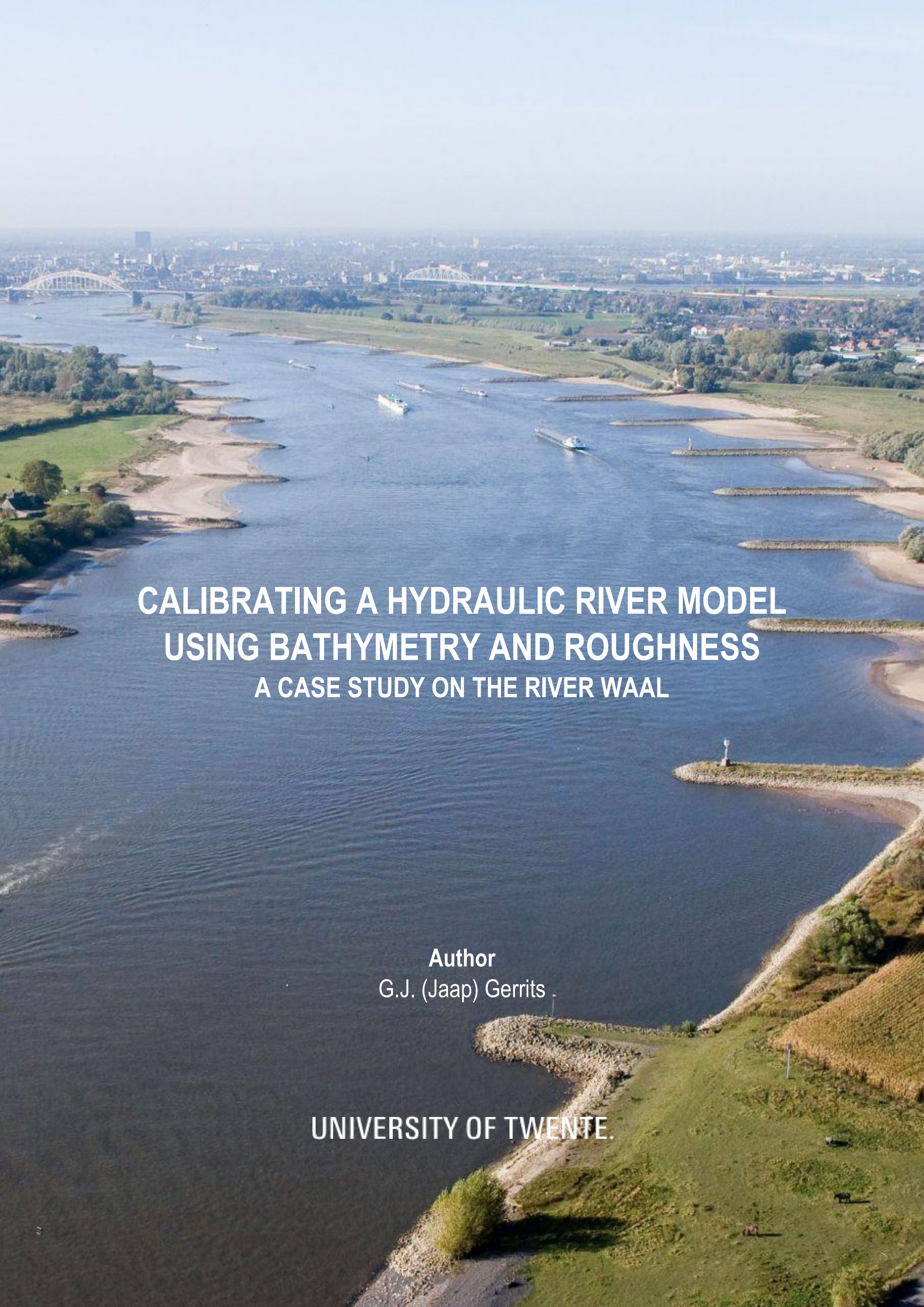

CALIBRATING A HYDRAULIC RIVER MODEL USING BATHYMETRY AND ROUGHNESS

A CASE STUDY ON THE RIVER WAAL

Author
G.J. (Jaap) Gerrits

UNIVERSITY OF TWENTE.

Calibrating a hydraulic river model using bathymetry and roughness: A case study on the River Waal

Master Thesis

June 2023

Author:
G.J. (Jaap) Gerrits

Supervised by:
P. Khorsandi Kuhanestani — University of Twente
Dr.ir. A. Bomers — Department of Civil Engineering & Management
Dr.ir. M.J. Booij — Research group Water Engineering and Management

Photo cover page: Joop van Houdt, Rijkswaterstaat

PREFACE

In front of you lies the thesis I wrote as the final part of the Master programme Civil Engineering and Management at the University of Twente. I wrote this thesis during my internal graduation from December 2022 till June 2023.

When I was deciding what kind of master thesis I would want to do I was looking for a thesis subject that was more applied instead of fully theoretical. Having done my bachelor at a university of applied sciences, I knew that a more practical thesis subject would suit me better. Of course, it would still be academic, but I would be pleased if I could use modelling software and models instead of building them from the ground up or programming them myself. The subject covered in this thesis fulfilled my demands perfectly, and I am very satisfied with the choice that I have made.

I am grateful towards all the people who have contributed to this report. I would like to start by thanking Parisa Khorsandi Kuhanestani, my daily supervisor from the University of Twente, for guiding me trough the process when necessary, giving input on the work that I did, and providing me with her expertise. I would also like to thank Anouk Bomers, my second supervisor from the University of Twente, for guiding me in the right direction at the start of the thesis, giving input on the work that I did, and also proving me with her expertise. I would also like to thank Martijn Booij from the University of Twente for overseeing my project, providing valuable feedback based on his expertise, and filling in the role of Anouk Bomers when she was unavailable in the second half of my thesis.

Furthermore, I would like to thank Matthijs Gensen from HKV for helping me with the modelling software SOBEK when I was unable to figure things out on my own. He provided me with ways to set up the model that I could not have known without his input. Even if things would eventually work out differently his input has been very valuable.

I hope you enjoy reading my thesis.

Jaap Gerrits
Rijssen, June 2023

SUMMARY

Rivers play an important role in shaping the earth's landscape and serve as a crucial resource for various human activities. However, rivers can also be the cause of flooding, which can be very dangerous for humans and other species living near the rivers. It is therefore important to accurately predict the behaviour of a river. This can be achieved by using hydraulic river models, which are valuable tools used to simulate and predict flow patterns, water levels, and sediment transport in river systems. To make the predictions of these models as accurate as possible they are calibrated by adjusting one or more model parameters.

The roughness of the river bed is commonly used as a calibration parameter for hydraulic river models because it is one of the main sources of uncertainty. An alternative to the roughness that is not used as often as a calibration parameter is bathymetry. The roughness and the bathymetry have the largest impact on predicting inundation and flow characteristics. However, the number of studies that include bathymetry in the calibration process is limited. It would therefore be interesting to investigate the use of bathymetry as a calibration parameter in a hydraulic river model. The bathymetry can then be compared to the roughness based on the effect it has on the water level, and the accuracy of the calibration when used as a calibration parameter.

The objective of this master thesis is to determine and compare the effect of the roughness and the bathymetry as calibration parameters on the accuracy of simulated water levels in a hydraulic river model. The study area that is used is the river Waal from the observation station Pannerdense kop to the observation station Hardinxveld.

To accomplish the objective a sensitivity analysis has been performed to compare the effect of the roughness and the bathymetry on the water level. Thereafter both parameters are used as calibration parameters to simulate the water level for the discharge wave of 1995. The calibrated models are subsequently validated using the 1993 and 2011 discharge waves. The accuracy in the calibration and validation is determined using the Root Mean Square Error (RMSE). This is all done using the modelling software SOBEK.

The most important result of the sensitivity analysis was that the roughness had a larger effect on the water level than the bathymetry for the chosen roughness value range and bathymetry height range. The bathymetry showed a linear and the roughness a slightly nonlinear relationship to the water level. The calibration resulted mainly in increases in the roughness values and the bathymetry height. The validation yielded comparable average RMSE values for the roughness and the bathymetry. The bathymetry showed slightly higher RMSE values on average, but these differences were not significant enough to deem the bathymetry less accurate as a calibration parameter than the roughness.

Overall, the results of this research show that the influence of the roughness on the water level is larger than the bathymetry. However, the accuracy of the roughness and bathymetry is comparable when using them as calibration parameters for a hydraulic river model. It is recommended to do further research into the effect of bathymetry as a calibration parameter on both the water level and the accuracy of the calibration. This can be performed for a different study area, using a different modelling approach, or for lower discharges. It is also recommended to do further research into the influence that the shape of a cross-section has on the effect of the bathymetry on the water level.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 BACKGROUND

Rivers play an important role in shaping the earth's landscape and serve as a crucial resource for various human activities. The Netherlands especially is shaped by rivers because it is a delta region. Flooding of rivers internationally costs many lives and causes large economic damage every year (Merz et al., 2021). It is therefore important to accurately predict the behaviour of a river, especially in a delta region that consists of many rivers. Understanding and accurately modelling river hydraulics is essential for effective river management, flood risk assessment, and ecosystem preservation.

Hydraulic river models are valuable tools used to simulate and predict flow patterns, water levels, and sediment transport in river systems. Inaccurate models could wrongly predict river behaviour, possibly leading to incorrect policies and management. This could indirectly cause flooding, limit the navigability of the river, or damage ecosystems that rely on the river. It is important to accurately model the river behaviour in a hydraulic river model because of these implications. Hydraulic river models contain uncertainties regarding the model outcome. These uncertainties can be a result of imperfect knowledge about physical processes and uncertainties in initial and boundary conditions (Khanarmuei et al., 2019; Warmink et al., 2010). Moreover, some physical processes are impractical to model, so this introduces more uncertainties.

To reduce the effect of these uncertainties hydraulic river models are calibrated. This is done to make sure that they are as accurate as possible for one or sometimes more model outcomes. In the case of flooding, the water level during high flows is the most important outcome to model accurately. Many parameters can be used to perform the calibration by adjusting the parameter value until the simulated outcome matches the observed outcome, but some parameters are more effective than others to reach this goal.

The roughness of the river bed is commonly used as a calibration parameter (Warmink et al., 2007) because it is one of the main sources of uncertainty in hydraulic models (Chang et al., 1993; Hall et al., 2005; Pappenberger et al., 2005; Warmink et al., 2011). There are various ways to describe the roughness of the main channel of rivers. Coefficients and formulae commonly used in open channels (such as rivers) are Chézy, Darcy-Weisbach, and Manning (Huthoff & Augustijn, 2005). Many calibration studies for hydraulic models have focused on roughness (Wood et al., 2016). It is considered the main parameter to be used for the calibration (Khanarmuei et al., 2019). Since the main channel roughness is much more uncertain than the floodplains, the main channel roughness is often used for calibration (Chang et al., 1993; van der Klis, 2003).

An alternative to the roughness that is not used as often as a calibration parameter is the bathymetry. The roughness and the bathymetry have the largest impact on predicting inundation and flow characteristics (Aronica et al., 1998; Hankin & Beven, 1998; Hardy et al., 1999; Rameshwaran & Willetts, 1999). However, the number of studies that include bathymetry in the calibration process is limited (Khanarmuei et al., 2019). It has been shown that when bathymetry is used as a calibration parameter, the performance of the model can be improved (Cea & French, 2012; Wang et al., 2009).

An alternative calibration method that has been proposed by Cea & French (2012) and Khanarmuei et al. (2019) shows that the roughness could be kept within a physically realistic range when the river bathymetry is used as an additional calibration parameter. However, this has only been tested for an estuarine region. The question that arises is if the same calibration method would work for a hydraulic river model.

1.2 RESEARCH GAPS

The applicability of bathymetry for the calibration of hydraulic river models is currently not well known in the literature. Using the bathymetry for the calibration of a hydraulic model has been tested for an estuarine region, but not for a river. Jiang et al. (2021) and Neal et al. (2015) combined the roughness and bathymetry into one parameter and used that parameter to perform the calibration, but this created a model that is more like a black box. The exact values of the roughness and bathymetry are not known using this method. This limits the insight into the contribution of both parameters to the calibration, and the effect both parameters have on the water level.

It would therefore be interesting to do research into the use of roughness and bathymetry as separate parameters for the calibration of hydraulic river models. Comparisons can then be made between the roughness and bathymetry regarding the effect they have on the water level, and the accuracy that can be achieved when using them as calibration parameters. The roughness is a good reference point for bathymetry since it has been used widely for the calibration of hydraulic river models.

1.3 OBJECTIVE AND RESEARCH QUESTIONS

The main objective of this master thesis is as follows: Determine and compare the effect of roughness and bathymetry as calibration parameters on the accuracy of simulated water levels in a hydraulic river model.

To reach this objective, five research questions have been defined:

Answering the first question gives insight into the influence of the roughness and bathymetry on the water level:

1. What is the influence of the roughness and bathymetry on the water level in a hydraulic river model?

Answering the second question obtains a reference point for the accuracy of the simulated water level:

2. What is the accuracy of the simulated water level in a hydraulic river model when using roughness as the calibration parameter?

Answering the third question gives insight into the accuracy of the simulated water level when the bathymetry is used as the calibration parameter:

3. What is the accuracy of the simulated water level in a hydraulic river model when using bathymetry as the calibration parameter?

Answering the fourth question gives insight into the accuracy when the main channel roughness is used for calibration. This is interesting since the main channel roughness is frequently used as a calibration parameter:

4. What is the accuracy of the simulated water level in a hydraulic river model when calibrating the model using the main channel roughness as the calibration parameter?

Answering the fifth and last question gives insight into the accuracy of the bathymetry compared to the roughness and main channel roughness when these parameters are used for calibration:

5. How does the accuracy of the simulated water level in the hydraulic river model compare using the roughness, main channel roughness, and bathymetry as calibration parameters?

The accuracy of the simulated water level is determined by comparing the simulated water level with the observed water level after validating the model. How this is done is explained in section 2.3.2.

1.4 OUTLINE

Chapter 2 describes the study area, the material, and the method that is used in this research. Chapter 3 describes the results of this study concerning the effect of the roughness and bathymetry on the water level and the use of these parameters for calibration. Chapter 4 discusses the limitations, potential, and generalizations of these findings. Finally, chapter 5 presents conclusions based on the results and the discussion, and provides recommendations for further research.

2 MATERIAL AND METHOD

2.1 STUDY AREA

The study area is the river Waal, which is the main branch of the river Rhine. The river Waal is important for the Netherlands because it is one of the main transportation routes for the harbour of Rotterdam to serve countries inland like Germany. It is also a freshwater source and a complex ecological system. Since it is such an important river for the Netherlands accurate calibration of the water level is important. Another reason that this study area is chosen is that the data necessary for this research is available for the Waal.

The study area ranges from observation station Pannerdense kop to observation station Hardinxveld, see Figure 1. This area is long enough (94 km) to ensure that the influence of backwater curves is negligible (de Vriend, 2015). Backwater curves are changes in the water level caused by a change in the river profile. This change could (among others) be an obstruction, change in depth, or change in roughness. These backwater curves influence the water level upstream from that change. The length of backwater curves depends on many factors such as the slope of the river, the roughness, and the discharge. Based on the effects of mining in the downstream part of the Waal the backwater curve extended approximately 20 km upstream (de Vriend, 2015). Since mining is a significant disruption in the river, it is assumed that the backwater curves for the uses of this research will be smaller than 20 km.

The length of the study area also reduces the influence of the downstream boundary condition on the simulated water level. However, it is still short enough to make sure that the computational time does not become too long.

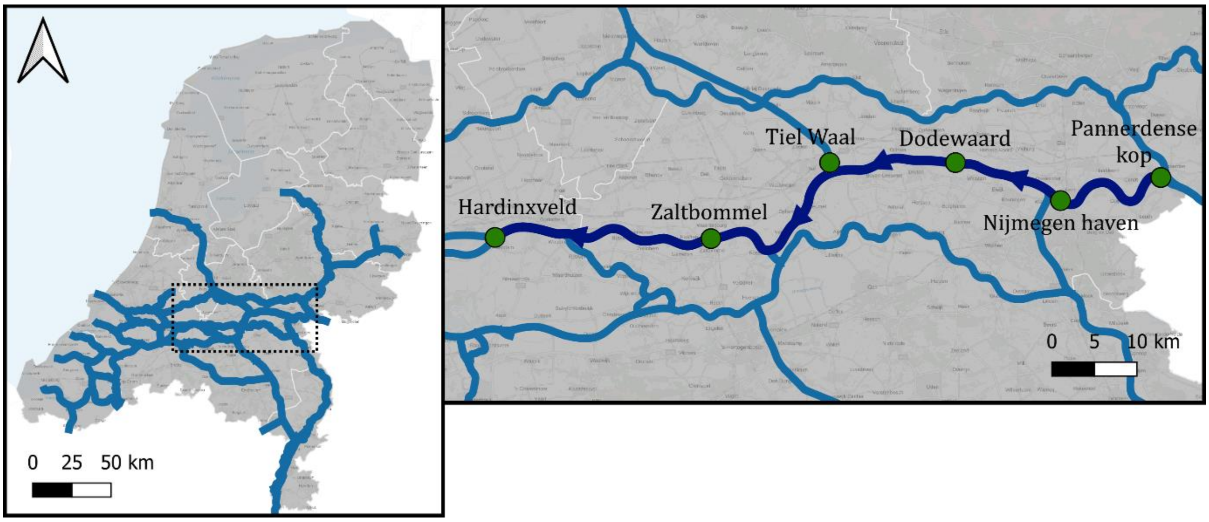

Figure 1: Map of the study area. The river Waal is shown in dark blue, the arrows indicate the flow direction. The green dots represent the observation stations (Rijkswaterstaat, 2021).

2.2 MATERIAL

To answer the research questions historic river discharges in the Waal are simulated. This is done by using discharge waves of specific years and matching them with the schematization of the Waal of the same year. Combining the discharge wave with the schematization in this way makes sure that the bathymetry conditions are close to the conditions that were present during the discharge event.

