The influence of lateral inflow on the water level in the IJssel

MSc Thesis

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28 th of June, 2024

Rijkswaterstaat
Ministry of Infrastructure and Water Management

UNIVERSITY OF TWENTE.

Colophon

Title: The influence of lateral inflow on the water level in the IJssel

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Date: 28th of June 2024

Place: Enschede

Version: Final

Preface

This master thesis; 'the influence of lateral inflow on the water level in the IJssel' represents the completion of the master Civil Engineering and Management at the University of Twente. This research was possible through the collaboration with Rijkswaterstaat.

I would like to take this opportunity to express my gratitude to my supervisors at Rijkswaterstaat, Emiel and Raymond, for dedicating time and effort in guiding me through Rijkswaterstaat. I appreciate the brainstorm sessions, where their professional expertise and practical insights were crucial to the success of this project. They also involved me in social activities and made sure I could present my results at Waterschap Rijn and IJssel. Additionally, I like to thank Denie Augustijn and Anouk Bomers from the University of Twente for their academic perspectives on this research. Their critical feedback refined my results and improved my writing.

Next to my supervisors, I would like to thank my friends and family. Rik, your enthusiasm motivated my during the more challenging phases of my research. The support of my parents gave me the confidence to start and complete this master's program. Lastly, I would like to thank my friends for supporting me and making memorable times in Enschede.

I hope you enjoy reading this thesis.

Emma Beelen

Enschede, June 2024

Abstract

The Meuse flood in 2021 in the Netherlands was not accurately predicted due to the lack of consideration of lateral inflow in the discharge forecasting. Similar events may occur in other basins and more frequently. In December 2023, the IJssel, a river branch of the Rhine, experienced higher water levels than expected due to high lateral inflows. To improve forecasting, lateral inflow should be considered. Researching its influence on water levels can help to determine if it should be considered. Therefore, the aim of this research is to analyse the influence of lateral inflow on the water level and the shape of the discharge wave in the IJssel.

Discharge waves in the Rhine, Oude IJssel and Twentekanaal from the last 30 years were analysed based on their peak discharge, duration and shape. The timing was changed such that the peak of the laterals enter the IJssel at the same time of the peak of the IJssel is at their confluence point, representing the reference timing. The influence of the reference timing on the water level and shape of the discharge wave in the IJssel downstream of the laterals was analysed. The shape of the discharge wave in the IJssel without lateral inflow was altered by adjusting the skewness and width of the discharge wave. The influence of the changed shape on the water levels in the IJssel downstream of the laterals was analysed.

The discharge wave analysis showed that the highest and longest discharge waves in the Rhine occurred during high water season (November to April) and the peak discharge and duration showed a linear relation. Conversely, the discharge waves in the Oude IJssel and Twentekanaal also had high peak discharges during low water season and they did not show a linear relation between the peak discharge and duration.

Subsequently, the results of the changed timing showed that the timing where the peak discharge of the lateral entered the IJssel at the same time as the peak discharge in the IJssel resulted in the highest increase in water level. The increase in water level differed per location along the IJssel, from +17 cm at Doesburg to +27 cm at Zutphen and Wijhe. This difference was caused by the amount of lateral inflow that entered the IJssel. At Doesburg only lateral inflow from the Oude IJssel entered the IJssel, while at Zutphen and Wijhe, the Twentekanaal entered the IJssel as well. Additionally, the peak discharge from the Rhine determined the water level in the IJssel and thus the position in the river profile. The changing river profiles along the IJssel influences the change in water level due to lateral inflow.

Then, the results of the change in shape of the discharge wave in the IJssel showed that it affects the increase in water level in the IJssel due to lateral inflow. This was mainly a result of a change in total volume of the different shapes of discharge waves which affected the water level in the IJssel. At certain peak discharges, floodplains inundate at some locations along the IJssel, as the river profiles are different. The difference in increase in water level per shape had a maximum of +/- 4 cm, which made the influence of the shape less important than the influence of the timing.

Overall, the timing of the lateral inflow caused a higher increase in water level than the shape of the discharge wave in the IJssel. However, the timing that caused the highest increase in water level differs 4 days from the timing that occurred most in historical data. At peak discharges lower than 7,000 m^3/s in the Rhine, the same lateral inflow had larger influence on the water Level in the IJssel. At these discharges, lateral inflow can make a difference for navigation or the timing at when the floodplains inundate. The influence of lateral inflow along the IJssel differed per location due to the differences in river profile. At wider river profiles the influence of lateral inflow was smaller. It can be concluded that lateral inflow from the Oude IJssel and Twentekanaal can increase the water level in the IJssel, but the amount of increase was dependent on the location along the IJssel and the peak discharge in the Rhine.

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1 Introduction

In Northern Europe, the risk of more frequent floods due to climate change is higher than other regions in Europe. Regional changes in the timing of floods have already been observed in many areas. Autumn and winter floods occur earlier in the year caused by more rainfall and early snowmelt. During summer months, the probability of more intensive precipitation which can lead to flooding is increasing, even if the mean summer precipitation is decreasing (Kundzewicz et al., 2004). In the summer of 2021, the Meuse and its tributaries flooded due to a high amount of precipitation in a short period of time (De Bruijn & Slager, 2022). This flood caused extensive damage and inconvenience for inhabitants and the surrounding. Lateral inflow from the Geul and Roer, had a contribution of 10% of the total discharge during this event and increased the peak discharge. The peak discharge of the Geul entered the Meuse at the same time as the peak discharge in the Meuse was at their point of confluence. The inflow of the Roer was later than the peak discharge of the Meuse. However, due to an extended period of increased discharge from the Roer it did contribute to the peak discharge in the Meuse as well.

Lateral inflow represents water from runoff and the drainage from a sub basin to the main river (Biancamaria et al., 2009). Lateral inflow during a flood can have a significant effect on the reservoir by affecting the shape of the hydrograph and water level in the main river. Lateral inflow can increase the peak height, may shift the peak forward and causes an increase in flood volume (Moramarco et al., 2005). The amount of lateral inflow is mainly determined by rainfall, snow melt and the topography of the sub basin. The topography of the basin contributes to the speed at which the water flows to the river and makes the influence of lateral inflow very case specific. It is important to take into account lateral inflow while modelling river floods.

