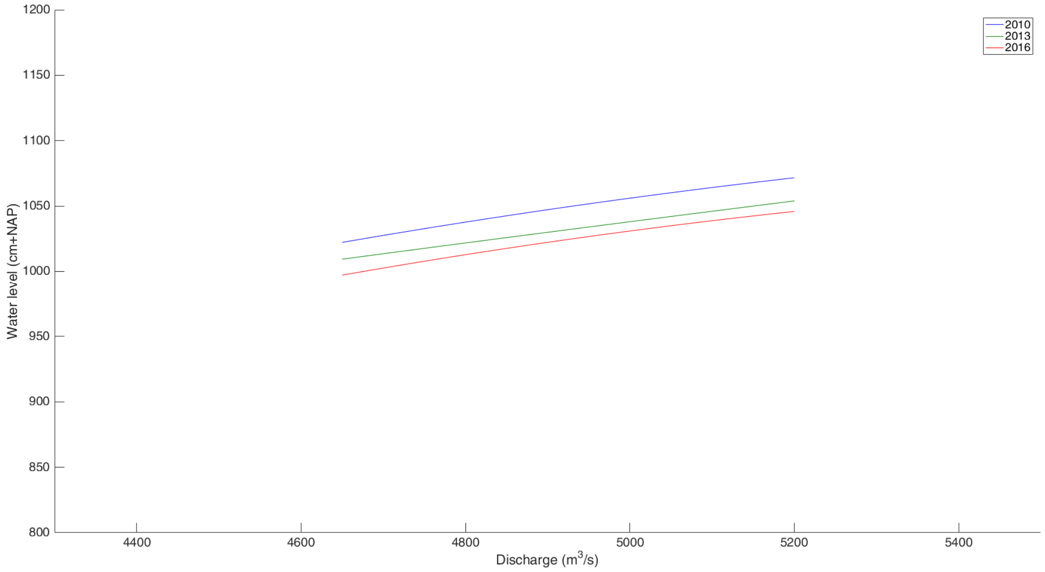


Figure 55: Fitted lines for water levels at the Port of Nijmegen and discharges at Lobith for discharges exceeding 4600 m^3/s at Lobith. Only years 2010, 2013 and 2016 are plotted.

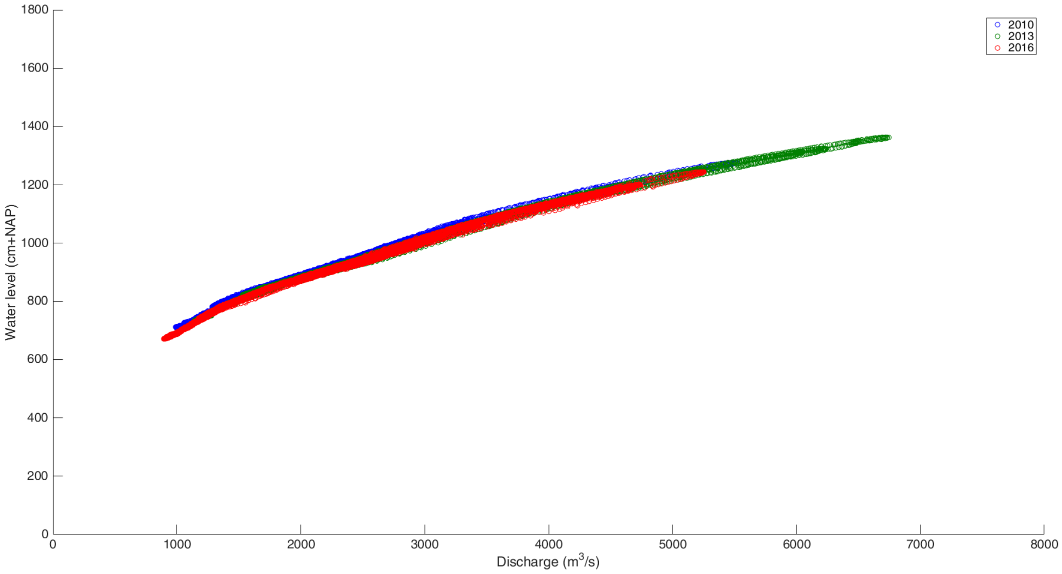


Figure 56: Hourly water levels at the Pannerdense Kop and discharges at Lobith for the years 2010, 2013 and 2016

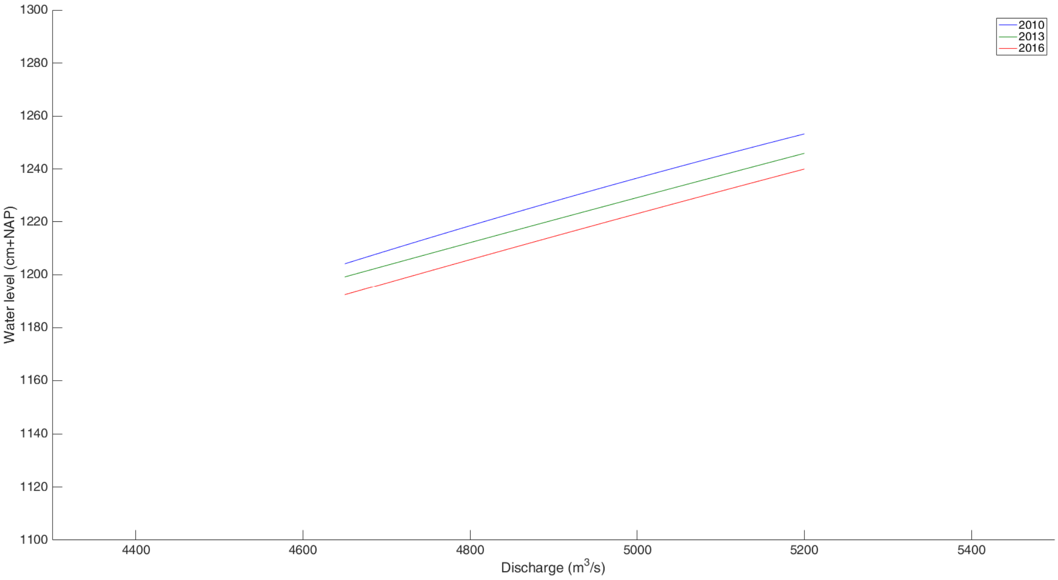


Figure 57: Fitted lines for water levels at the Pannerdense Kop and discharges at Lobith for discharges exceeding 4600 m^3/s at Lobith. Only years 2010, 2013 and 2016 are plotted