Inaccurate predictions of high water levels and flooding are indirectly one of the more immediate dangers to humans. Inaccurate predictions might cause false alarms or misses during flood events, which can lead to evacuation or no evacuation of people at the wrong times. It could also lead to inaccurate policies or management in the long term. Therefore the accurate modelling of high water levels is the main interest of this research. The discharge waves that are going to be used are those from 1993, 1995, and 2011, see Figures 2 to 4. All discharge waves have high peak discharges compared to the other years in the past 30 years (between 5500 m^3/s and 7600 m^3/s). Table 1 shows the combinations of discharge wave years and schematization years that are going to be used.

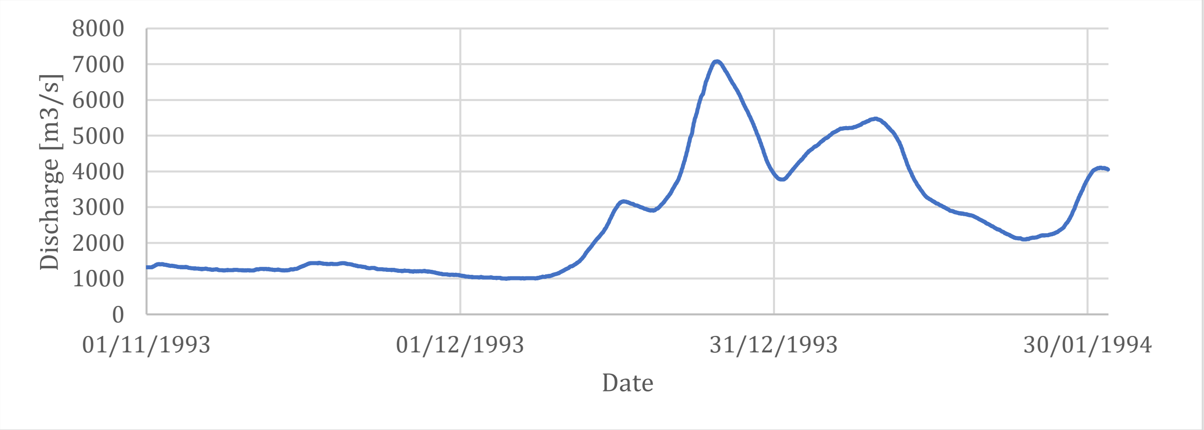

Figure 2: 1993 discharge wave at Pannerdense kop (Rijkswaterstaat, 2016).

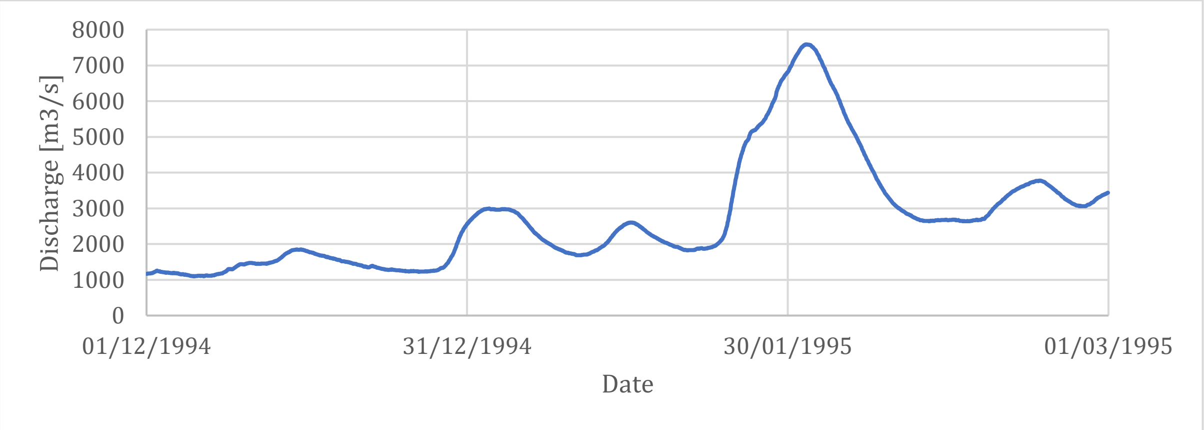

Figure 3: 1995 discharge wave at Pannerdense kop (Rijkswaterstaat, 2016).

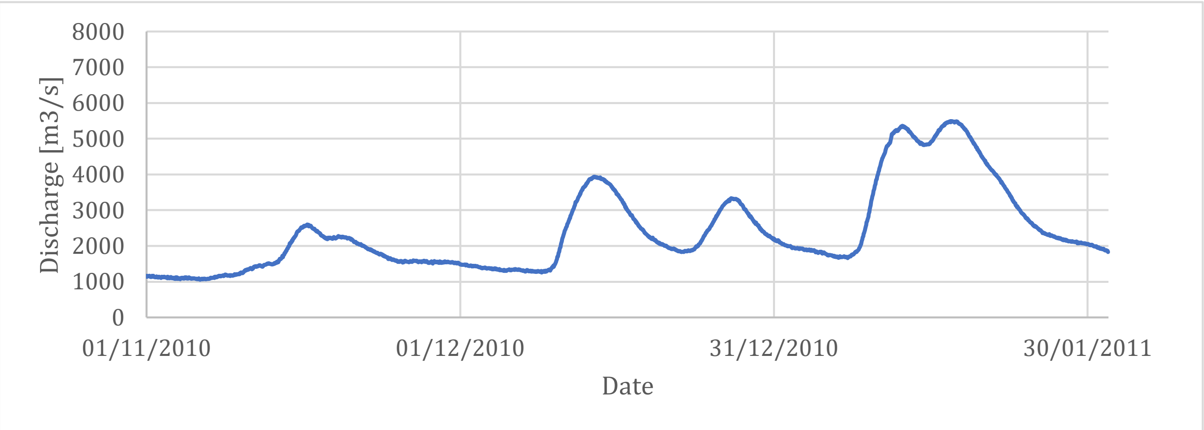

Figure 4: 2011 discharge wave at Pannerdense kop (Rijkswaterstaat, 2016).

The software that is going to be used to model the case study is SOBEK 3.4.2 (Deltares, 2015). This software is chosen because it uses integrated 1D/2D modelling. This integration is achieved by combining 2D cross-sections and a 1D longitudinal profile. The advantage of this over normal 2D modelling for the purposes of this research is that no grid is used. The shape and size of a grid may affect the model output (Bomers et al., 2019), which adds an extra source of uncertainty to the results. Since the goal is to compare the use of roughness and bathymetry for calibration, all other variables must be kept as constant as possible. An integrated 1D/2D model is less complex than a 2D model and is thus better suited for this goal. Another advantage is that the computational time is generally lower compared to 2D or even 3D modelling.

The SOBEK schematizations for the Waal have been requested via the website 'Informatiepunt Leefomgeving' (IPLO) (Rijksoverheid, 2022). Table 1 gives an overview of the schematizations that are going to be used.

Table 1: Overview of the combinations of discharge waves and schematizations that are going to be used (Rijksoverheid, 2022; Rijkswaterstaat, 2016).

Discharge wave year	Discharge wave period	Schematization year	Schematization name
1993	01/11/1993 – 31/01/1994	1993	SOBEK-Rijn-j93_5-v4
1995	01/12/1994 – 28/02/1995	1995	SOBEK-Rijn-j95_5-v4
2011	01/11/2010 – 31/01/2011	2011	SOBEK -Rijn-j11_5-v1

2.3 METHOD

This section describes the methods used to answer the research questions and the main objective. The first research question is answered by performing a sensitivity analysis (SA). The method is described in section 2.3.1. The second research question is answered by calibrating using roughness as the calibration parameter and validating the results afterwards. The method is described in section 2.3.2. The third research question is answered by calibrating using the bathymetry as the calibration parameter and validating the results afterwards. The method is described in section 2.3.3. The fourth research question is answered by calibrating using the main channel roughness as the calibration parameter and validating the results afterwards. The method is described in section 2.3.4. The fifth research question is answered by comparing the results of the calibration variants.

2.3.1 Sensitivity analysis

A SA is the study of how (uncertainty in) the output of a model (numerical or otherwise) can be apportioned to different sources of (uncertainty in) the model input (Saltelli et al., 2007). In this case the output is the water level, and the inputs are the roughness and bathymetry.

The SA method is a simple perturbation of parameters. It varies the input parameters of the model from their nominal values one at a time while keeping the other model parameters constant. This means this is a local SA, because not the entire space of variability of the input parameters is taken into account. This is sufficient for the SA because the chosen parameters (roughness and bathymetry) become physically unrealistic outside this range. The interest of the effect of these parameters in mainly in the physically realistic range, and the local SA covers that. The result is that the effect of both parameters on the water level can be compared, and it can be determined which of the two is the most influential.

A steady-state simulation is performed by keeping the discharge constant. The height of the constant discharge could affect the influence of the roughness and bathymetry on the water level.

Boundary and initial conditions

The schematizations, boundary conditions, and initial conditions that are used for the SA are provided in Table 2.

Table 2: Overview of the model, boundary conditions, and initial conditions that are used in the SA.

River branch	Schematization name	Upstream boundary condition	Downstream boundary condition	Initial water flow	Initial water depth
Rhine	SOBEK-Rijn-j95_5-v4	Constant discharge	Constant water level based on local cross-section, roughness value, and discharge	0 m^3/s in the whole model	0 m in the whole model

The upstream boundary condition at Pannerdense kop is a constant discharge. The discharge values are based on the return periods of these discharges for the river Waal, as shown in Table 3. The downstream boundary condition at Hardinxveld is a constant water level. This water level is calculated using the local cross-section and the Manning equation. The slope used for the Waal in the Manning equation is $1.1*10^{-4}$. This water level is kept constant per discharge, as shown in Table 3. The water level is below the mean sea level for discharges of 4000 m^3/s and 5300 m^3/s. This is because the lowest point in the cross-section at Hardinxveld is also below mean sea level (-6.2 m). The eventual water depth is positive, as shown in Table 3.

Table 3: Discharge and water level values used in the SA (Hegnauer et al., 2015).

Return Period [years]	Discharge at Pannerdense kop [m^3/s]	Water level at Hardinxveld [m above mean sea level]	Water depth at Hardinxveld [m]
T=2	4000	-0.9	5.3
T=5	5300	-0.1	6.1
T=10	6100	0.3	6.5
T=50	7800	1.3	7.5

Input parameters

Roughness

For the roughness, the physically possible range of the Manning base n value [$s/m^{1/3}$] for river main channels lies between 0.012 (sand, 0.2 mm median size) and 0.070 (boulders) (Arcement & Schneider, 1989). For floodplains, the same range can be used to determine the roughness of the natural bare soil surface. Adjustments can then be made based on the type of vegetation that is present on the floodplain. Grasslands result in a roughness increase from 0.001 to 0.010, resulting in a physically realistic roughness range for floodplains from 0.013 to 0.080 for a sand river such as the Waal. The unit of the Manning roughness value is represented by [n] throughout the rest of the thesis.

The SA uses a slightly smaller range of roughness values from 0.012 to 0.060. The upper limit of 0.060 is determined by testing for which roughness value the outer embankment started to overflow when a constant discharge value of 7800 m^3/s flowed through the river. 7800 m^3/s is chosen because it is the highest constant discharge used in the SA. Overflow did not occur in combination with a roughness value of 0.060. Higher roughness values did cause overflow and this stopped the water level from increasing. The results of higher roughness values would therefore not be valuable for the SA, because the influence on the water level cannot be determined. Moreover, a roughness value of 0.060 is on the higher end for a river like the Waal since it is located in a delta region. The sediment size in the Waal is small when compared to rivers located further upstream, resulting in lower roughness values.

Three different variants are analysed in the SA. The first variant changes both the main channel and floodplain roughness at the same time from 0.012 to 0.060. The second variant changes the floodplain roughness from 0.012 to 0.060 but keeps the main channel roughness constant at 0.030. The latter value represents an average value for coarse sand with a diameter between 1 and 2 mm (Arcement & Schneider, 1989). This is based on the D_{50} sand diameter found in the Waal between 1966 and 2020 during measurements (Ylla Arbos, 2021). The third variant changes the main channel roughness from 0.012 to 0.060 but keeps the floodplain channel roughness constant at 0.030. Even though grass has a roughness value of 0.035 (Chow, 1959), 0.030 is chosen to keep consistency in input between the second and third variants.

Bathymetry

The bathymetry present in the schematizations is based on an average height over a certain period. This could be a weekly or even monthly average. Because of the relative coarse time scale differences in height over smaller periods are not taken into account. River dunes are wavelike features in sandy riverbeds that move slowly in the downstream direction (Lokin et al., 2022). They can roughly be divided into small and large river dunes (Ten Brinke et al., 2009).

The range of the bathymetry is based on the size of the small river dunes in the Rhine (60 cm in height, 15 m in length (Ten Brinke et al., 2009)). These small river dunes are superimposed on the large river dunes (1.2 m in height, ~55 m in length). These smaller dunes can cause uncertainties in the average bathymetry height because they migrate relatively fast. Using the height of these small river dunes as a range will therefore be interesting for the SA. The range of the bathymetry will be a 60 cm increase and a 60 cm decrease from the original bathymetry height. This makes sure that the lowest points in the bathymetry can change in height up until the highest points and vice versa. Using a range of only 30 cm would allow the lowest and highest points to reach the average height, but not the other extreme. Figure 5 shows how this works.

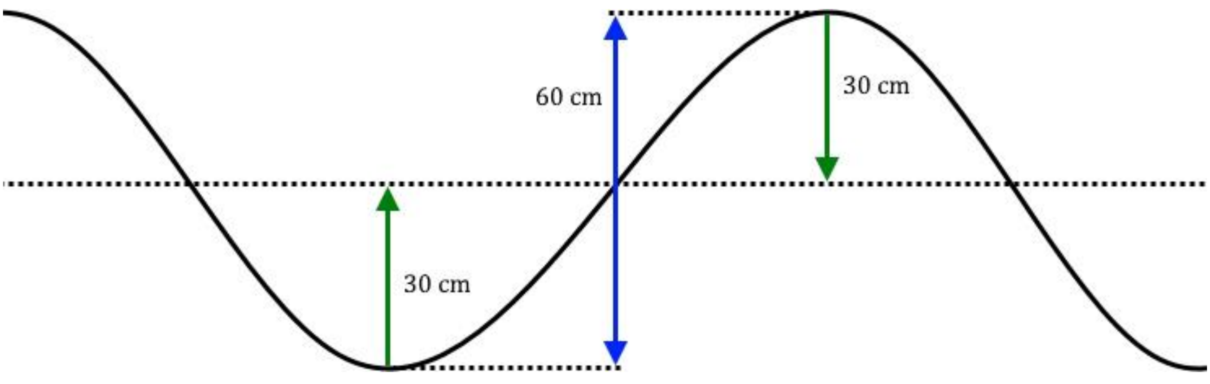

Figure 5: The blue arrow indicates the bathymetry range used in the SA. If the range was 30 cm only the average height could be reached from the lowest and highest points.

Measurement points

The schematization in SOBEK contains multiple observation points. At these points the water levels, discharges, and water depths are monitored during a simulation. The water levels of the five points that are shown in Figure 6 are combined into one average water level. This creates one water level that varies based on the discharge, roughness, and bathymetry. The first point is located near the municipality of Beuningen. The second point is located near the village of Deest. The third point is located near the village of Beneden-Leeuwen. The fourth point is located near the village of Dreumel. The fifth and last point is located near the village of Opijnen and the municipality of Zaltbommel.

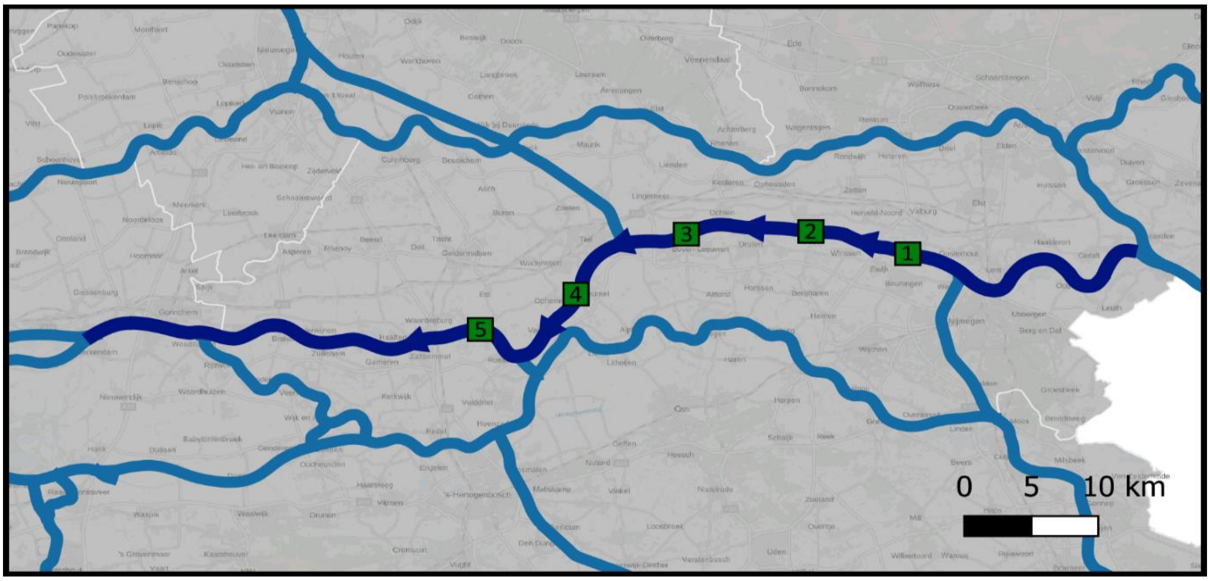

Figure 6: Observation points used to monitor the simulated water levels (Rijkswaterstaat, 2021).

2.3.2 Roughness calibration and validation

The second research question will be answered by using the main channel and floodplain roughness as calibration parameters. First, a calibration is performed using one of the schematizations and discharge waves, and then the results are validated using two other schematizations and discharge waves.