1.1 Knowledge gap and research

When predicting the flood in the Meuse in 2021 in the Netherlands, the influence of lateral inflow was not taken into account properly when the discharge wave was forecasted. Lateral inflow changed the shape of the discharge wave by increasing the peak discharge and changing the peak time (Task Force Fact-finding hoogwater, 2021). It is likely that similar events may happen in other basins as well and they will occur more frequently.

Another event happened in the IJssel in December 2023. The IJssel is a river branch of the Rhine with several tributaries that can cause high lateral inflow (Van Zetten et al., 2020). During this event, the water level in the IJssel was higher than would be expected based on the discharge from the Rhine at Lobith, indicating the presence of lateral inflow. The Oude IJssel and Twentekanaal had high discharges for a long period of time, which contributed to a higher water level in the IJssel (Deltares, 2024b).

Forecasting of the water levels in the IJssel is now mainly based on the discharge in the Rhine at Lobith, and less on lateral inflow. To improve forecasting of water levels in the IJssel, lateral inflow can be important. By researching the influence of lateral inflow on the water level in the IJssel, their influence can be clarified. Based on the results it can be determined whether lateral inflow needs to be taken into account or not.

1.2 Research aim and questions

The aim of this study is to analyse the influence of lateral inflow on the water level and on the shape of the discharge wave in the IJssel. The research aim can be translated into the following main research question:

"What influence does lateral inflow exert on the shape of the discharge wave in the IJssel?"

The main question can be answered by answering three sub-questions. The first sub-question emphasizes on analysing discharge waves during increased discharges in the Rhine, Oude IJssel and Twentekanaal. This will provide insight into the types of waves that occur within these rivers and canal.

RQ1: What are characteristic shapes of discharge waves in the Rhine, Oude IJssel and Twentekanaal?

The second sub-question will focus on the timing of confluence between the discharge wave in the IJssel and those the discharge waves from the Oude IJssel and Twentekanaal. The situation that causes the highest increase in water level will be found by varying the timing.

RQ2: What timing of confluence between the laterals and the IJssel results in the highest increase in water level due to lateral inflow in the IJssel?

The third sub-question will focus on the influence of different shapes of the discharge waves in the IJssel.

RQ3: At what shape of discharge wave in the IJssel does lateral inflow result in the highest increase in water level in the IJssel?

1.3 Study area

The IJssel is a branch of the Rhine in the Dutch part of the Rhine basin (Figure 1). The Rhine originates in the Swiss Alps and flows into the North Sea in the Netherlands. 5 km downstream of Lobith, where the Rhine enters the Netherlands, the Rhine splits into the Waal and the Pannerdensch kanaal. The Waal flows to the west and ultimately into the North Sea and the Pannerdensch kanaal splits after 6 km in the IJssel and the Nederrijn. The Nederrijn turns into the lek and then flows west towards the North Sea. The IJssel flows north into the Ketelmeer which is connected with the IJsselmeer.

The Rhine enters the Netherlands at Lobith with a mean discharge around 2,200 m^3/s. In the last 100 years, the discharge varied between 600 to 12,600 m^3/s (Expertise Netwerk Waterkeren, 2007). The approximate distribution of the discharge from the Rhine is as follows: 2/3 to the Waal, 1/3 and Pannerdensch kanaal. The discharge from the Pannerdensch kanaal splits into the Nederrijn/Lek and the IJssel, which receive 2/9 and 1/9 of the discharge from the Rhine respectively. This distribution can change during high and low discharges due to the deployment of weirs in the Nederrijn and the regulation works at the bifurcation points (Havinga, 2016).

High discharges in the Dutch Rhine branches are caused by high amounts of rainfall and/or melt water in the whole Rhine basin. The water level in the Dutch Rhine branches is mainly determined by the discharge from the Rhine, but can be influenced by local inflow. In the downstream sections of the Rhine branches, the sea level in the North Sea and the water level in the IJsselmeer also have influence on the water level in the Rhine (Expertise Netwerk Waterkeren, 2007).

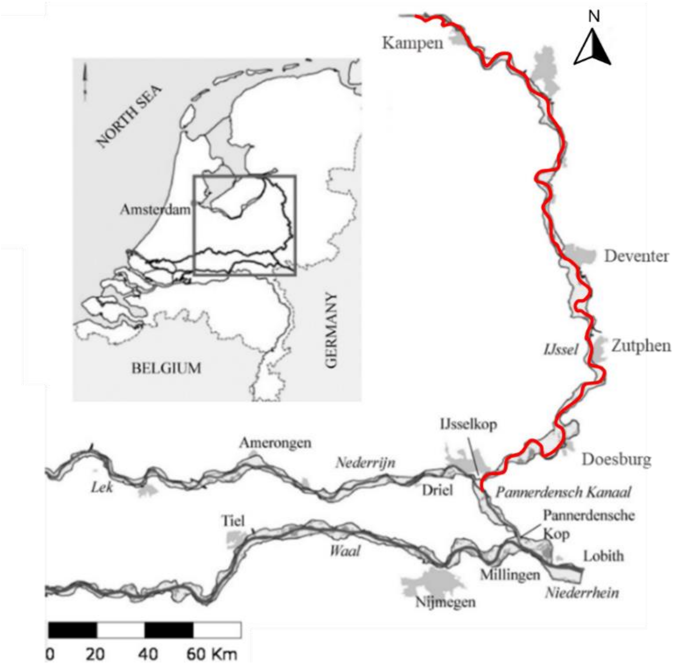

Figure 1 Overview of the Dutch Rhine system (Havinga, 2016), with in red the IJssel

The IJssel splits from the Nederrijn at Westervoort, upstream from Arnhem, and flows into the IJsselmeer. The length of the river is approximately 127 km and the width of the main channel varies between 70 and 140 meters. The normal discharge that enters the IJssel at Westervoort is between 170 and 590 m^3/s. Increased water levels in the IJssel are mainly caused by high discharges from the Rhine, rainfall in the catchment area and high water levels in the IJsselmeer caused by storm (Rijkswaterstaat, 2023b).

The IJssel meanders more compared to the other Rhine branches which is still visible in the number of bends. Especially the part between the IJsselkop and Deventer consists of several large bends, while downstream from Deventer the IJssel becomes more straight and wider. Nowadays, the IJssel is trained with groynes and bank reinforcements (Makaske et al., 2008). The part where the IJssel enters the IJsselmeer is called the IJsseldelta. The IJsseldelta is characterized by creeks and intervening islands. The IJsselmeer, IJssel, Vecht, Drentse kanalen and the Sallandse Weteringen converge, which makes the water system complex and vulnerable (Drents Overijsselse Delta, 2022). A special characteristic of the IJssel is the high amount of lateral inflow compared to other Rhine branches (Van Zetten et al., 2020).

The focus of this study will be on the inflow of the Oude IJssel and Twentekanaal as they have the highest extreme discharges. From the eight main laterals (RURA-Arnhem, 2018), the other six laterals have a small normal discharge (<5 m^3/s) and a relatively small extreme discharge (40 m^3/s, return period= 1/100 years) (Waterschap Rijn en IJssel, n.d.).

The Oude IJssel originates in Germany and joins the IJssel at Doesburg (Figure 2). In Germany, the Oude IJssel starts as a small stream and becomes larger further downstream, up to a width of 65 meters. The total length of the river is approximately 81 km of which 26 km is located in the Netherlands. The normal discharge of the Oude IJssel is up to 35.7 m^3/s. The water level in the Oude IJssel at Doesburg is mainly determined by the water level in the IJssel, while further upstream, at Doetinchem, the water level is mainly determined by the discharge of the Oude IJssel itself. A weir structure is situated near Doesburg that regulates the water level in the Oude IJssel up to +10m NAP. When the water level in the IJssel is higher than +10m NAP, an open connection arises between the IJssel and the Oude IJssel, resulting in a situation where water can flow from the IJssel to the Oude IJssel. However, a water level higher than +10m NAP in the IJssel is an extreme high water level and does not occur often. High water levels in the Rhine are often accompanied by high water levels in the Oude IJssel (Botterhuis & Klopstra, 2004).

The Twentekanaal starts at Enschede and joins the IJssel north from Zutphen (Figure 2). Downstream from Hengelo there is a branch going to Almelo. The part between Enschede and Zutphen has a length of 47 km and the branch to Almelo has a length of 16 km. The canal has a width of 50 meters. The normal discharge at Almen varies between -30 and 50 m^3/s. When the water level in the Twentekanaal becomes too low, water is pumped from the IJssel into the Twentekanaal, resulting in a negative discharge. The total height difference between Enschede and Zutphen is around 20 meters. Three locks in the canal make up for this height difference. These locks are situated close to Hengelo, Delden and Eefde. The two main functions of the Twentekanaal are shipping and water availability (Rijkswaterstaat, 2023a).

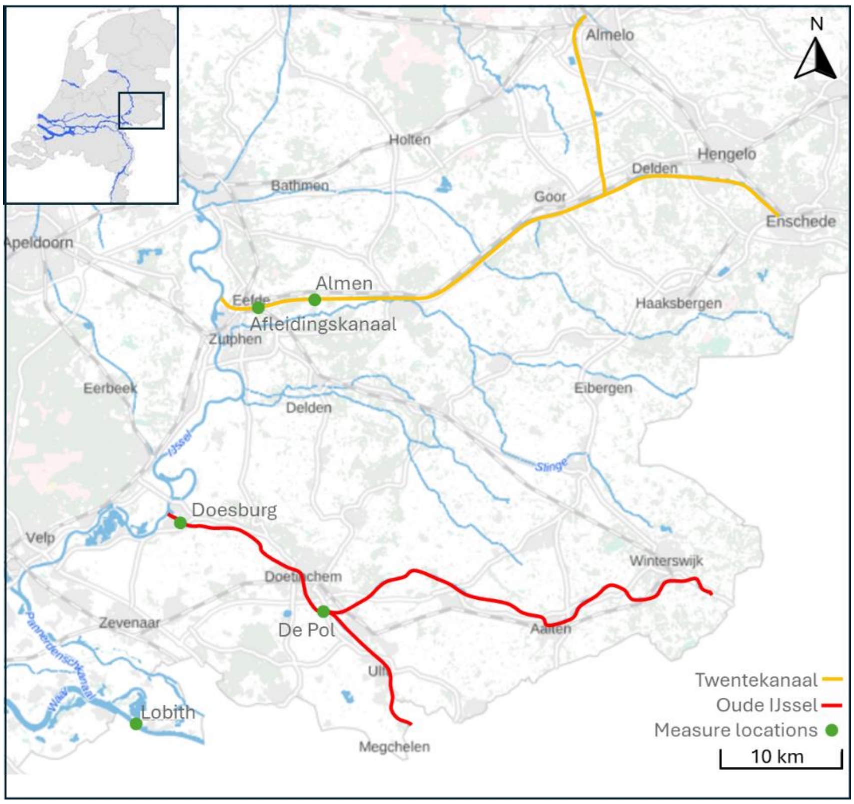

Figure 2 Overview of the position of the Oude IJssel and Twentekanaal in the Netherlands, including measure locations used for data analysis. Background obtained from (Kadaster, n.d.)

1.4 Outline

The structure of the report is as follows: Chapter 2 describes the model and the data that is used in this study. The methodology is described in chapter 3, which contains the methodology for the discharge wave analysis, the influence of timing of the lateral inflow and the shape of discharge waves in the IJssel. The results are given in chapter 4. In chapter 5, the results of this study are discussed. Finally, the conclusion and recommendations are given in chapter 6.

2 Model and Data

This chapter gives a description of the model that is used during this study, including river profiles, boundary conditions, lateral inflow and observation points. In addition, an overview of the data used in this study is given.

2.1 SOBEK model

SOBEK is a software package for the modelling and analysis of diverse hydraulic systems such as, irrigation and drainage systems, river systems and sewerage. The modules within the SOBEK modelling suite can simulate the complex flows and related processes in almost any system. They accurately represent various phenomena and physical processes within a 1D network systems. Some of the models available through SOBEK can have 2D horizontal grids to model floodplains additionally to the 1D network system (Deltares, n.d.).

One model that is available through SOBEK is D-Flow 1D, a product line designed for the simulation of water flows in open channels. This software can calculate the 1D water flow for shallow water in simple water systems or complex channel networks with more than thousand cross sections and structures. Various types of boundary conditions can be applied in the model, as well as lateral inflow and outflow using time series or standard formulae (Deltares, 2024a). The flow in a 1D model is simplified to a one-directional flow in a network of branches and nodes. The quality of the model network largely determines the accuracy of the model (Berends et al., 2022). D-Flow 1D is capable of modelling complex cross-sectional profiles consisting of multiple sub sections, such as left floodplain, right floodplain and main channel with different roughness (Deltares, 2024a). Figure 3 shows an example of a river profile and shows the separation between the main channel and the floodplains. The river profiles consist of two types of profiles, the total profile and the flow profile. The difference between the two profiles is the storage area. The storage area represents parts of the river profile where there is water, but no flow.