Calibration

The calibration is performed using the 1995 Rhine schematization for the period 01/12/1994 to 28/02/1995 as mentioned in Table 1. The upstream boundary condition is the observed discharge wave at Pannerdense Kop for this period. The downstream boundary condition is the observed water level at Hardinxveld for the same period. This is a fictive location upstream from the observation station Werkendam located in the Boven Merwede river. Werkendam is not optimal since it is located in the river Nieuwe Merwede downstream from the bifurcation of the river Boven Merwede into the rivers Beneden Merwede and Nieuwe Merwede. The water levels at Hardinxveld are determined by a regression formula. This is the same regression formula used in the report 'Rijn-modellen 5e generatie' for determining the water levels at Hardinxveld using the water levels at observation station Werkendam (Berends, 2014).

The model has a warm-up period of approximately four days. This is not an issue however since the calibration will focus on the peak discharge, and this peak occurs approximately at day 61 in the model run. The calibration will not include the warm-up period in this way. The details of the calibration window are explained below.

A 14-day window is set around the observed peak discharge and only the simulated and observed water levels within this window are compared to each other. Seven days before and seven days after the peak discharge are included. The observed peak discharge is set exactly in the middle of this window, so the seven days before and after the peak are taken into account. This results in a period from 25/01/1995 to 07/02/1995, see Figure 7. The discharge within this window ranges from 3500 m^3/s to 7600 m^3/s.

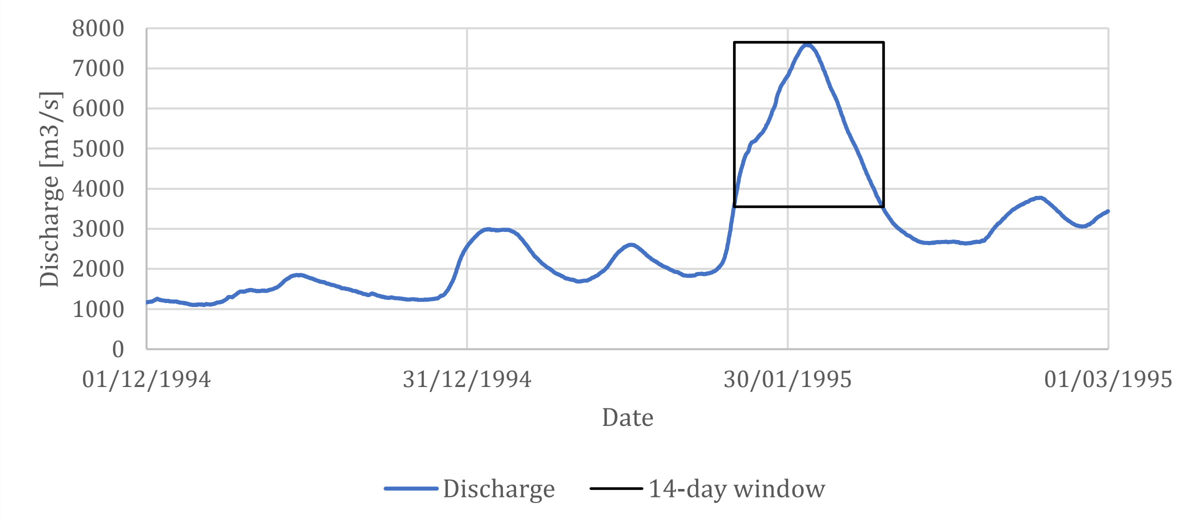

Figure 7: 14-day window set around the peak discharge of 1995 (Rijkswaterstaat, 2016).

The study area is divided into multiple sections that are calibrated consecutively. Each section ranges from one observation station to the next one. Table 4 shows the sections, including the upstream and downstream observation stations. These observation stations are also shown in Figure 1.

Table 4: Sections including upstream and downstream observation stations.

Section number	Upstream observation station	Downstream observation station	Start chainage (km)	End chainage (km)	Section length (km)
1	Pannerdense kop	Nijmegen haven	867	884.9	17.9
2	Nijmegen haven	Dodewaard	884.9	899.1	14.2
3	Dodewaard	Tiel Waal	899.1	913.4	14.3
4	Tiel Waal	Zaltbommel	913.4	934.7	21.3
5	Zaltbommel	Vuren	934.7	951.8	15.5
6	Vuren	Hardinxveld	951.8	961	9.2

The calibration is performed from downstream to upstream to reduce the effect of backwater curves. Backwater curves influence the upstream water level, so performing the calibration from upstream to downstream would give less accurate results. The first section to be calibrated is thus section 6.

The sections are calibrated using the Root Mean Square Error (RMSE) as the objective function. This objective function is chosen because it has also been used in the official calibration of the used models by Rijkswaterstaat (Berends, 2013). The simulated water level is compared to the observed water level at the upstream observation station of each section. The roughness value that results in the smallest RMSE is deemed optimal for that section.

The calibration is performed by changing the roughness in a structured way. The initial roughness values for each section are 0.030 for the main channel and 0.035 for the floodplains. A value of 0.030 is based on a sediment diameter of 1 to 2 mm (Arcement & Schneider, 1989). This is based on the D_{50} sand diameter found in the Waal between 1966 and 2020 during measurements (Ylla Arbos, 2021). A value of 0.035 is based on the floodplains being mostly covered by grass (Chow, 1959). These roughness values are increased or decreased using percentages of the initial value. This keeps the ratio between the main channel and floodplain roughness constant. This means that the floodplain roughness increases faster in absolute terms compared to the main channel roughness.

A limitation is set on the minimum step size. The step size cannot be smaller than 1 percentage point. This means that the smallest step size is $3.0*10^{-4}$ and $3.5*10^{-4}$ for the main channel and floodplain respectively.

Once the smallest RMSE is found, the roughness values are set in place for that section and the next section upstream is calibrated in the same way. This process repeats until the last section (section 1) is calibrated. After this is done the complete model is calibrated.

Validation

The validation is performed using the 1993 and 2011 Rhine schematizations mentioned in Table 1 for the periods 01/11/1993 to 31/01/1994 and 01/11/2010 to 31/01/2011, respectively. The upstream boundary conditions are the discharge waves at Pannerdense Kop for the respective periods. The downstream boundary conditions are the water levels at Hardinxveld for the same periods. These water levels are determined using the same method as described for the calibration.

As with the calibration, the focus of the validation is only on the water levels within the 14-day window around the peak discharge. This results in a period from 21/12/1993 to 03/01/1994 for the 1993 model and a period from 09/01/2011 to 22/01/2011 for the 2011 model, see Figures 8 and 9. This results in a discharge ranging from 3000 m^3/s to 7100 m^3/s for the 1993 model and 2800 m^3/s to 5500 m^3/s for the 2011 model.

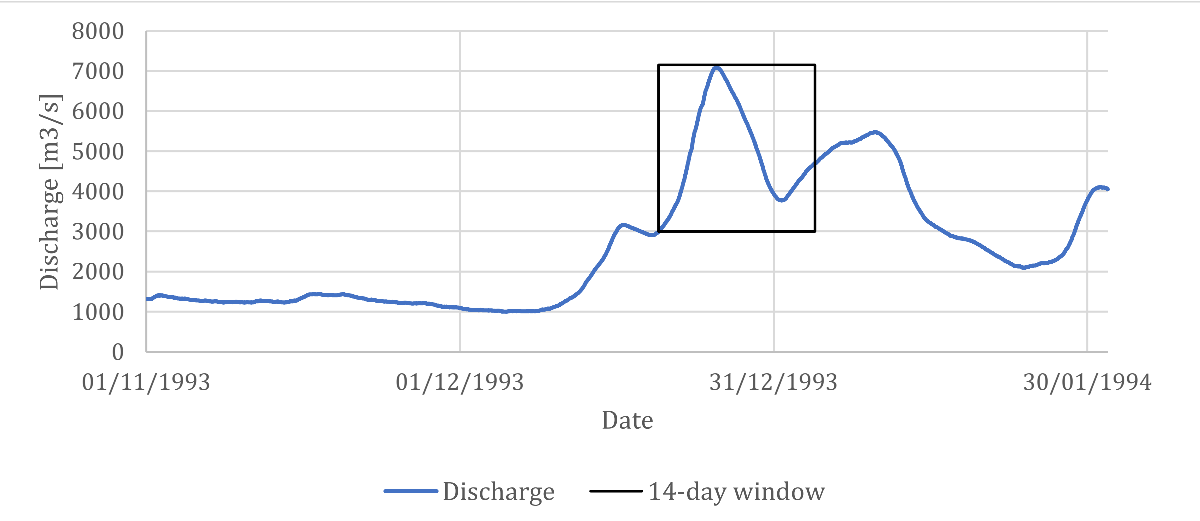

Figure 8: 14-day window set around the peak discharge of 1993 (Rijkswaterstaat, 2016).

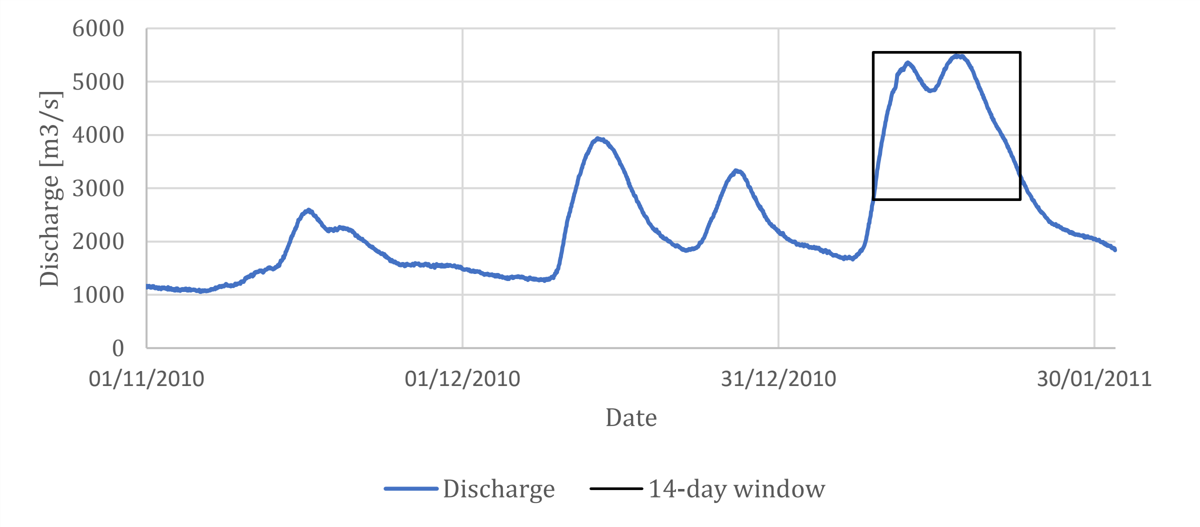

Figure 9: 14-day window set around the peak discharge of 2011 (Rijkswaterstaat, 2016).

The optimal roughness values for each section are transferred from the 1995 model to the 1993 and 2011 models. Each section uses the roughness value that was found to be optimal for that section during the calibration. Running the model with these roughness values results in an RMSE value for each section. The average RMSE of the sections determines the accuracy of the simulated water level when using roughness as a calibration parameter.

2.3.3 Bathymetry calibration and validation

The third research question will be answered by using bathymetry as a calibration parameter. This method is mostly the same as the method described in section 2.3.2, except for the steps specifically related to the roughness. The steps specifically related to the bathymetry for the calibration and validation are described below.

Calibration

The bathymetry is adjusted by altering the height of the cross-sections in the model. This is done per section, starting downstream and ending upstream. These sections are calibrated using the RMSE as the objective function, and the bathymetry height that results in the smallest RMSE is deemed optimal for that section.

The initial bathymetry height matches the original bathymetry of the 1995 schematization, so no increase or decrease in height for all sections. During the calibration, the height of all cross-sections within a section is increased or decreased by a minimum of 5 cm per step. A limitation is set on the step size because the calibration is performed manually. Once the smallest RMSE is found, the bathymetry heights are set in place for that section and the next section upstream is calibrated in the same way. This process repeats until the last section is calibrated. After this is done the complete model is calibrated.

Validation

The optimal increases or decreases in bathymetry height are used for the validation. They are used to change the bathymetry heights in the 1993 and 2011 schematizations. For example, if the bathymetry in section 3 needed a 40 cm increase to be optimal, then the bathymetry of section 3 in the 1993 and 2011 schematizations will also get a 40 cm increase for the validation. This means that the original bathymetry height of the 1993 and 2011 schematizations is used as a starting height and not the 1995 bathymetry height. Running the model with these bathymetry changes results in an RMSE value for each section. The average RMSE of these sections determines the accuracy of the simulated water level when using bathymetry as a calibration parameter.

2.3.4 Main channel roughness calibration and validation

The fourth research question will be answered by using the main channel roughness as a calibration parameter. This method is almost the same as the one described in section 2.3.2. The only difference is that the floodplain roughness is kept constant at 0.035 for the calibration. This is the roughness value for floodplains covered with grass (Chow, 1959). All other steps are the same.

3 RESULTS

This chapter covers the results that will aid in answering the research questions and achieving the main objective. Section 3.1 describes the results of the sensitivity analysis. Section 3.2 describes the results of the calibration and validation using the different calibration variants.

3.1 SENSITIVITY ANALYSIS

The SA has been performed for the four constant discharges 4000 m^3/s, 5300 m^3/s, 6100 m^3/s, and 7800 m^3/s (see Table 3). The SA yielded results that can be analysed in multiple ways. Three comparisons are included in the results:

1. A comparison of the influence of roughness on the water level for the three different variants. These variants were:
   - Adjusting main channel and floodplain roughness.
   - Adjusting main channel roughness while keeping floodplain roughness constant.
   - Adjusting floodplain roughness while keeping main channel roughness constant.
2. A comparison of the influence of bathymetry on the water level for four different discharges.
3. A comparison between the effect of roughness and bathymetry on the water level. For the roughness the variant that adjusts both the main channel and the floodplains is used in this comparison.

3.1.1 Main channel and floodplain roughness influence

In the first comparison, the influence of the roughness on the water level is determined by altering the roughness in three variants: both the main channel and floodplain roughness, only the main channel roughness, and only the floodplain roughness.

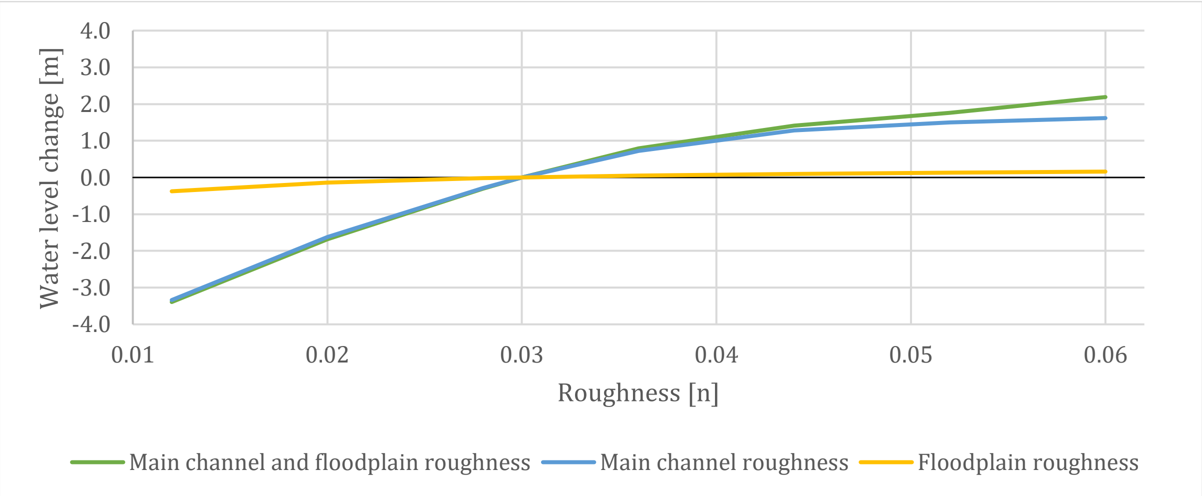

Figure 10: The influence of roughness on the water level for the three different variants at a discharge of 4000 m^3/s.

Figure 10 shows the influence of the roughness on the water level for the three different variants at a discharge of 4000 m^3/s. It shows the change in water level compared to the base situation with 0.030 roughness values for the main channel and floodplains. Only changing the floodplain roughness has a smaller influence on the water level compared to the other two variants. Because of the relatively low discharge, the main channel roughness has a much larger influence on the water level than the floodplain roughness. However, the effect of the floodplain roughness is not zero, even at the smallest chosen discharge of 4000 m³/s. This discharge is still relatively high for the Waal, so it could be that for lower discharges the influence of the floodplain roughness becomes zero. This happens when the discharge is so low that there is no more water flowing in the floodplains.

At higher roughness values (0.045 to 0.060) a small difference in water level is noticeable between the variants 'Main channel roughness' and 'Main channel and floodplain roughness'. At higher roughness values the water level becomes higher, resulting in more water in the floodplains. More water in the floodplains means a larger effect of the floodplain roughness on the water level. This causes the increasing difference between the variants 'main channel roughness' and 'main channel and floodplain roughness' for higher roughness values.

Figures 11 to 13 show the graphs for the other three discharges. They show the same general patterns, but some minor differences are interesting to discuss.