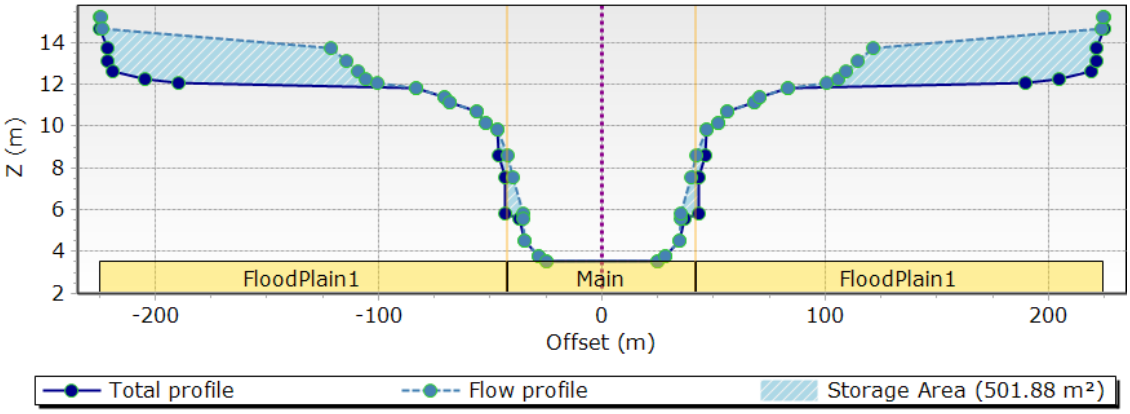

Figure 3 Example of a river profile implemented in D-Flow 1D. This is the river profile at Westervoort, the start of the IJssel

A SOBEK model (sobek-rijn-j22_6-v1a2) of the Rhine branches in the Netherlands, including the Waal, Nederrijn/Lek and IJssel, is available internally at Rijkswaterstaat (Figure 5). This 1D model is completely derived from the calibrated 2D (DFLOWFM2D) model in both data, river profiles and roughness. The entire model will be used rather than limiting it to the IJssel only. The complete Rhine model includes the distribution of discharge among the Rhine branches, which would be disrupted by reducing the model. Additionally, if the model is reduced, recalibration is necessary which would be challenging and time consuming. Using the whole Rhine model does not have any disadvantages, since the run time is around 2 minutes and the distribution of the discharge ensures that the right amount of water flows into the IJssel.

The model includes boundary conditions at four locations: upstream at Dornick, and downstream at Ketelbrug (IJssel), Krimpen aan de Lek (Nederrijn/Lek) and Hardinxveld (Waal). The upstream boundary condition at Dornick is a Q(t) relation and will be adjusted in this study by implementing other Q(t) relations. The downstream boundary conditions are implemented as Q(h) relation and will remain standard during the study (Figure 4).

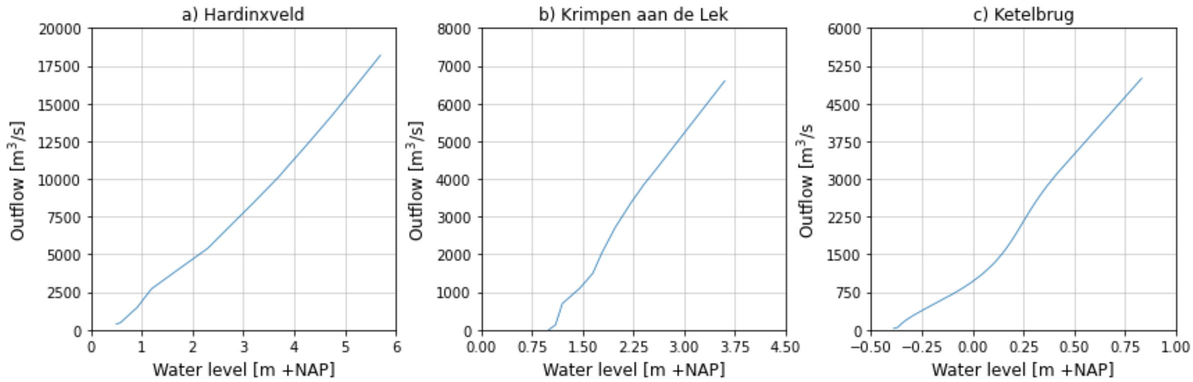

Figure 4 Q(h) relations of the downstream boundary conditions at a) Hardinxveld (Waal), b) Krimpen aan de Lek (Nederrijn/Lek) and c) Ketelbrug (IJssel)

The 2D model consists of 96 points of lateral sources which all are imported in the 1D model (Berends et al., 2022). Examples of lateral sources are sewage treatment plants, sluices, pumping stations and streams. Both, the Oude IJssel and Twentekanaal are implemented in the model as lateral source. All lateral sources are implemented in the model with a Q(t) relation based on the discharge in the Rhine at Dornick. For this study, the lateral inflow at the Twentekanaal (TK_3.3_R_Beek_Twentekanaal-Sluis-Eefde) and the lateral inflow at the Oude IJssel (IJ_901.8_R_Beek_Oude-IJssel) will be adjusted. All other lateral flows will not be changed.

When currently modelling in SOBEK, standard boundary conditions and lateral inflow are used, which can be steady or non-steady. In case of the steady conditions, the upstream boundary at Dornick and the lateral inflows have steady values, which are constant over time. The discharge at Dornick is set and differs from 600 m^3/s to 16,000 m^3/s. In case of the non-steady conditions, the upstream boundary at Dornick and the lateral inflows do change over time. The discharge wave of the boundary at Dornick have peak discharges of 6,000 m3/s to 16,000 m3/s. These discharge waves are based on a GRADE generated discharge wave. GRADE is a combination of a stochastic weather generator, a hydrological model and a hydrodynamic model and is used to simulate extreme discharges in the Rhine at Lobith and the Maas at Borgharen (Hegnauer et al., 2023). The GRADE database consists of 50,000 yearly peak discharges along with corresponding flood waves for the Rhine at Lobith. From this database, several discharge classes are defined for which an average hydrograph shape is calculated. The downstream boundary conditions are the same for both steady and non-steady conditions for all peak discharges at the upstream boundary at Dornick.