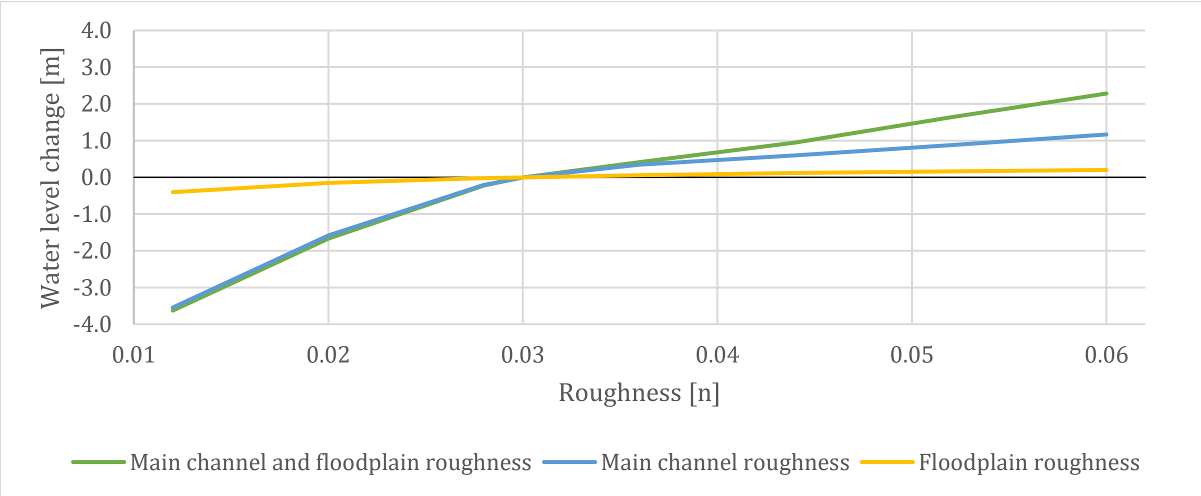

Figure 11: The influence of roughness on the water level for the three different variants at a discharge of 5300 m³/s.

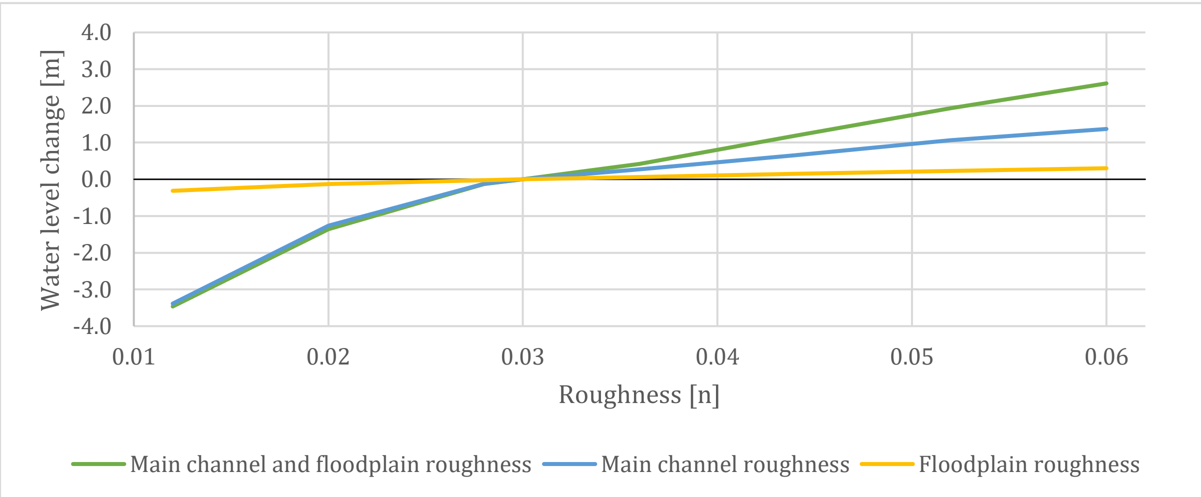

Figure 12: The influence of roughness on the water level for the three different variants at a discharge of 6100 m³/s.

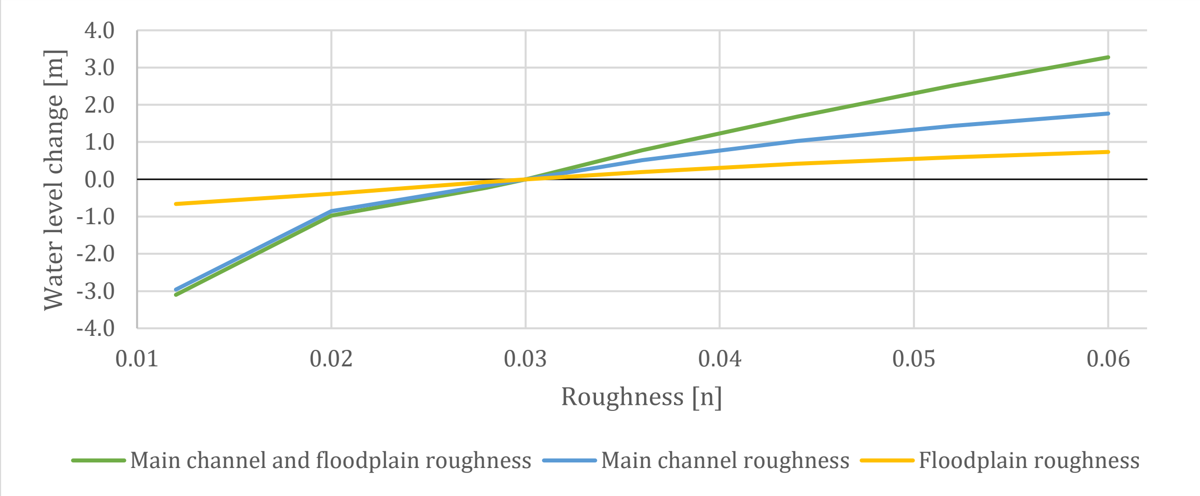

Figure 13: The influence of roughness on the water level for the three different variants at a discharge of 7800 m³/s.

Higher roughness values have a larger effect on the water level for higher discharges. This is the case for all three variants. Lower roughness values have a similar effect on the water level for all discharges.

For higher discharges, the floodplain roughness starts to play a larger role than at lower discharges. The higher discharge results in a higher water level, which results in more water in the floodplains. More water in the floodplains means that the floodplain roughness contributes more to the total roughness and consequently to the total water level change. The main channel roughness still has a larger influence, but the floodplain roughness plays a larger role with higher discharges.

Another noticeable difference between Figures 10 to 13 is at what roughness value the graphs for the variants 'Main channel roughness' and 'Main channel and floodplain roughness' start to deviate. For higher discharges, this deviation starts at a lower roughness value. This is caused by higher water levels because of the higher discharge, and thus more water in the floodplains for lower roughness values.

3.1.2 Bathymetry influence for different discharges

In the second comparison the influence of bathymetry on the water level for the four aforementioned discharges is determined, see Figure 14. The influence is the largest for the lowest discharge of 4000 m^3/s, and the smallest for the 6100 m^3/s discharge. Decreasing the bathymetry height has an equal effect on the water level for the 5300 m^3/s and 7800 m^3/s discharges. When increasing the bathymetry height the effect on the water level is comparable for the 4000 m^3/s and 7800 m^3/s discharges.

There seems to be no clear relationship between increasing the discharge and the effect this has on the influence of bathymetry on the water level. Most interesting is that the influence is largest for the lowest and highest chosen discharge while being smaller for the two discharges in between.

A possible explanation for the lack of a clear relationship is that the influence of bathymetry on the water level is largely dependent on the shape of the cross-section. The influence of the bathymetry then depends on the starting point of the water level in a cross-section. If an increased discharge causes the water level to enter the floodplains the effect of the bathymetry could be altered. However, it is not clear if this would increase or decrease the effect of the bathymetry, because Figure 14 does not show a clear difference between discharges that cause the water to be mainly in the main channel (4000 m³/s) and mainly in the floodplains (7800 m³/s).

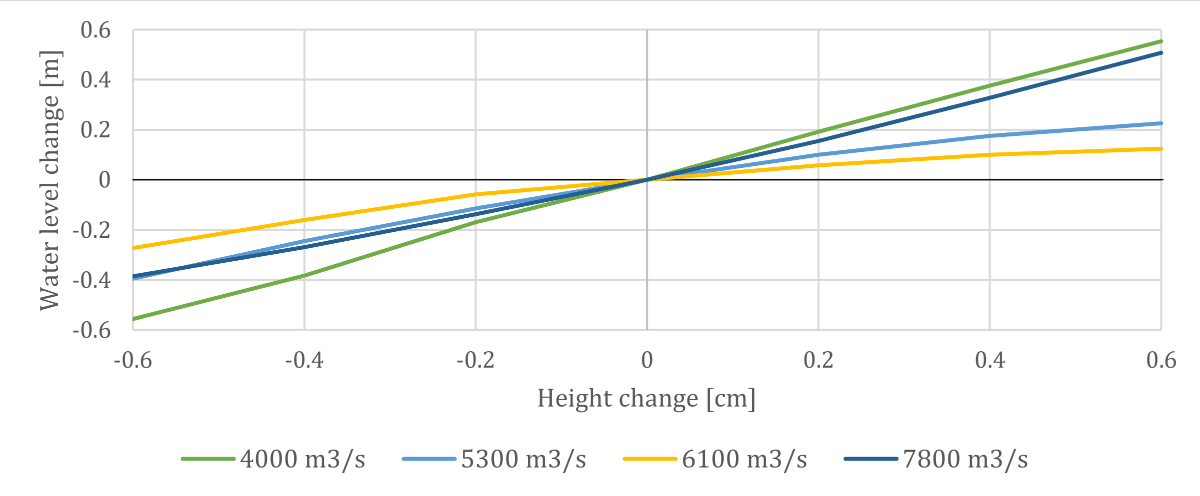

Figure 14: The influence of bathymetry on the water level for four discharges.

3.1.3 Roughness and bathymetry influence

In the third comparison, the effect of roughness and bathymetry on the water level are determined. This is the most important comparison for the calibration because it will indicate which parameter has a larger influence on the water level.

Table 5: Change needed for a 10 cm water level increase.

Discharge (m³/s)	4000	5300	6100	7800	Average
Roughness (n)	$8.60*10^{-4}$	$8.12*10^{-4}$	$7.90*10^{-4}$	$7.53*10^{-4}$	$8.04*10^{-4}$
Bathymetry (m)	0.11	0.19	0.30	0.13	0.18

Table 5 shows the change in roughness and bathymetry that is needed to get a 10 cm increase in water level. The effect of the roughness gets slightly larger with an increase in discharge because less change in roughness is needed for the same change in water level. The difference is small, but there is a clear trend. For the bathymetry, the trend is less clear. The outlier in this case is the result for a discharge of 6100 m³/s. A 30 cm increase is needed for a 10 cm increase in water level. This relatively small effect can also be seen in 3.1.2. The other three results have the same order of magnitude, but there is no clear trend in increasing or decreasing effectiveness with an increasing discharge.

Figure 15 shows the influence of the roughness and bathymetry on the water level averaged for all four discharges. The graphs for each specific discharge are shown in Appendix A: roughness and bathymetry influence on the water level per discharge. The changes in bathymetry and the changes in roughness are shown on the upper and lower x-axis respectively. Figure 15 shows that the roughness has a larger effect than the bathymetry on the water level for the chosen range of values. The relationship between the bathymetry and the water level is almost linear. The relationship between the roughness and water level is slightly nonlinear. The roughness has a larger effect on the water level for lower roughness values. This can be explained by the relationship between the roughness coefficient and the area and hydraulic radius in the Manning equation for discharge:

$$Q = \left(\frac{1}{n}\right) AR^{\frac{2}{3}}\sqrt{S} \rightarrow \frac{Q}{\sqrt{S}} = \frac{AR^{2/3}}{n}$$

In this equation Q is the discharge in $[m^3/s]$, n is the Manning roughness coefficient in $[s/m^{1/3}]$, A is the flow area in $[m^2]$, R is the hydraulic radius in $[m]$, and S is the slope of the river in $[m/m]$. During the SA, Q and S are constant. If n increases, $AR^{2/3}$ also needs to increase. However, this increase is not linear because of $R^{2/3}$. This results in a water level that increases less steep for higher roughness values compared to lower ones.

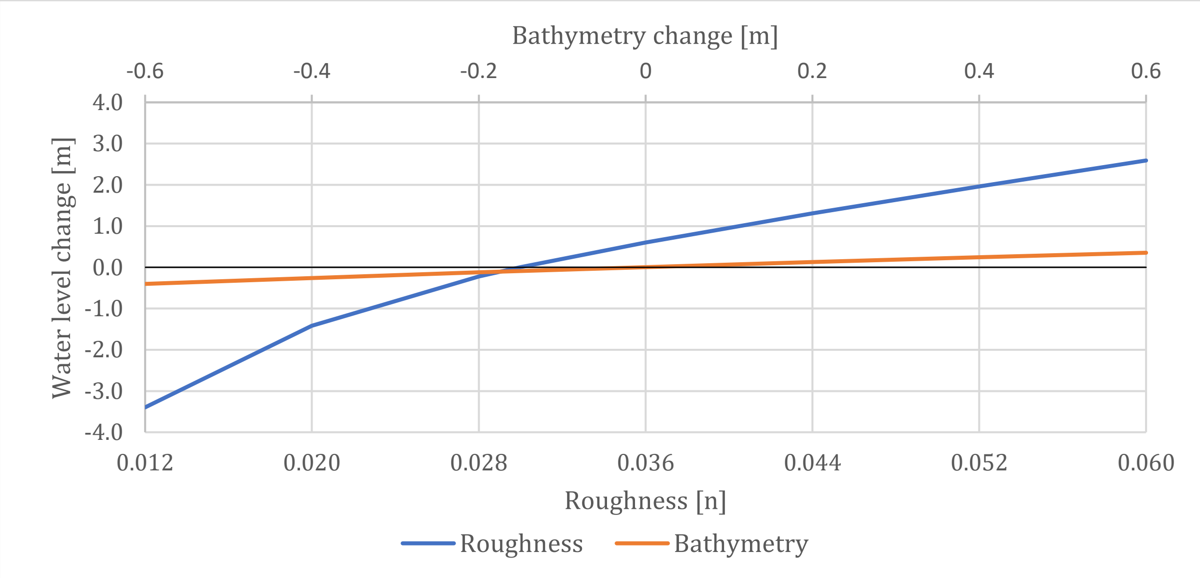

Figure 15: Influence of roughness and bathymetry on the water level, averaged for all four discharges.

3.2 Calibration and validation

3.2.1 Roughness

Figure 16 shows the change in roughness for the sections mentioned in Table 4. This change is given as a percentage increase or decrease with respect to the starting roughness values of 0.030 and 0.035. The river chainage is shown on the x-axis and is given downstream to upstream. These increases or decreases in roughness values gave the lowest RMSE value per section. The largest increase in roughness value is seen in section 6 (most left in the graph). This is probably caused by the downstream boundary condition influencing the water level in this section considerably. The roughness needs to be altered by a larger percentage to get the same increase in water level compared to a situation when there is no downstream boundary condition present.

Another interesting result is that there needs to be a decrease in roughness for section 3, whereas all other sections need roughness increases. This could perhaps be explained by the calibration of section 4. This section has a relatively large increase in roughness value compared to the other sections (except for section 6). This increase could be caused by the location of the observation station Tiel Waal, which is used for the calibration of this section. This observation station is located in a side channel, and it could be that the observed water level measured at this station is a bit higher than the actual water level in the Waal. This then causes roughness values in the calibration of section 4 that are relatively high. To compensate, section 3 has to lower the roughness value to lower the relatively high water level resulting from the calibration of section 4.

In general, the change in roughness tends to decrease the further upstream a section is located. A possible explanation for this is the reduced influence of uncalibrated sections the further the calibration moves upstream. The further upstream, the smaller the number of uncalibrated sections between the upstream boundary condition and the section that is currently calibrated. Less influence of uncalibrated sections probably means a smaller difference between simulated and observed water levels. This then means that the roughness has to increase or decrease less to match the simulated with the observed water level.

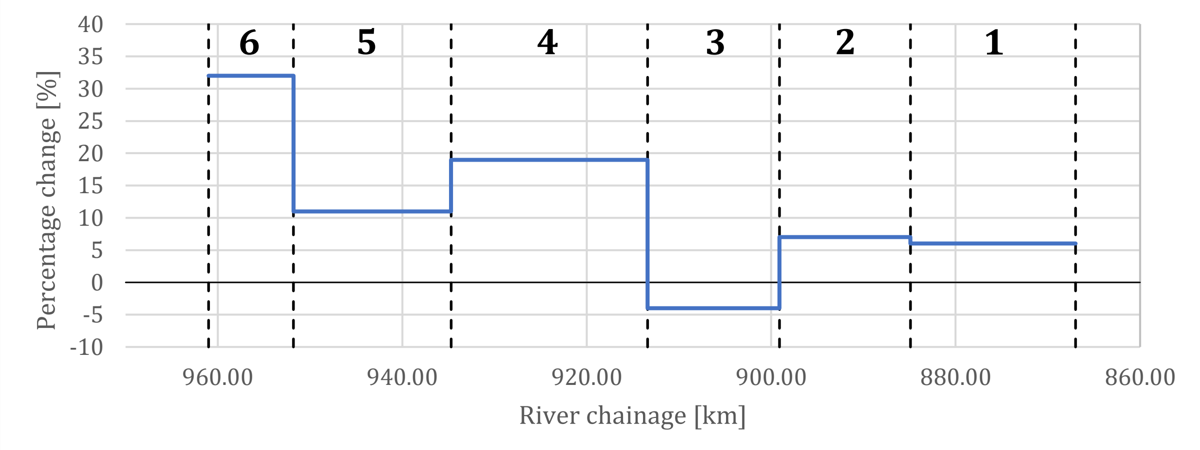

Figure 16: Percentage change in roughness for the sections along the river chainage. The section numbers are indicated at the top of the graph.

Figure 17 shows the RMSE values after the calibration with the roughness and the 1993 and 2011 validation. The most interesting result is that the RMSE is smaller for the 2011 model compared to the calibration. Another interesting result is the relatively large RMSE for section 4 for the calibration and 1993 validation.