The lateral inflow in the steady and non-steady conditions for the 8 most important laterals, including the Oude IJssel and Twentekanaal, are derived from RGWM (Randvoorwaarden Generator Water Modellen). In RGWM, a relation between the discharge in the Rhine at Lobith and the laterals is set up, such that the discharge in the laterals can be determined based on the discharge in the Rhine at Lobith when measurements of the laterals are not available (RURA-Arnhem, 2018).

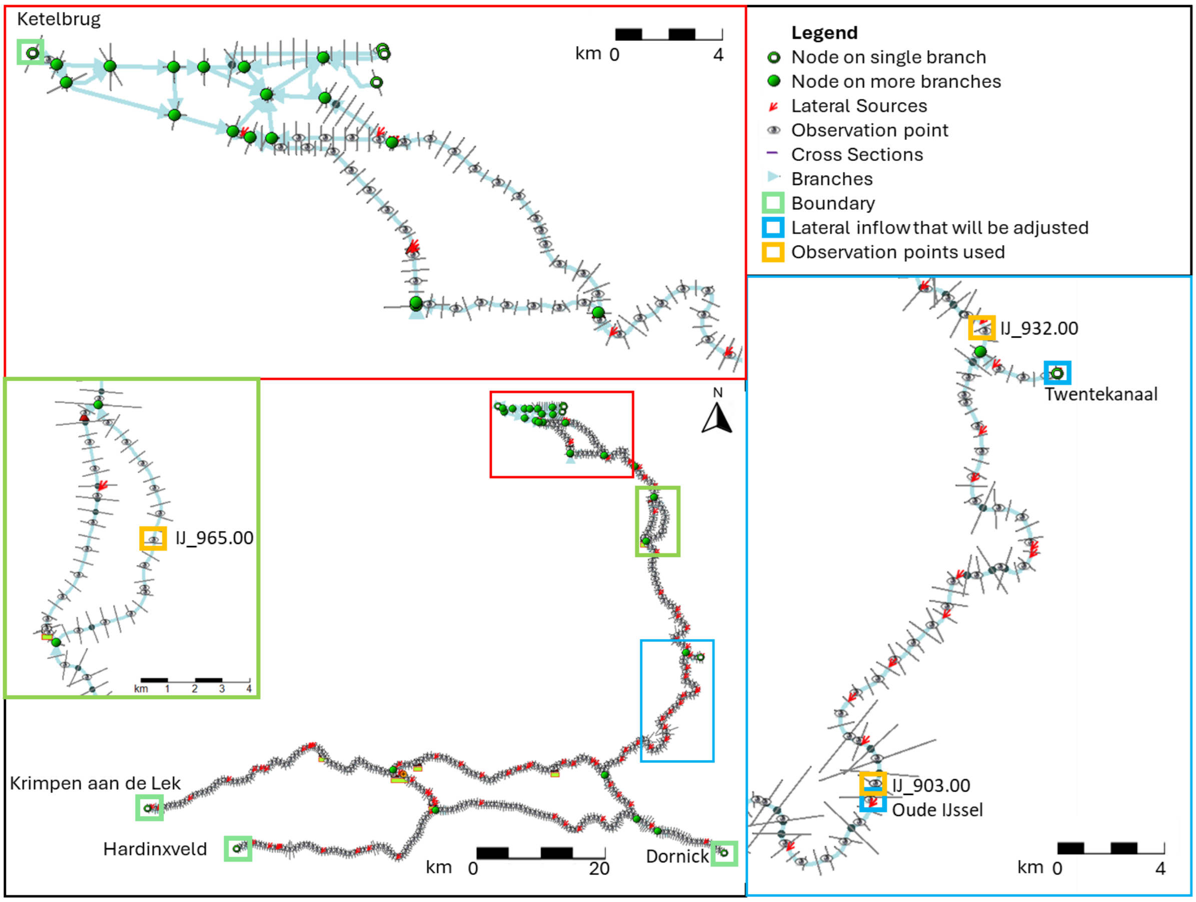

Figure 5 Schematization of the Rhine river basing in D-Flow 1D. The details in red is the IJssel delta, in green the high water channel Veessen-Wapenveld and in blue the lateral sources of the Oude IJssel and Twentekanaal

Results of the study will be analysed at several observation points (Figure 5). The first observation point is IJ_903.00 which is situated just downstream of the location where the Oude IJssel flows into the IJssel, referred to as Doesburg. The second observation point is IJ_932.00 which is situated just downstream of the location where the Twentekanaal flows into the IJssel, referred to as Zutphen. The last observation point is IJ_965.00 which is situated at Wijhe.

2.2 Data description

To identify discharge waves, historical data of the past 30 years (1993-2023) from the Rhine, Oude IJssel and Twentekanaal will be collected. The measurements for Twentekanaal are available from 2000. The measurement locations are shown in Figure 2 and include Lobith for the Rhine, Doesburg and Weir de Pol for the Oude IJssel, and Almen and Afleidingskanaal for Twentekanaal. The measurement location for the Rhine is different than the boundary of the Rhine in the model, which is at Dornick. The data for Lobith is easier to access and downloads for more years are available. Additionally, the difference between the two locations is only 16 km, which corresponds to a travel time of 3 hours, the dispersion between the two locations is negligible and there is no lateral inflow (RURA-Arnhem, 2022). Comparing a discharge wave at Lobith and Dornick shows that they have a very similar shape as well.

Both Oude IJssel and Twentekanaal feature two measurement locations. For Twentekanaal, this is attributed to the absence of a measurement station more downstream. The sum of the measurement stations Almen and Afleidingskanaal approaches the discharge of the Twentekanaal that flows into the IJssel.