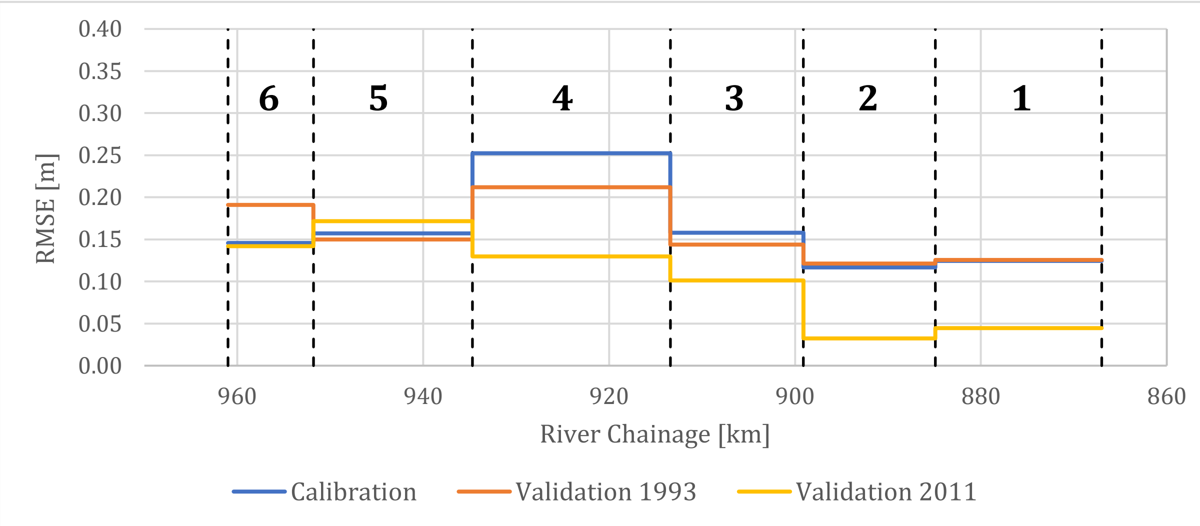

Figure 17: RMSE values for the sections after calibration and validation using roughness. The section numbers are indicated at the top of the graph.

Figures 18 and 19 show the simulated and observed water levels in the sections with the smallest and largest RMSE values. The smallest and largest RMSE values are found in section 2 of the 2011 validation and section 4 of the calibration respectively. Figure 18 shows that the simulated water level matches almost perfectly with the observed water level. The water level values and general shape match. The simulated water level values are not as close to the observed water levels in Figure 19 compared to Figure 18. The shape of the simulated water level is also different from the observed water level. In the first few days, the simulated values are lower than the observed ones, but the reverse is true for the last few days after the peak. The difference is the largest on the first and last day of the 14-day window. The complete wave seems shifted a couple of hours in time compared to the observed water level. This could have to do with the location of the observation station Tiel Waal as mentioned earlier, but how this location would give rise to this effect is unclear.

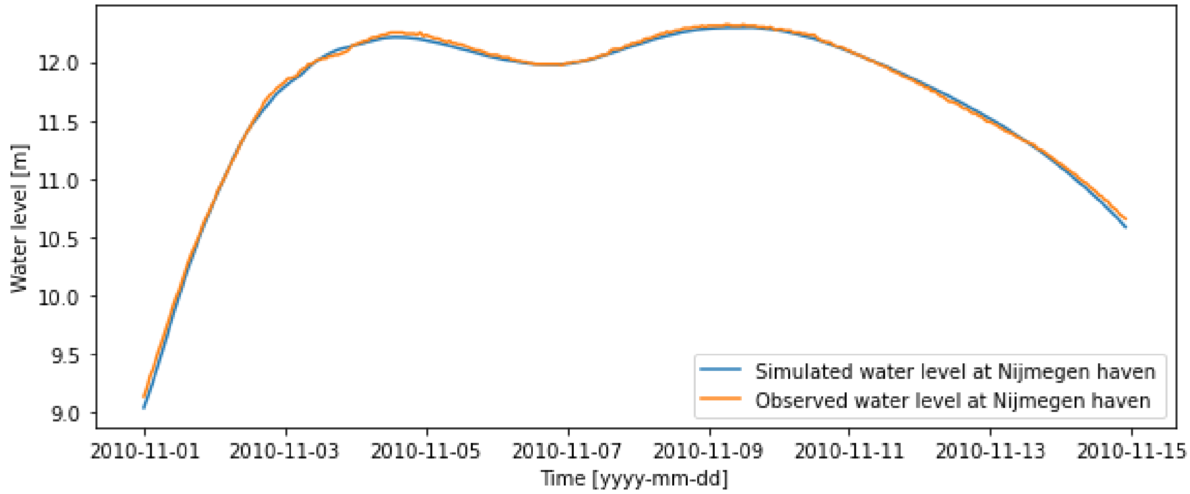

Figure 18: Hydrograph of section 2 of the 2011 validation.

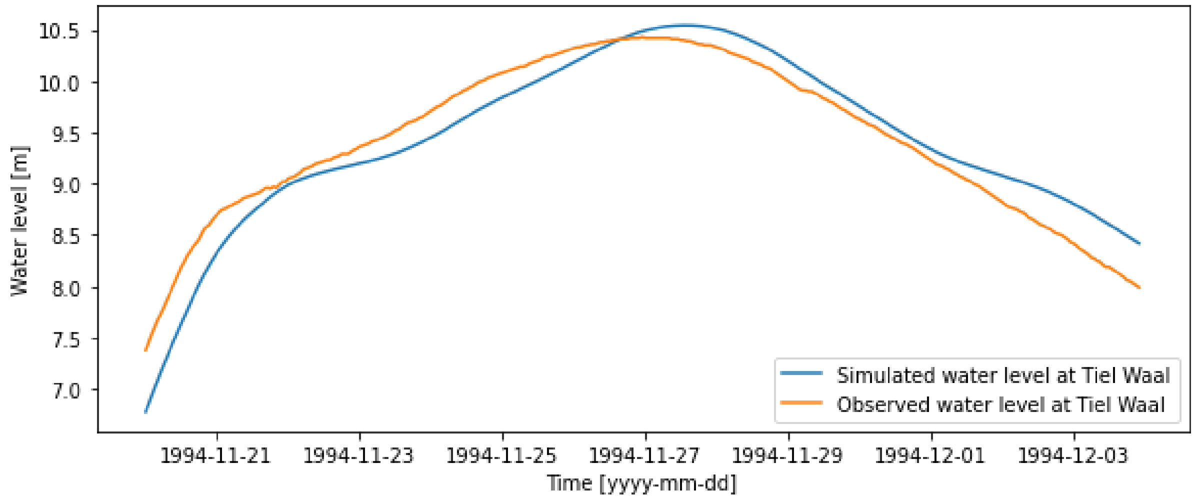

Figure 19: Hydrograph of section 4 of the calibration.

3.2.2 Bathymetry

Figure 20 shows the change in bathymetry for the sections along the river chainage. The pattern is very similar to that of the roughness as shown in Figure 16. The largest increase is found in section 6, and section 3 is the only section with a decrease instead of an increase in bathymetry height. This makes sense because both higher roughness values and higher bathymetry heights cause higher water levels.

The increases in bathymetry in sections 6 and 4 are large when compared to the range chosen for the SA. A value of 60 cm was the maximum increase or decrease, and sections 6 and 4 are outside of this range. The other four sections show more moderate increases or decreases in bathymetry height.

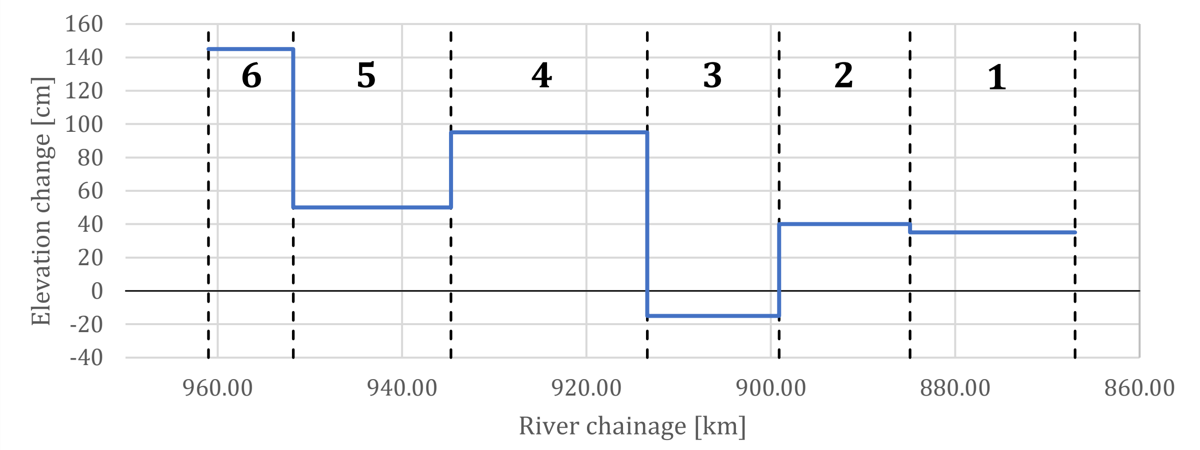

Figure 20: Change in bathymetry for the sections along the river chainage. The section numbers are indicated at the top of the graph.

Figure 21 shows the RMSE values after the calibration with the bathymetry and the 1993 and 2011 validation. Overall the 2011 validation shows the smallest RMSE values, with the exception being section 4. The results of the calibration and the 1993 validation are similar for most sections, with the largest differences being in sections 4 and 5.

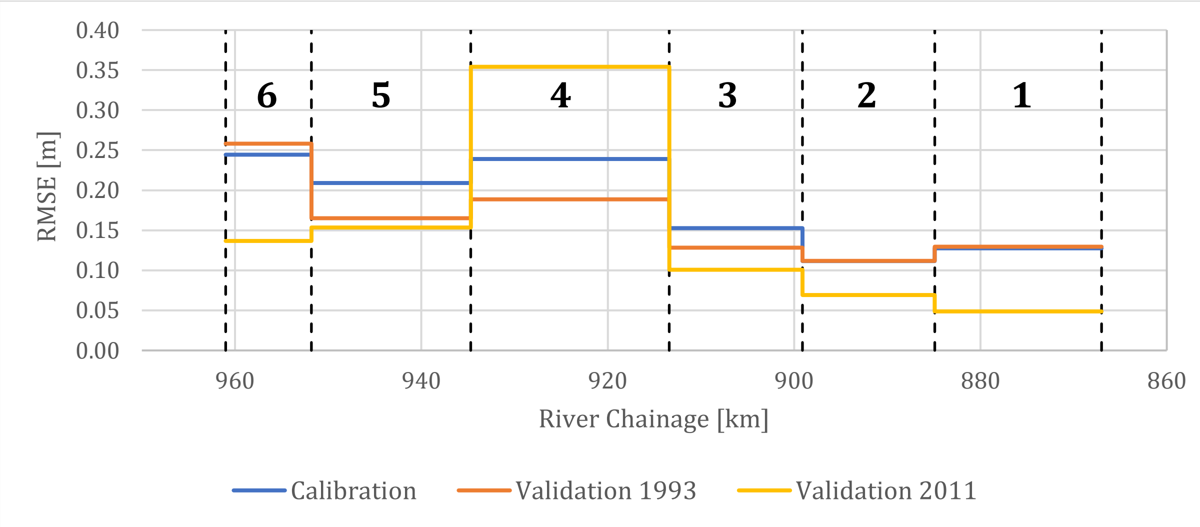

Figure 21: RMSE values for the sections after calibration and validation using bathymetry. The section numbers are indicated at the top of the graph.

Figures 22 and 23 show the simulated and observed water levels in the sections with the smallest and largest RMSE values. The smallest and largest RMSE values are found in sections 4 and 1 of the 2011 validation respectively. Figure 22 shows that the simulated water level matches almost perfectly with the observed water level. The simulated water level values are a bit lower than the observed water levels, but the shape matches. In Figure 23 the shape of the water level does match, but the simulated water level is much lower than the observed water level. This could be caused by the location of the observation station Tiel Waal as mentioned earlier. This station could possibly observe higher water levels than those actually in the Waal because it is located in a side channel. This would then explain the difference between the simulated and observed water levels for the 2011 validation of section 4.

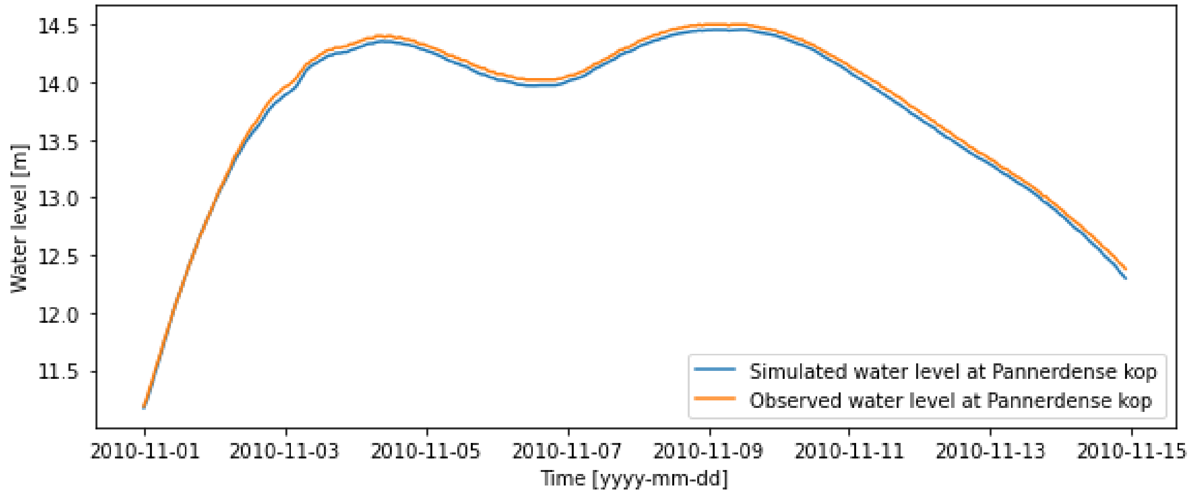

Figure 22: Hydrograph of section 1 of the 2011 validation.

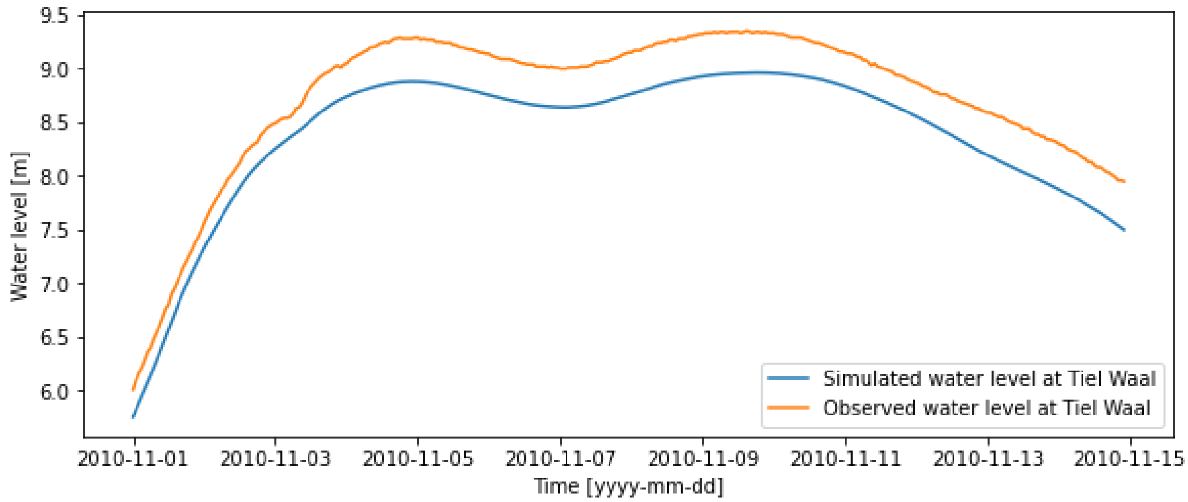

Figure 23: Hydrograph of section 4 of the 2011 validation.

3.2.3 Main channel roughness

Figure 24 shows the percentage change in main channel roughness for the sections along the river chainage. The pattern is the same as in Figure 16 and Figure 20. The percentage change is slightly larger for each section compared to Figure 16. This is caused by only varying the main channel roughness and keeping the floodplain roughness constant. This means the average roughness increases less, which means that the water level increases less. The main channel roughness thus needs to increase more to get the same water levels. However, the percentage changes are not much larger compared to Figure 16. This is in line with the results from the SA. There the main channel roughness had a substantially larger effect on the water level compared to the floodplain roughness. With a slightly larger increase or decrease in roughness values, the same water levels can be obtained compared to changing the main channel and floodplain roughness.

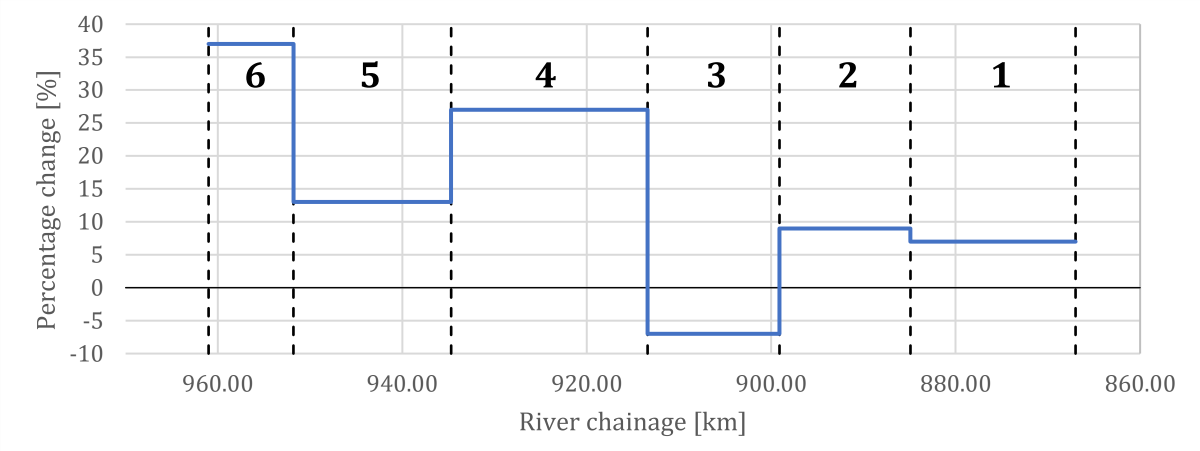

Figure 24: Percentage change in main channel roughness for the sections along the river chainage. The section numbers are indicated at the top of the graph.

Figure 25 shows the RMSE values after the calibration with the main channel roughness and the 1993 and 2011 validation. The pattern is the same as in Figure 17, with the 2011 validation having the smallest RMSE values and the calibration and 1993 validation having comparable results. The large difference in RMSE values could be caused by the differences in discharges for the calibration, 1993 validation, and 2011 validation. The discharge used in the 2011 validation is less extreme compared to the other two (5500 m^3/s compared to 7600 m^3/s and 7100 m^3/s). Since this discharge is less extreme it could be that the water levels are also less extreme and therefore simulated more accurately by SOBEK. However, the main channel roughness values are calibrated using the 7600 m^3/s peak discharge, so it would be more logical for the RMSE values to be lower for discharge values close to this. The use of different peak discharges is discussed further in the chapter Discussion. Compared to Figure 17 the calibration and 1993 validation show similar or slightly higher RMSE values, and the 2011 validation shows slightly lower RMSE values.

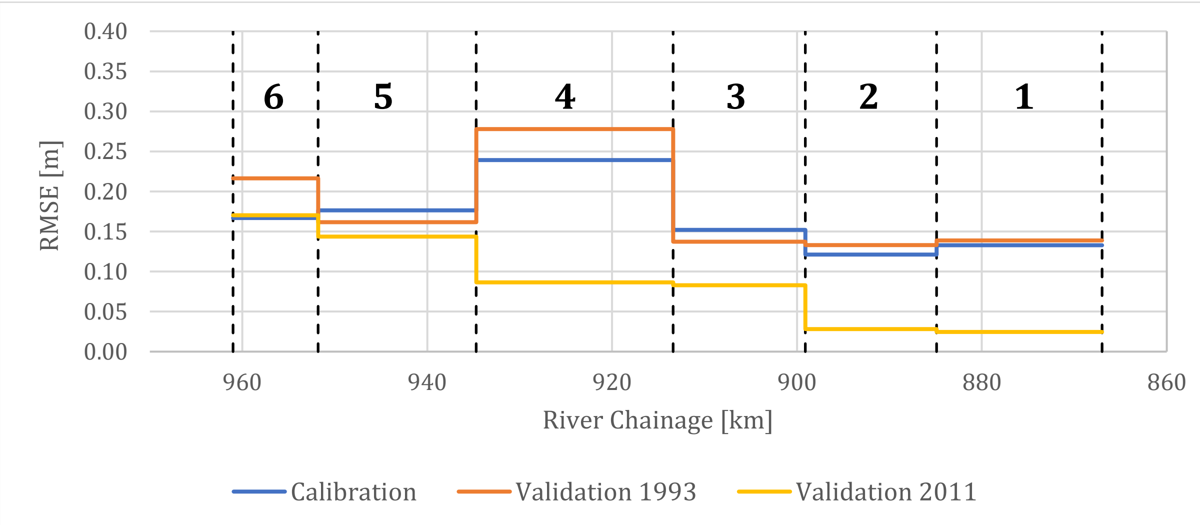

Figure 25: RMSE values for the sections after calibration and validation using main channel roughness. The section numbers are indicated at the top of the graph.

Figures 26 and 27 show the simulated and observed water levels in the sections with the smallest and largest RMSE values. The smallest and largest RMSE values are found in section 1 of the 2011 validation and section 4 of the 1993 validation, respectively. Figure 26 shows that the simulated water level matches almost perfectly with the observed water level. The water level values and general shape match. This is not the case for Figure 27. The shape matches mostly, but not for all 14 days. The simulated water levels are higher than the observed water levels for almost the complete period. The difference is largest on the 31st of October 1993.

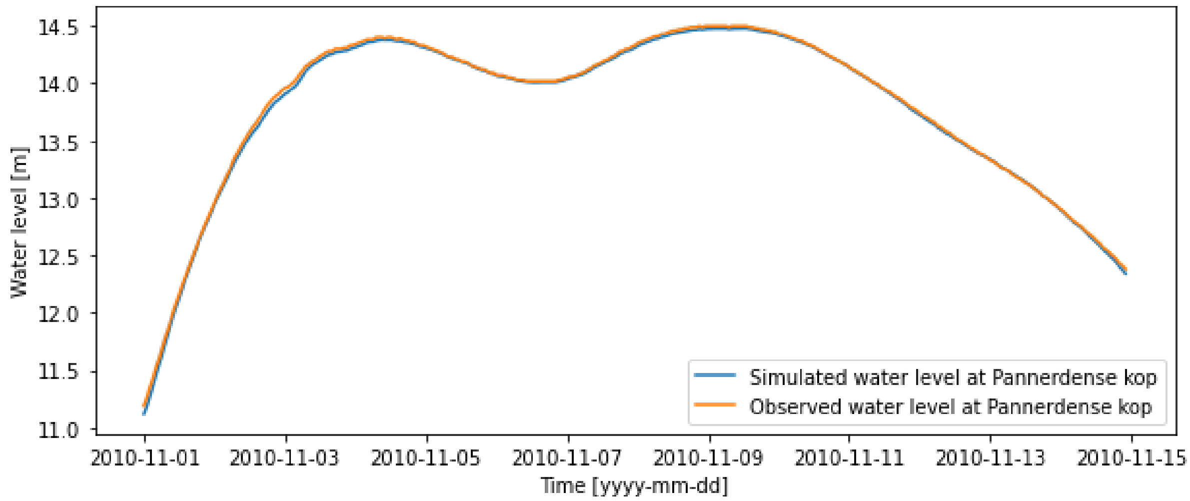

Figure 26: Hydrograph of section 1 of the 2011 validation.

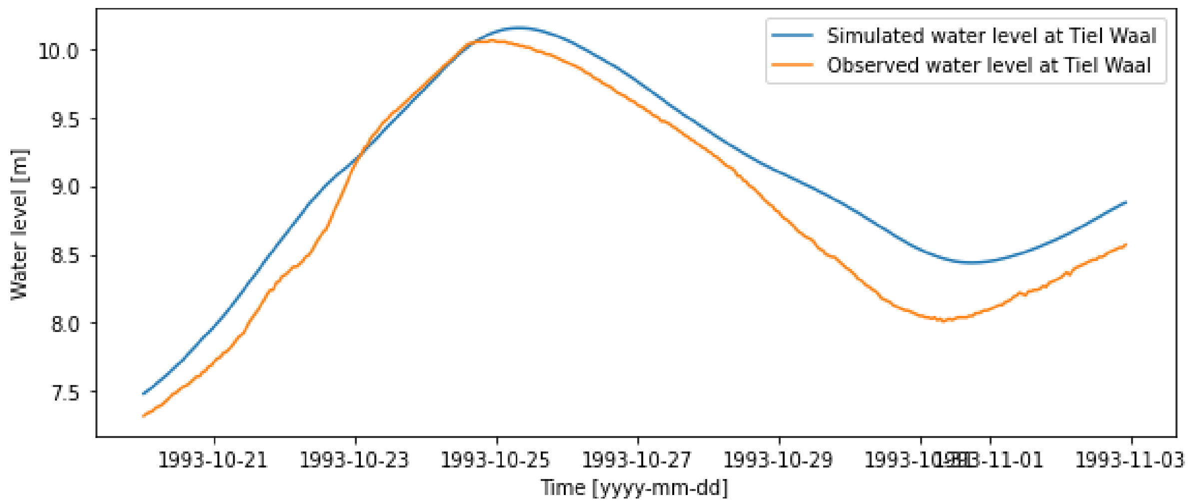

Figure 27: Hydrograph of section 4 of the 1993 validation.

3.2.4 Calibration variants comparison

Table 6 shows the average RMSE values for each calibration variant. Overall the RMSE values do not vary much between the calibration variants. However, the bathymetry shows slightly larger RMSE values compared to the roughness or main channel roughness on average for the calibration and both validations. Based on these results the accuracy of the bathymetry is not significantly higher or lower than the accuracy of the roughness or main channel roughness.

Table 6: Average RMSE values (in m) for each calibration variant.

Calibration parameter	Calibration	Validation 1993	Validation 2011	Validation average
Roughness	0.159	0.157	0.104	0.130
Bathymetry	0.181	0.164	0.144	0.154
Main channel roughness	0.165	0.177	0.089	0.133

The accuracy of the calibration did not improve when first calibrating with the roughness and subsequently with the bathymetry or vice-versa. This shows that the near-optimal RMSE was reached using only one of the two parameters for the calibration.

Figures 28 to 30 compare the RMSE values of the calibration variants per section. Figure 28 shows the RMSE values after the calibration. Here the roughness and main channel roughness have approximately the same RMSE values for each section. The bathymetry has approximately the same RMSE values as the roughness and main channel roughness for sections 1 to 4 but has larger values for sections 5 and 6. The RMSE values for sections 1 to 3 are relatively small for all three variants.

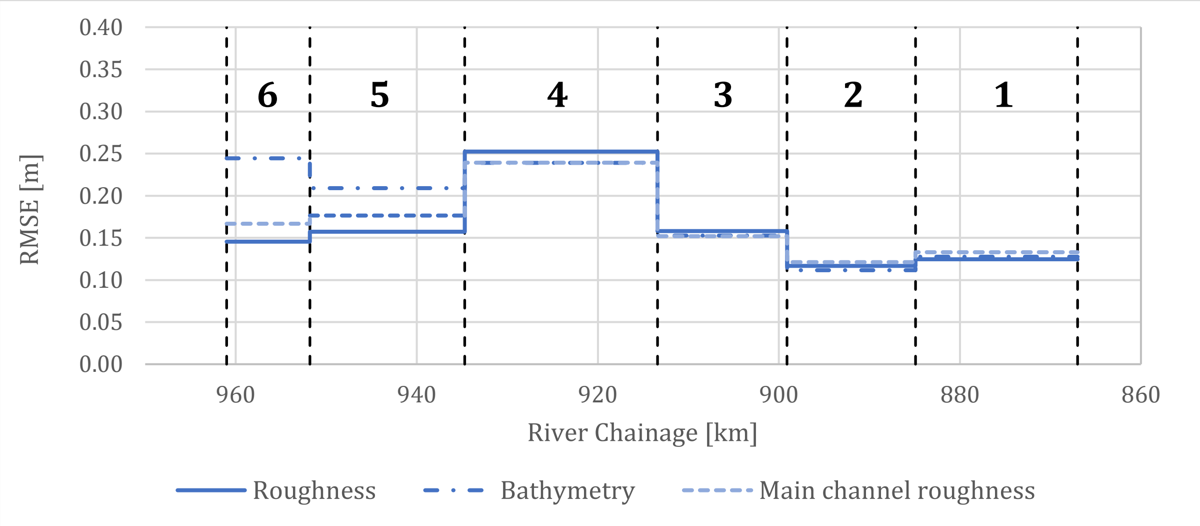

Figure 28: Comparison of the RMSE values of the calibration variants after the calibration.

Figure 29 shows that the RMSE values are approximately the same for most sections, with the exceptions being sections 4 and 6. In section 4 the main channel roughness has a significantly larger RMSE compared to the other two variants, and in section 6 the bathymetry has a significantly larger RMSE compared to the other two variants. Just as in Figure 28, the RMSE values for sections 1 to 3 are relatively small for all three variants.

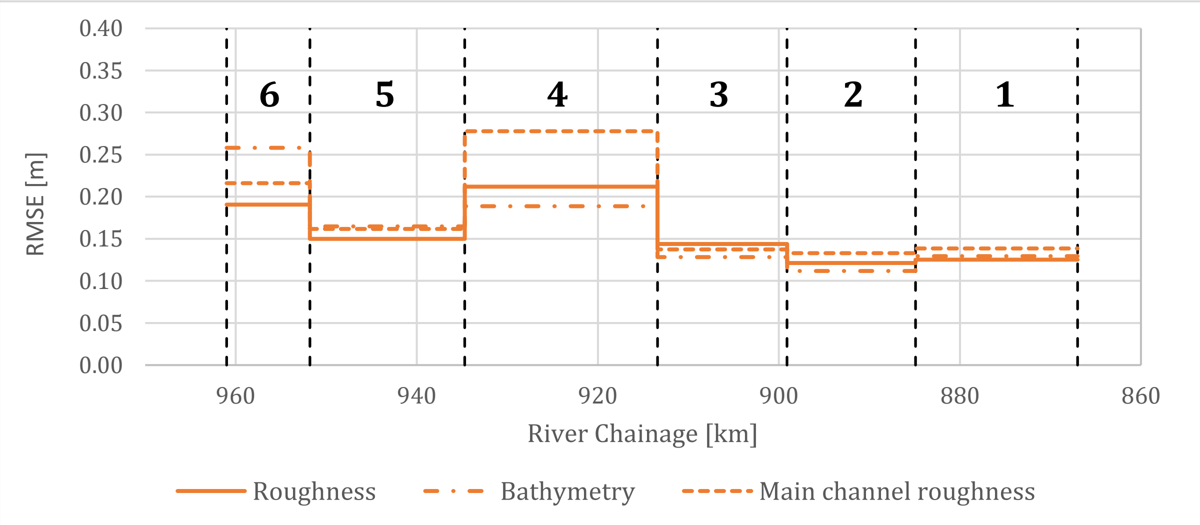

Figure 29: Comparison of the RMSE values of the calibration variants after the 1993 validation.

Figure 30 shows that the RMSE values have approximately the same order of magnitude for each section, with the exception being the bathymetry in section 4. Sections 2 and 6 also show some differences between the variants but these are not as large as in section 4. The RMSE values are relatively small in sections 1 to 3 just as in Figures 28 and 29.

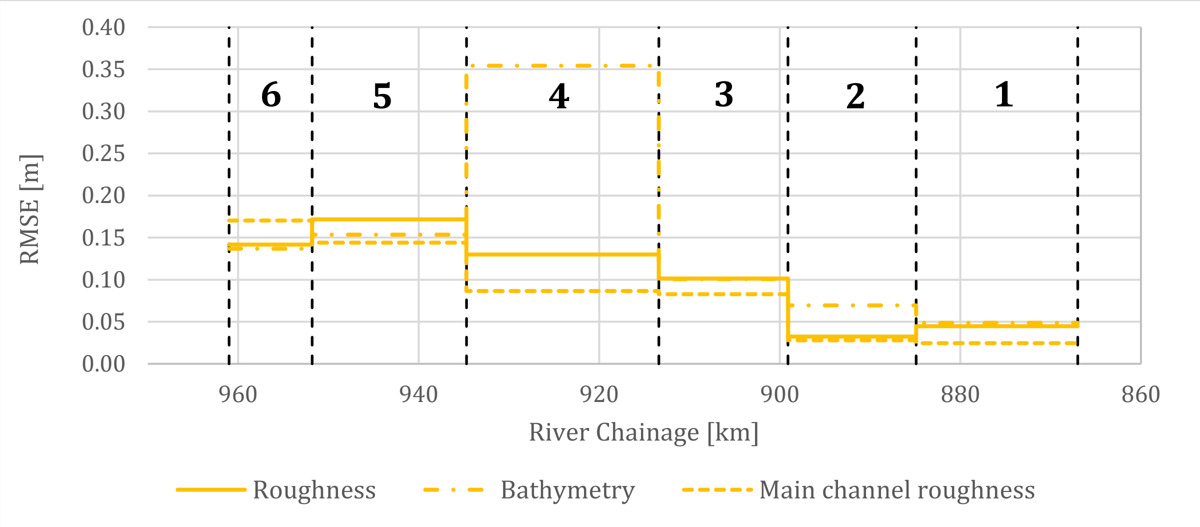

Figure 30: Comparison of the RMSE values of the calibration variants after the 2011 validation.

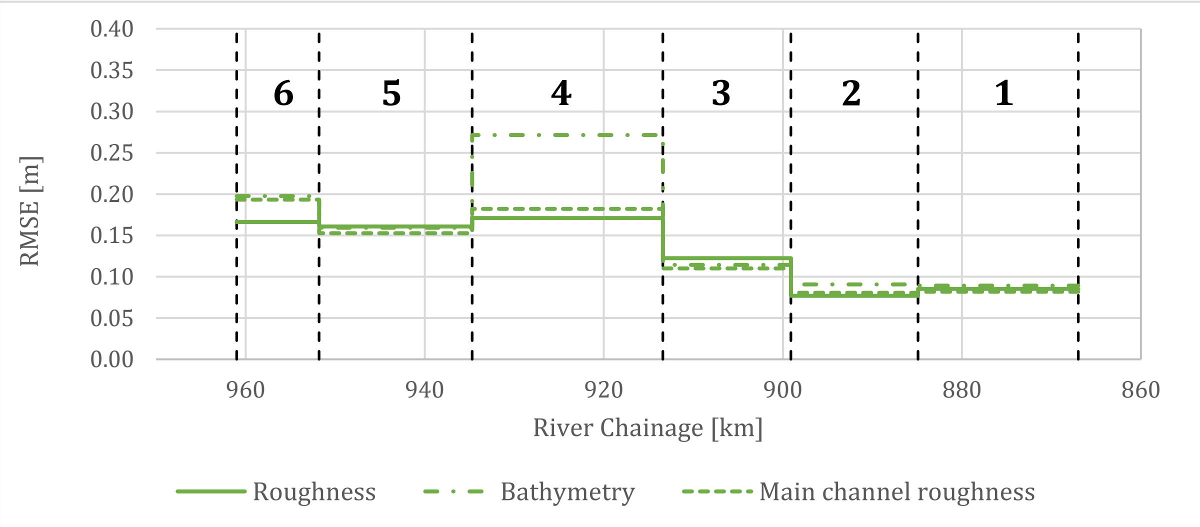

Figure 31: Comparison of the average RMSE values per section of the calibration variants after validation.