In the case of Oude IJssel, measurements from Doesburg will be utilised whenever they are available. The measurement station at Doesburg fails when the water level in the IJssel is higher than +10 m NAP. When measurements are unavailable at Doesburg, data from the measurement location weir de Pol will be used. Weir de Pol is situated 16 km upstream from Doesburg and typically constitutes approximately two-thirds of the discharge observed at Doesburg. Estimating the discharge at Doesburg can be achieved by implementing the following relation function (Van Der Veen, 2018):

$$Q_{de\ Pol} < 61.24\ m^3/s \qquad Q_{Doesburg,t=0} = 1.31 * Q_{de\ Pol,t=-1h} \tag{1}$$

$$Q_{de\ Pol} \geq 61.24\ m^3/s \qquad Q_{Doesburg,t=0} = 1.10 * Q_{de\ Pol,t=-1h} + 12.86 \tag{2}$$

Discharge waves will be identified from the collected data. Discharge waves start when the discharge exceeds a certain threshold (Table 1) and end when the discharge drops again below this threshold. When an event has several peaks while the discharge stays above the threshold, they belong to the same event. The events have at least hourly measurements and 4 measurements in a row that have a value above the threshold.

Table 1 Thresholds and return periods that are used to determine the discharge waves at Lobith (Chbab, 2017), Doesburg (Botterhuis & Klopstra, 2004) and Eefde (Rijkswaterstaat, n.d.)

	Lobith (Rhine)	**Doesburg (Oude IJssel)**	**Eefde (Twentekanaal)**
Threshold discharge	> 4450 m^3/s	> 36 m^3/s	> 50 m^3/s
Return period of threshold	1/year	14 days/ year	1/year

3 Methodology

An overview of the methodology used to determine the influence of lateral inflow on a discharge wave in the IJssel is given in Figure 6.

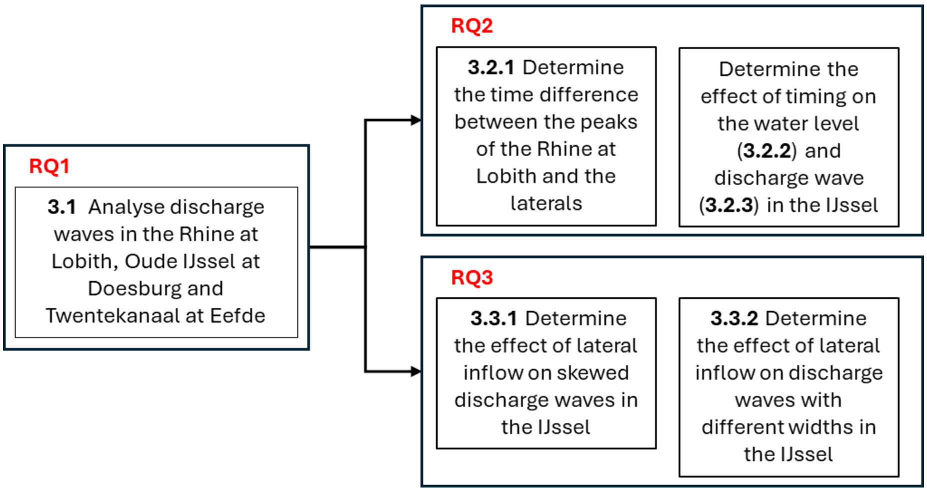

Figure 6 Overview of the methodology, including the corresponding research questions in red and section numbers in bold in which the methodology is described

Discharge waves in the Rhine at Lobith, Oude IJssel at Doesburg and Twentekanaal at Eefde are analysed (RQ1). Several of these discharge waves will serve as input for modelling the effect of lateral inflow. The time difference between the days of the peak of discharge waves in the Rhine at Lobith, Oude IJssel at Doesburg and Twentekanaal at Eefde are determined. The timing of inflow of the laterals is changed and the effect on de water level and discharge wave is analysed (RQ2). Lastly, the effect of lateral inflow on various shapes for discharge waves in the IJssel are analysed (RQ3). The shapes includes skewed discharge waves and discharge waves with varying widths.

3.1 Discharge waves analysis

The first phase of the study aims to identify and analyse discharge waves in the Rhine, Oude IJssel and Twentekanaal. This analysis provides insight into the different types of waves that occur within these rivers and canal. Several discharge waves are selected for modelling based on the peak discharge and shape of discharge wave.

The identified discharge waves are analysed based on their peak discharge, the timing of the peak discharge and duration. A distinction is made between discharge waves occurring during high water season (November to April) and low water season (April to November) to see if they are different. The range of peak discharges and duration is described and correlated. A trendline is established to determine the correlation and the coefficient of determination (R^2) is calculated to measure how well the trendline fits the datapoints. The most extreme values are linked to a return period based on their peak discharge.

The shape of the discharge waves are analysed through two distinct methods: determination of skewness and visual inspection. Skewness is determined for discharge waves with one peak and is a statistical measure quantifying the degree of asymmetry of a probability distribution around its mean. Skewness is derived through the calculation of Pearson's second coefficient of skewness (Spiegel & Stephens, 2007):

$$skewness = \frac{3(\mu - Me)}{\sigma}$$

Where μ = mean; Me = median and σ = standard deviation. When the skewness value approaches zero, it signifies a nearly symmetrical shape. A negative skewness value means that the mass of the distribution is concentrated on the right with a longer and flat tail on the left side. A positive skewness value means that the mass of the distribution is concentrated on the left with a longer and flat tail on the right.

Discharge waves with several peaks will be analysed based on visual inspection. The discharge wave with the most peaks is analysed.

3.2 Timing

3.2.1 Time difference between the discharge waves

First, the time difference between the historical peak discharges in the Rhine and the laterals is determined to analyse what time differences occurred and if they differ from the standard time difference used in the non-steady conditions (described in section 2.1). When the peaks of the Rhine and the laterals fall within a 7-day time frame, the discharge waves are matched and the time difference between their peaks is determined. Additionally, the same is done for the difference between the Oude IJssel and Twentekanaal, since in some cases there is no increased discharge in the Rhine at Lobith, but the laterals do both have an increased discharge. The time difference that occurred the most is compared to the timing applied in the standard non-steady conditions. The time difference between the Rhine at Dornick and the laterals is also determined in the non-steady conditions. This time difference is the same for all peak discharges in the Rhine. The standard timing following from the standard non-steady conditions are as follows:

- The peak discharge of the Oude IJssel at Doesburg is 3 days and 5 hours earlier than the peak discharge of the Rhine at Dornick
- The peak discharge of the Twentekanaal at lock Eefde is 3 days and 10 hours earlier than the peak discharge of the Rhine at Dornick
- The peak discharge of the Twentekanaal at Lock Eefde is 5 hours earlier than the peak discharge of the Oude IJssel at Doesburg

3.2.2 The influence of the timing of lateral inflow on the water level in the IJssel

The effect of the timing of high lateral inflow on the water level in the IJssel is determined for various peak discharges in the Rhine at Lobith. To achieve this, symmetrical discharge waves with varying peak discharges are assumed for the Rhine at Lobith. These discharge waves are based on a GRADE generated discharge wave (explained in section 2.1), as the discharge wave analysis might not result in symmetrical discharge waves. Symmetrical waves are preferred to solely analyse the effect of the lateral inflow, rather than the shape of the discharge wave in the IJssel. The average symmetrical discharge wave with a peak discharge of 14,500 m^3/s is scaled to smaller peak discharges by decreasing the peak discharge with 10% each time. The scaling results in 10 discharge waves for the Rhine at Dornick, shown in Figure 7a.