Based on the results shown in Figures 28 to 31 it can be said that for most sections the bathymetry has a similar RMSE value when compared to the roughness and main channel roughness. This means that the accuracy is also similar for most sections. The exception is section 4 after validation. Overall the bathymetry seems a viable alternative to roughness and main channel roughness when looking at the average RMSE values and the RMSE values per section.

Figures 32 and 33 show the water levels during the calibration of section 6 using roughness and bathymetry. The shapes of the simulated water levels are different in Figures 31 and 32. Figure 33 shows a slightly flatter curve and as a result a less good fit compared to Figure 32. This is similar for most sections. The curve of the water level was flatter when increasing the bathymetry height compared to increasing the roughness value. This is probably a result of the linear and slightly nonlinear relationships of the bathymetry and roughness to the water level (as discussed in section 3.1.3.). The shape of the water level curve stays the same when adjusting the bathymetry height, but becomes steeper or flatter when increasing or decreasing the roughness values.

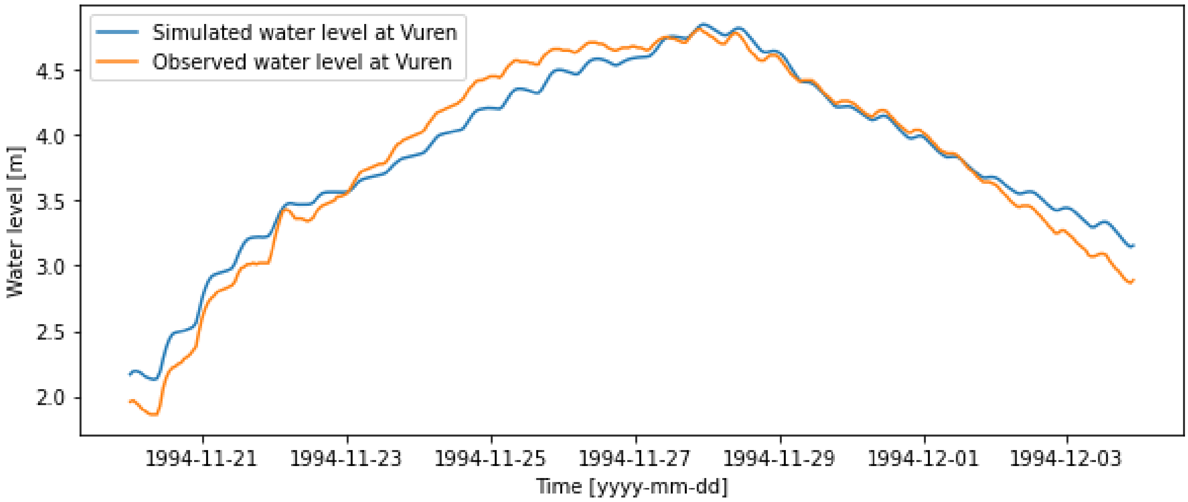

Figure 32: Hydrograph of section 6 calibrated using the roughness.

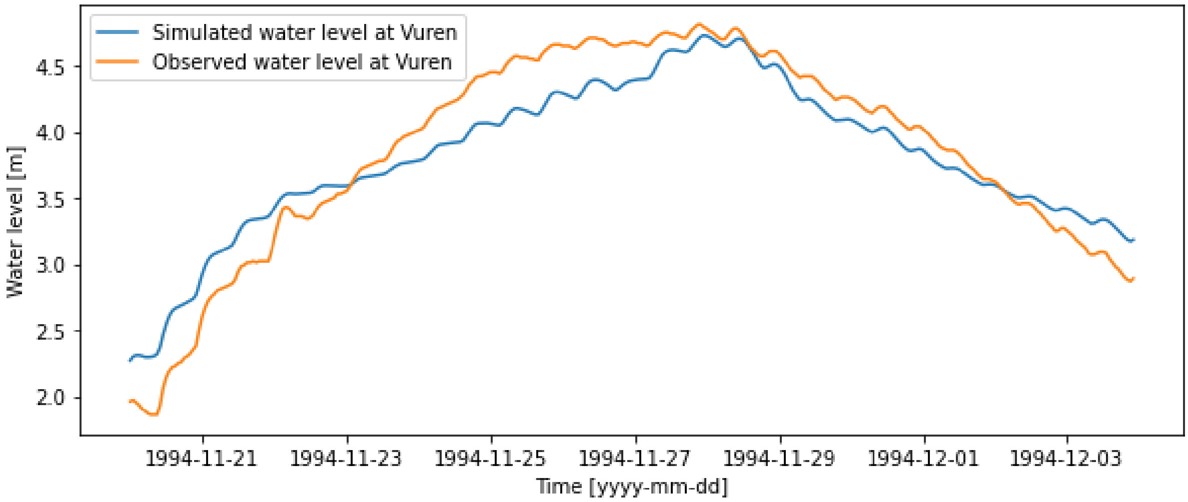

Figure 33: Hydrograph of section 6 calibrated using the bathymetry.

4 DISCUSSION

4.1 COMPARISON WITH OTHER STUDIES

Jiang et al. (2021) combined the roughness and bathymetry into one parameter and used that to calibrate the hydraulic model. This resulted in RMSE values of 0.44 m and 0.50 m at two observation stations, which is significantly larger than the results in this report. However, the research by Jiang et al. (2021) was performed using a larger study area (433 km long), and there was no geometry data.

Neal et al. (2015) obtained the same accuracy for a calibration were the bathymetry was included as a calibration parameter compared to a calibration without including the bathymetry and only using the roughness. The results in this report show a similar pattern, where the use of bathymetry as a calibration parameter is just as accurate as using roughness.

However, Neal et al. (2015) did show that the Manning roughness coefficient was much higher when the bathymetry was not included. This was caused by a lack of bathymetry data. They assumed a rectangular channel, and this meant that the roughness had to adjust a lot to reduce this uncertainty. The lack of bathymetry data made the use of bathymetry as a calibration parameter valuable. The results presented in this report are based on a case were the bathymetry geometry is already known quite precisely. This is reflected in the roughness values in the calibration because they did not increase or decrease to physically unrealistic values. It is very likely that if a rectangular channel was assumed for the Waal, high roughness values would have resulted from the calibration.

Khanarmuei et al. (2019) reported significant improvement in RMSE and NSE values when calibrating using bathymetry and roughness compared to only roughness. This is different compared to the findings of Neal et al. (2015). However, Khanarmuei et al. (2019) performed the calibration for an estuarine region, while Neal et al. (2015) performed it for a river channel. The results from this report do not show an improvement when using both parameters in combination. The RMSE values obtained by using roughness as a calibration parameter did not improve with additional calibration using bathymetry. This is probably caused by the fact that the bathymetry was known quite precisely, and the roughness values were able to reduce the small uncertainty introduced by the bathymetry.

Cea & French (2012) did show that calibration that incorporates bathymetric uncertainty can be significantly more efficient than calibrating using only the roughness as a calibration parameter. The results in this report show no improvement when both the roughness and the bathymetry are used as calibration parameters. As mentioned in the previous paragraph, this probably has to do with the fact that the bathymetry was already known quite precisely. Also, Cea & French (2012) did perform their research for an estuarine region whereas this report focussed on a river.

4.2 LIMITATIONS

Material

The peak discharges of the three discharge waves differ in height. This can be an advantage and disadvantage. For comparison of the roughness and bathymetry, it can be seen as a disadvantage because it is an extra factor that changes between the calibration and validations. It can also be seen as an advantage because the effect of roughness and bathymetry on the water level for different peak discharges can be studied. However, something similar has been done in the SA so it does not add much in the calibration.

Another limitation is the changing bathymetry between the calibration and validations. Because both the bathymetry and the discharge wave change between the calibration and validations the effect of only one of the individual parameters is not clear. However, using a discharge wave from a different year with the 1995 bathymetry is not a realistic scenario. It could have been an option for the validation, but the choice has been made to match the discharge waves with the schematizations from the same year.

Method

Sensitivity analysis

The method used for the SA is a simple perturbation of parameters. The limitation of this method is that it does not take the entire space of variability of the input parameters into account. This means that only the effect of the input parameters within certain boundaries is studied. This is not a problem however, since the relative linear relationships of the roughness and bathymetry with the water level suggests that the effect on the water level outside of the chosen boundaries is approximately the same. Moreover, moving far beyond the chosen ranges of roughness and bathymetry is of no use for the calibration and validation, so the effect on the water level is less important at these extremes.

It is assumed that the roughness and bathymetry are independent variables that do not influence each other. This is not completely true, but the influence of the roughness on the bathymetry and vice versa is deemed small enough to analyse them as independent parameters. If this effect has to be included a multi-variate analysis needs to be performed. Herein the combined effect of the roughness and bathymetry on the water level is analysed.

The downstream boundary condition is a constant water level. It is calculated based on the local cross-section, roughness value, and discharge. The calculation is a theoretical water level and not an observed one. This means that the water level may differ from the observed water level for the same cross-section, roughness value, and discharge. Since it has a significant influence on the downstream part of the study area it does introduce some inaccuracy in the results. For the SA this inaccuracy has been reduced by choosing measurement points further upstream away from the downstream boundary condition.

Both the roughness and bathymetry are studied within a certain range. These ranges are hard to compare directly. It is hard to quantify how much roughness change is equal to a certain amount of bathymetry change. The effect of the roughness on the water level is much larger than that of the bathymetry for the chosen range. It is possible to reduce this difference by just decreasing the range of the roughness or increasing the range of the bathymetry. Both ranges are based on physically realistic values, but that does not guarantee that the comparison is completely fair.

Roughness calibration and validation

The method of calibration and validation using the main channel roughness is the same as when using the main channel and floodplain roughness, so the limitations mentioned here apply to that variant as well.

The calibration window of 14 days is used for all three discharge waves. This creates differences in the discharge range. So besides the differences in peak discharge, there is also a difference in the discharge range between the calibration and validations. This is not optimal if the goal is to compare the roughness and bathymetry, because it introduces an extra variable that influences the results. However, the same 14-day windows were used for the roughness and bathymetry, so in that way, the consistency was still there.

The starting value for the main channel roughness is somewhat high in hindsight. A roughness value of 0.030 based on a sediment diameter of 1 to 2 mm is relatively large for the Waal because this corresponds to coarse sand (Arcement & Schneider, 1989). A smaller diameter of 0.5 mm for example corresponding to an average sand channel (Arcement & Schneider, 1989) would have been more realistic. This would have resulted in a starting roughness value of 0.022. This starting value influences the step size used in the calibration and in the end the percentage change of the roughness. A smaller starting value results in a larger change in roughness needed for the optimal RMSE.

The limitations of the validation were mainly caused by the discharge waves and schematizations that were used, and this has been discussed in the section Material.

Bathymetry calibration and validation

The bathymetry has been altered by adjusting the main channel and the floodplain bathymetry heights. The range of the bathymetry was based on the uncertainty caused by small sand dunes. These small sand dunes are found mainly in the main channel, so only adjusting the main channel bathymetry height would have been more realistic. This has not been done due to practical reasons, since only adjusting the main channel height would have been much more time intensive compared to adjusting the complete cross-section. This is because of the way cross-sections are programmed in SOBEK. It is made up of multiple points in an x and z plane. Increasing the height of all points in a cross-section does not cause problems, but when only raising certain points (only the main channel) the cross-sections get abnormal shapes. To correct this each cross-section needs to be adjusted individually, instead of all cross-sections at once in a section. This takes much more time and is impractical, so the choice has been made to raise the complete cross-section.

Calibration variants comparison

The minimal step size for the roughness is 1 per cent of the initial value, resulting in a step size of $3.0*10^{-4}$ and $3.5*10^{-4}$ for the main channel and floodplain, respectively. The minimal step size for the bathymetry is 5 cm. It is hard to quantitatively compare these minimal step sizes. The minimal step size does have an influence on the RMSE and thus the accuracy of the calibration variants. It is therefore important that the minimal step sizes are comparable, but this is not thoroughly investigated in this research.

4.3 Potential

This research gives a first insight into the applicability of bathymetry as a calibration parameter for a hydraulic river model in addition to physical roughness. This was not well known in the current literature as indicated in section 1.2. It gives a first indication of the feasibility of the bathymetry as a calibration parameter compared to the roughness. The bathymetry may have a smaller influence on the water level than the roughness, but the effect is still large enough to be considered in the calibration. A good situation where the bathymetry can be used as a calibration parameter is one where the roughness values of a river are well-known but the bathymetry data is uncertain.

4.4 GENERALISATIONS

A single study area was used, which means that the results could be specific to the river Waal. If an additional study area was used containing a river with different properties, the results of both areas could be compared and some similarities and differences could have been determined.

However, the results can still apply to rivers with approximately the same properties. The main focus of the research was on roughness and bathymetry, so rivers that have roughness or bathymetry properties similar to the Waal could benefit from these results.

The research was carried out using SOBEK as the modelling software, which uses integrated 1D/2D modelling. The results are nonetheless not limited to these types of models, but can also apply to 2D or even 3D modelling. The roughness and the bathymetry are fundamental properties of rivers and hydraulic river models, so the same patterns should show up in all modelling variants. The exact influences of the roughness and bathymetry on the water level will probably vary between different modelling variants, but the general patterns should stay consistent.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The main objective of this master thesis was to determine and compare the effect of roughness and bathymetry as calibration parameters on the accuracy of simulated water levels in a hydraulic river model. Five research questions were defined to reach this objective.

The research questions have been answered and the main objective has been achieved by performing several steps. Firstly a sensitivity analysis (SA) was done where the influence of the roughness and the bathymetry on the water level was investigated. The results of this SA answer the first research question.

Thereafter the river Waal was calibrated using the main channel and floodplain roughness, bathymetry, and main channel roughness as calibration parameters. This was done using the 1995 schematization and discharge wave. These calibrated models were thereafter validated using the 1993 and 2011 schematizations and discharge waves. The accuracy of these different calibration variants was determined based on the Root Mean Square Error (RMSE). The results of the calibration and validation answer the second to last research questions.

Research question 1: Sensitivity analysis

The results of the SA showed that the main channel roughness had a much larger influence on the water level than the floodplain roughness for all discharges. The effect of the floodplain roughness did increase with increasing discharge, but the main channel roughness was dominant in all tested cases.

The SA also showed that the effect of the bathymetry on the water level did not increase or decrease for different discharges. This indicates that the discharge is not the main factor in determining the effect of the bathymetry on the water level. Instead, it seems that the cross-section of the river plays a larger role in increasing or decreasing this effect.

The most important result of the SA was that the roughness had a larger effect on the water level than the bathymetry for the chosen roughness value range and bathymetry height range. The bathymetry showed a linear and the roughness a slightly nonlinear relationship with the water level.

Research questions 2 to 5: Calibration and validation

Calibration using the roughness showed increases in roughness values for all sections except one. The bathymetry also increased in all sections except one. The calibration using the main channel roughness provided similar changes in roughness values compared to calibration using the main channel and floodplain roughness, albeit with slightly larger increases or decreases in roughness values.

The validation yielded similar average RMSE values for all three calibration variants. The bathymetry showed slightly higher RMSE values on average, but these differences were not significant enough to deem the bathymetry less accurate as a calibration parameter than the roughness. Incidentally, there were large differences between the calibration methods for a single section, but overall the RMSE values for single sections were comparable.

Main objective

Overall this research shows that using the bathymetry as a calibration parameter for a hydraulic model is as accurate as using the roughness. However, the effect of the bathymetry on the water level is smaller than that of the roughness.

5.2 RECOMMENDATIONS

Further research is recommended into the use of bathymetry for calibrating a hydraulic river model. This research can extend into four directions that are explained below.

The first recommended direction for further investigation is the effect of bathymetry as a calibration parameter on both the water level and the accuracy of the calibration for a different study area. This study area should contain a river with different roughness and bathymetry properties compared to the Waal. The river could be much narrower or have a larger average grain size than the Waal. This can be a river inside or outside the Netherlands, as long as enough data is available for the sediment sizes, bathymetry, discharge, and water levels. The most ideal situation would be to do this research using modelling software that uses an integrated 1D/2D modelling approach. This would reduce the uncertainties introduced by using another modelling approach. The results of this research could be compared to the results of the Waal and comparisons can be made between the two different rivers.

The second recommended direction for further investigation is the effect of bathymetry as a calibration parameter both on the water level and the accuracy of the calibration with the use of a different modelling approach. This could be 1D or 2D modelling. 3D modelling would also be possible, but realistically 3D modelling does not add much over 2D modelling for the given scenario. It is expected that the use of a different modelling approach does not result in completely different outcomes compared to the results described in this report. However, additional research is necessary to confirm these claims.

The third recommended direction for further investigation is the effect of the bathymetry on the accuracy of the calibration when calibrating for low discharges. The results presented in this report are all based on high discharges, but the effects of the bathymetry and roughness could be different when the discharge is lower.

The fourth and last recommended direction is the effect the shape of a cross-section has on the influence of the bathymetry on the water level. The SA did not show a clear relationship between the discharge and the effect of the bathymetry on the water level. It was proposed that the cross-section was of larger influence than the discharge, but the relationship was not exactly clear. It would be interesting to do further research into this.