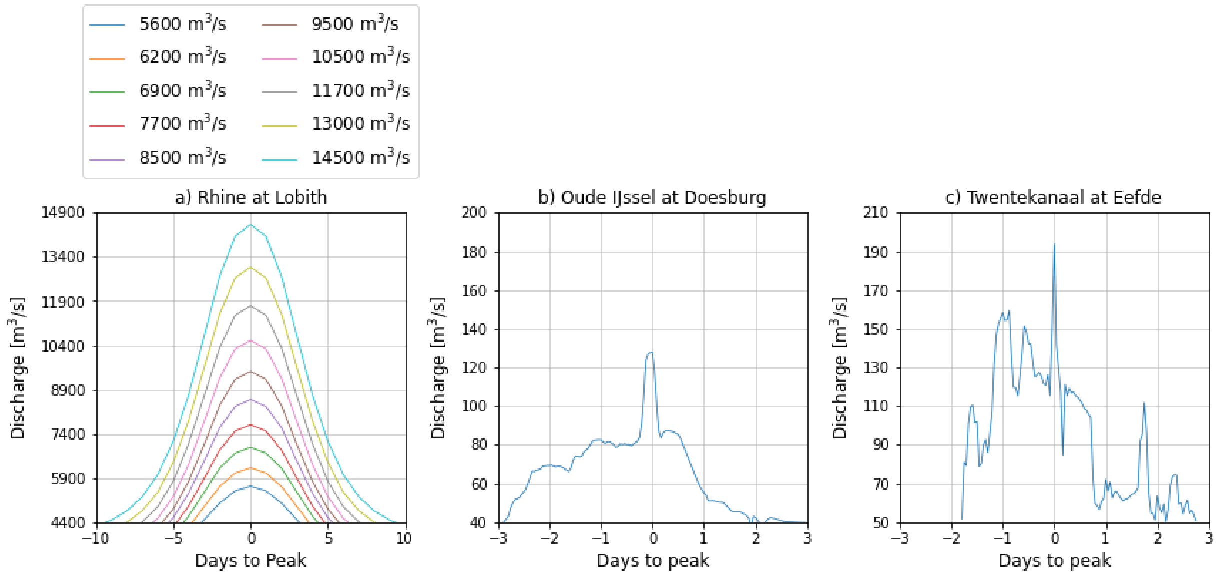

Figure 7 a) Symmetrical discharge waves for the Rhine, b) historical discharge wave of the Oude IJssel with highest peak, c) historical discharge wave of Twentekanaal with highest peak

Two types of discharge waves are used as input for lateral inflow from the Oude IJssel and Twentekanaal as comparison. The first ones are historical discharge waves with the highest peak discharges, which are a result of section 3.1 and shown in Figure 7b and c. These discharge waves, representing high lateral inflow, are used as input at all peak discharges in the Rhine. The influence of high lateral inflow is compared to the effect of steady lateral inflow following from the steady conditions (described in section 2.1). The standard steady lateral inflow is a constant value over time and depends on the peak discharge in the Rhine at Dornick (Table 2). The duration of the steady laterals is similar to the duration of the high lateral inflow, six days for the Oude IJssel and 5 days for the Twentekanaal.

Table 2 Standard steady values for lateral inflow from the Oude IJssel and Twentekanaal for the peak discharges of the symmetrical discharge waves in the Rhine

Peak discharge in the Rhine at Dornick [m^3/s]	Oude IJssel [m^3/s]	Twentekanaal [m^3/s]
5,600 - 6,900	37.55	34.87
7,700 - 8,500	40.53	37.87
9,500 - 10,500	43.51	40.87
11,700 - 13,000	50.18	46.46
14,500	57.34	50.51

The timing of the laterals, in case of the high lateral inflow and the steady lateral inflow, is changed to determine the impact of timing on the water level in the IJssel. It is expected that when the peak discharges of the IJssel and laterals confluence in the IJssel at the same time, the increase in water level is highest. The timing causing this scenario is referred to as the reference timing.

When both the Oude IJssel and Twentekanaal have increased discharges around the same time, it is likely that they are a result of the same rainfall event, given their geographical location. A fixed time difference between the peaks of the Oude IJssel and Twentekanaal is used, based on the assumption that the peaks occur around the same time. The time difference between the peak of the Oude IJssel and the peak of the Twentekanaal is the same as in case of the non-steady conditions, where the peak of the Twentekanaal at lock Eefde is 5 hours earlier than the peak of the Oude IJssel at Doesburg.

The reference timing will be based on the confluence of the peak discharge of the IJssel and the peak discharge of the Oude IJssel at Doesburg. The confluence of the peaks is dependent on the travel time of the discharge wave from the Rhine at Dornick to the IJssel at Doesburg. The travel time for water levels at Lobith higher than 12 m +NAP is approximately 22 hours, which consists of 3 hours from Dornick to Lobith (RURA-Arnhem, 2022) and 19 hours from Lobith to Doesburg (Bod, 2021). For simplicity, the 22 hours is rounded to 1 day, as the discharge in the Rhine two hours before the peak is less than 1% lower than the peak discharge. The reference timing occurs when:

- The peak discharge of the Oude IJssel at Doesburg is 1 day later than the peak discharge of the Rhine at Dornick
- The peak discharge of the Twentekanaal at lock Eefde is 19 hours later than the peak discharge of the Rhine at Dornick
- The peak discharge of the Twentekanaal at Lock Eefde is 5 hours earlier than the peak discharge of the Oude IJssel at Doesburg

Additionally to the reference timing, 4 other timings are used to determine the effect of the change in timing along the river. The other timings may result in a higher increase in water level along the IJssel, since the reference timing is based on the confluence of peak discharges of the IJssel and Oude IJssel at Doesburg. For the 4 other timing the peak discharge of the Oude IJssel and Twentekanaal is changed to one day earlier, 2 days earlier, one day later and two days later than the reference timing.