REFERENCES

Arcement, G. J., & Schneider, V. R. (1989). Guide for selecting Manning's roughness coefficients for natural channels and flood plains. In *US Geological Survey Water-Supply Paper* (Vol. 2339). https://doi.org/10.3133/wsp2339 (last visited on 24/10/2022)

Aronica, G., Hankin, B., & Beven, K. (1998). Uncertainty and equifinality in calibrating distributed roughness coefficients in a flood propagation model with limited data. *Advances in Water Resources*, *22*(4), 349–365. https://doi.org/10.1016/S0309-1708(98)00017-7 (last visited on 25/10/2022)

Berends, K. (2013). *Rijnmodellen 5e generatie SOBEK*. https://iplo.nl/thema/water/applicaties-modellen/modelschematisaties/contact-modelschematisaties/aanvraagformulier/ (visited on 05/12/2022)

Berends, K. (2014). *Rijnmodellen 5e generatie SOBEK concept*. https://iplo.nl/thema/water/applicaties-modellen/modelschematisaties/contact-modelschematisaties/aanvraagformulier/ (last visited on 05/12/2022)

Bomers, A., Schielen, R. M. J., & Hulscher, S. J. M. H. (2019). The influence of grid shape and grid size on hydraulic river modelling performance. *Environmental Fluid Mechanics*, *19*(5), 1273–1294. https://doi.org/10.1007/s10652-019-09670-4 (last visited on 12/09/2022)

Cea, L., & French, J. R. (2012). Bathymetric error estimation for the calibration and validation of estuarine hydrodynamic models. *Estuarine, Coastal and Shelf Science*, *100*, 124–132. https://doi.org/10.1016/j.ecss.2012.01.004 (last visited on 12/09/2022)

Chang, C., Yang, J., & Tung, Y. (1993). Sensitivity and uncertainty analysis of a sediment transport model: a global approach. *Stochastic Hydrology and Hydraulics*, *7*(4), 299–314. https://doi.org/10.1007/BF01581617 (last visited on 18/10/2022)

Chow, V. Te. (1959). *Open Channel Hydraulics*. McGraw Hill. https://heidarpour.iut.ac.ir/sites/heidarpour.iut.ac.ir/files/u32/open-chow.pdf (last visited on 14/06/2023)

de Vriend, H. (2015). The long-term response of rivers to engineering works and climate change. *Proceedings of the Institution of Civil Engineers - Civil Engineering*, *168*(3), 139–144. https://doi.org/10.1680/cien.14.00068 (last visited on 20/10/2022)

Deltares. (2015, July 8). *SOBEK Suite Deltares*. https://www.deltares.nl/en/software-and-data/products/sobek-suite (last visited on 25/05/2023)

Hall, J. W., Tarantola, S., Bates, P. D., & Horritt, M. S. (2005). Distributed Sensitivity Analysis of Flood Inundation Model Calibration. *Journal of Hydraulic Engineering*, *131*(2), 117–126. https://doi.org/10.1061/(ASCE)0733-9429(2005)131:2(117) (last visited on 12/09/2022)

Hankin, B. G., & Beven, K. J. (1998). Modelling dispersion in complex open channel flows: Equifinality of model structure (1). *Stochastic Hydrology and Hydraulics*, *12*(6), 377–396. https://doi.org/10.1007/s004770050026 (last visited on 25/10/2022)

Hardy, R. J., Bates, P. D., & Anderson, M. G. (1999). The importance of spatial resolution in hydraulic models for floodplain environments. *Journal of Hydrology*, *216*(1–2), 124–136. https://doi.org/10.1016/S0022-1694(99)00002-5 (last visited on 25/10/2022)

Hegnauer, M., Kwadijk, J., & Klijn, F. (2015). The plausibility of extreme high discharges in the river Rhine. *Technical Report*, *November*. https://doi.org/10.13140/RG.2.1.1325.5768 (last visited on 14/06/2023)

Huthoff, F., & Augustijn, D. C. M. (2005). Channel roughness in 1D steady uniform flow: Manning or Chézy? In A. Makaske, H. P. Wolfert, & A. G. van Os (Eds.), *Proceedings NCR-days 2004, Research for managing rivers; present and future issues, NCR publication 26-2005* (Issues 1568-234X, pp. 98–100). https://research.utwente.nl/en/publications/channel-roughness-in-1d-steady-uniform-flow-manning-or-ch%C3%A9zy (last visited on 14/06/2023)

Jiang, L., Westphal Christensen, S., & Bauer-Gottwein, P. (2021). Calibrating 1D hydrodynamic river models in the absence of cross-section geometry using satellite observations of water surface elevation and river width. *Hydrology and Earth System Sciences*, *25*(12), 6359–6379. https://doi.org/10.5194/hess-25-6359-2021 (last visited on 24/09/2022)

Khanarmuei, M., Suara, K., & Brown, R. J. (2019). Calibration and Assimilation in Hydrodynamic Model of a Micro-Tidal Estuary and Comparison with Lagrangian Drifter Data. *38th IAHR World Congress - "Water: Connecting the World," 38*, 6359–6368. https://doi.org/10.3850/38WC092019-1928 (last visited on 14/06/2023)

Lokin, L. R., Warmink, J. J., Bomers, A., & Hulscher, S. J. M. H. (2022). River Dune Dynamics During Low Flows. *Geophysical Research Letters*, *49*(8). https://doi.org/10.1029/2021GL097127 (last visited on 25/05/2023)

Merz, B., Blöschl, G., Vorogushyn, S., Dottori, F., Aerts, J. C. J. H., Bates, P., Bertola, M., Kemter, M., Kreibich, H., Lall, U., & Macdonald, E. (2021). Causes, impacts and patterns of disastrous river floods. *Nature Reviews Earth & Environment*, *2*(9), 592–609. https://doi.org/10.1038/s43017-021-00195-3 (last visited on 13/06/2023)

Neal, J. C., Odoni, N. A., Trigg, M. A., Freer, J. E., Garcia-Pintado, J., Mason, D. C., Wood, M., & Bates, P. D. (2015). Efficient incorporation of channel cross-section geometry uncertainty into regional and global scale flood inundation models. *Journal of Hydrology*, *529*, 169–183. https://doi.org/10.1016/j.jhydrol.2015.07.026 (last visited on 24/09/2022)

Pappenberger, F., Beven, K., Horritt, M., & Blazkova, S. (2005). Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations. *Journal of Hydrology*, *302*(1–4), 46–69. https://doi.org/10.1016/j.jhydrol.2004.06.036 (last visited on 12/09/2022)

Rameshwaran, P., & Willetts, B. B. (1999). Conveyance prediction for meandering two-stage channel flows. *Proceedings of the Institution of Civil Engineers - Water, Maritime and Energy*, *136*(3), 153–166. https://doi.org/10.1680/iwtme.1999.31747 (last visited on 25/10/2022)

Rijksoverheid. (2022). *Rivieren - Informatiepunt Leefomgeving*. https://iplo.nl/thema/water/applicaties-modellen/modelschematisaties/rivieren (last visited on 14/06/2023)

Rijkswaterstaat. (2016). *Rijkswaterstaat Waterinfo*. https://waterinfo.rws.nl/#!/thema/Waterkwantiteit (last visited on 25/05/2023)

Rijkswaterstaat. (2021). *oppervlaktewaterlichamen-KRW | Data overheid*. https://data.overheid.nl/en/community/datarequest/oppervlaktewaterlichamen-krw (last visited on 25/05/2023)

Saltelli, A., Ratto, M., Andres, T., Campolongo, F., Cariboni, J., Gatelli, D., Saisana, M., & Tarantola, S. (2007). Global Sensitivity Analysis. The Primer. In *John Wiley & Sons Ltd.* Wiley. https://doi.org/10.1002/9780470725184 (last visited on 28.09/2022)

Ten Brinke, W. B. M., Wilbers, A. W. E., & Wesseling, C. (2009). Dune Growth, Decay and Migration Rates during a Large-Magnitude Flood at a Sand and Mixed Sand–Gravel Bed in the Dutch Rhine River System. In *Fluvial Sedimentology VI* (pp. 15–32). Blackwell Publishing Ltd. https://doi.org/10.1002/9781444304213.ch2 (last visited on 28/09/2022)

van der Klis, H. (2003). *Uncertainty Analysis applied to Numerical Models of River Bed Morphology* [Delft University of Technology]. https://repository.tudelft.nl/islandora/object/uuid%3A22f7f615-c54f-4a0d-8dc8-daca5ef2d273 (last visited on 18/10/2022)

Wang, B., Fringer, O. B., Giddings, S. N., & Fong, D. A. (2009). High-resolution simulations of a macrotidal estuary using SUNTANS. *Ocean Modelling*, *26*(1–2), 60–85. https://doi.org/10.1016/j.ocemod.2008.08.006 (last visited on 13/09/2022)

Warmink, J. J., Booij, M. J., Van Der Klis, H., & Hulscher, S. J. M. H. (2007). Uncertainty in water level predictions due to various calibrations. *CAIWA*, 1–18. https://research.utwente.nl/en/publications/uncertainty-in-water-level-predictions-due-to-various-calibration (last visited on 12/09/2022)

Warmink, J. J., Janssen, J. A. E. B., Booij, M. J., & Krol, M. S. (2010). Identification and classification of uncertainties in the application of environmental models. *Environmental Modelling & Software*, *25*(12), 1518–1527. https://doi.org/10.1016/j.envsoft.2010.04.011 (last visited on 13/06/2023)

Warmink, J. J., Van der Klis, H., Booij, M. J., & Hulscher, S. J. M. H. (2011). Identification and Quantification of Uncertainties in a Hydrodynamic River Model Using Expert Opinions. *Water Resources Management*, *25*(2), 601–622. https://doi.org/10.1007/s11269-010-9716-7 (last visited on 25/10/2022)

Ylla Arbos, C. (2021). *Bed elevation and bed surface grain size (D50) Bovenrijn and Waal, 1926-2020*. 4TU.ResearchData. https://doi.org/10.4121/13065359.v2 (last visited on 10/06/2023)

APPENDIX A: ROUGHNESS AND BATHYMETRY INFLUENCE ON THE WATER LEVEL PER DISCHARGE

Figures A.1 to A.4 show the influence of the roughness and the bathymetry on the water level per discharge value. These results are part of section 3.1.3.

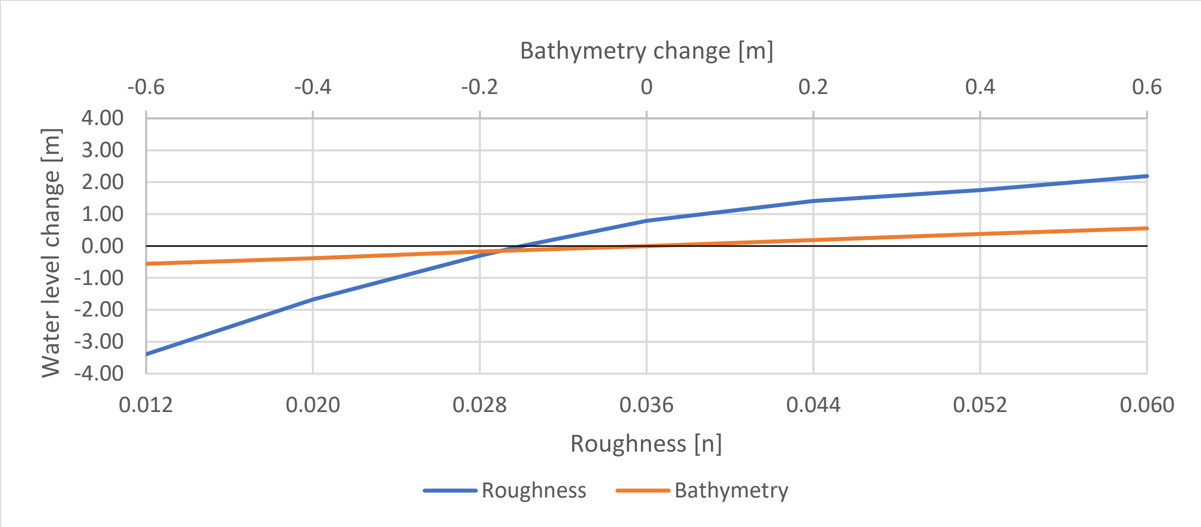

Figure A.1: Influence of the roughness and the bathymetry on the water level at a discharge of 4000 m³/s.

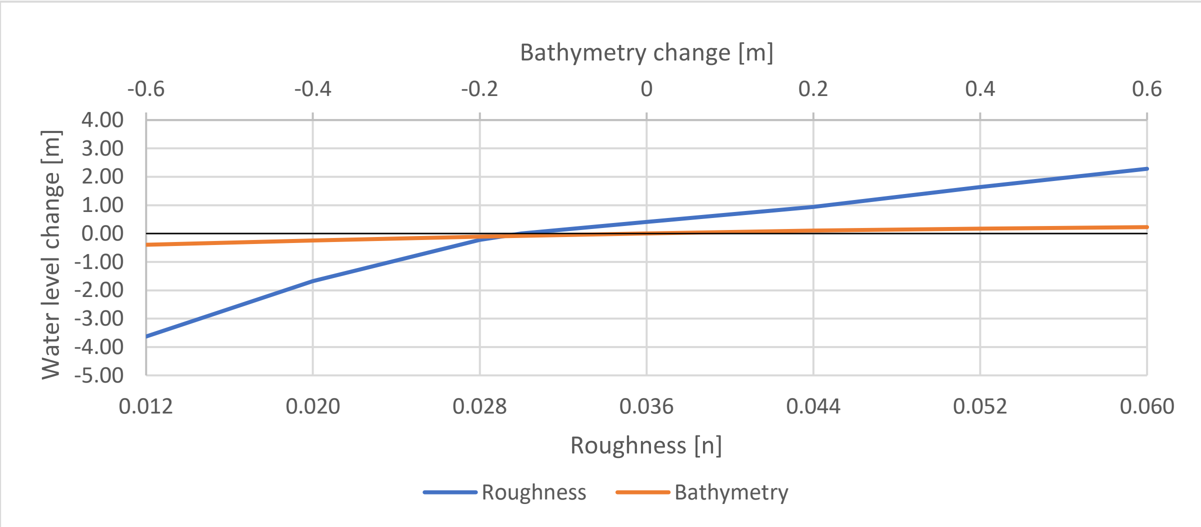

Figure A.2: Influence of the roughness and the bathymetry on the water level at a discharge of 5300 m³/s.

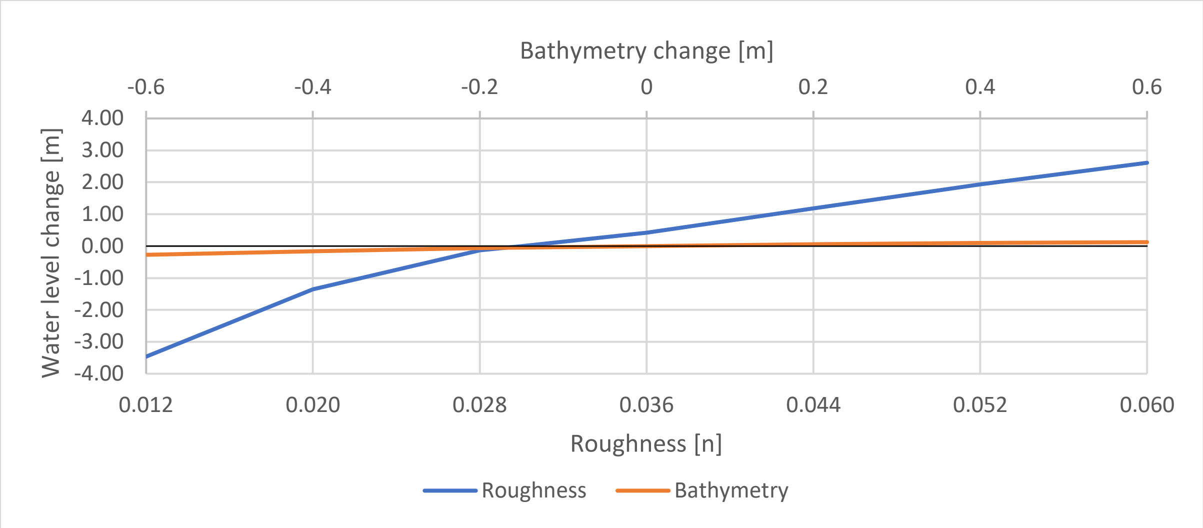

Figure A.3: Influence of the roughness and the bathymetry on the water level at a discharge of 6100 m³/s.

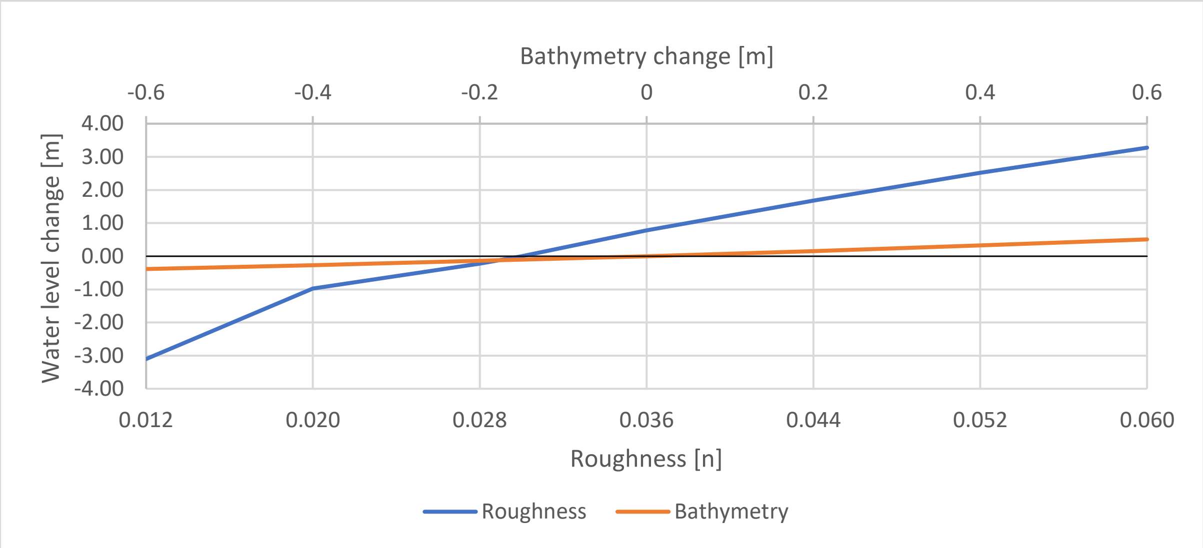

Figure A.4: Influence of the roughness and the bathymetry on the water level at a discharge of 7800 m³/s.