The results with steady lateral inflow are compared to those with high lateral inflow to determine how much impact the high laterals have on the water level in the IJssel. This is done for the different discharge waves in the Rhine at Dornick and the 5 different timings (Table 3). First, the change in water level along the IJssel for the lowest and highest peak discharge in the Rhine with reference timing is analysed. Additionally, the influence of the timing of lateral inflow on the water level is analysed at the three observation points (Figure 5).

Table 3 Overview of the scenarios modelled in section 3.2.2. For both steady lateral inflow and high lateral inflow, all timings with all peak discharges in the Rhine will be modelled. The timing relative to the peak discharge at Dornick represents the time difference between the peaks of the Oude Ijssel at Doesburg and the Rhine at Dornick

Timing	**Timing relative to the peak discharge at Dornick**	**Lateral inflow**	**Discharge wave in the Rhine**
Reference timing	+ 1 day	- Steady lateral inflow - High lateral inflow	- Symmetrical shape - peak discharges from 5,600 m^3/s to 14,500 m^3/s
One day **earlier** than the reference timing	0 days		
two days **earlier** than the reference timing	-1 day		
One day **later** than the reference timing	+2 days		
Two days **later** than the reference timing	+3 days		

3.2.3 The influence of timing of lateral inflow on the shape of the discharge wave in the IJssel

The influence of timing of lateral inflow on the shape of the discharge wave in the IJssel is analysed by comparing the shape of the discharge wave with adjusted timing to the discharge wave with the standard timing. As input discharge wave for the Rhine at Dornick, a symmetrical wave is used with a peak discharge that resulted in the highest increase in water level in section 3.2.2. The high lateral inflow following from historical data served as input for the Oude IJssel and Twentekanaal and are given in Figure 7b and c.

The timing is adjusted to the reference timing, two days earlier- and two days later than the reference timing. The shape of the discharge waves with these timings are compared to the constant timing following from the non-steady conditions in SOBEK. The change in shape of discharge wave is analysed at the same observation points. When the shape of the discharge wave changes, it might also affect the water level. The influence of the change in discharge wave on the water level is analysed by presenting a Q-h relation.

Table 4 overview of the scenarios modelled in section 3.2.3. The timing relative to the peak discharge at Dornick represents the time difference between the peaks of the Oude IJssel at Doesburg and the Rhine at Dornick.

Timing	**Timing relative to the peak discharge at Dornick**	**Lateral inflow**	**Discharge wave in the Rhine**
Reference timing	+ 1 day	High lateral inflow	- Symmetrical shape - Peak discharge that resulted in the highest increase in water level in section 3.2.2
Two days earlier	-1 day		
Two days later	+ 3 days		
Constant timing	-3 days and 5 hours		

3.3 Shape

To determine whether lateral inflow has a different effect on the water level in the IJssel with other shapes of discharge waves in the IJssel, several shapes of discharge waves in the IJssel are implemented. To achieve this, different types of shapes for discharge waves in the Rhine at Lobith served as input. This includes skewed discharge waves and discharge waves with varying widths. For all different shapes of discharge waves in the IJssel, several peak discharges are used.

The skewed discharge waves include negatively and positively skewed discharge waves (Figure 8). They are based on the historical discharge wave with the most extreme skewness coefficient and the shape is comparable with the characteristic shape. Following from section 3.1, the discharge wave with a skewness coefficient of 0.98 closely resembles the characteristic shape. This discharge wave is scaled to higher and lower peak discharges, by increasing and decreasing the peak discharge by 10% each time. Then, these discharge waves are mirrored such that the discharge waves negatively skewed and those positively skewed have similar tails.

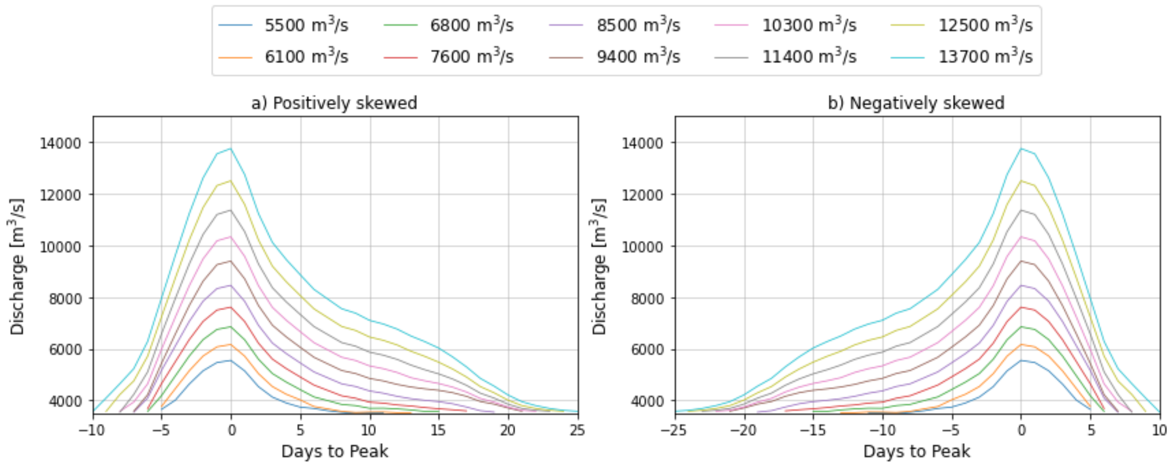

Figure 8 Input discharge waves for skewed shapes with varying peak discharges in the Rhine at Dornick. a) Positively skewed (rightward) and b) Negatively skewed (leftward)

The symmetrical discharge waves with various widths are based on the symmetrical discharge waves following from GRADE (Figure 7a). The middle waves, given in Figure 9b are based on these symmetrical wave from GRADE. The middle discharge waves are scaled to steeper and wider waves while remaining the same peak discharge. The steep discharge waves follow by dividing the duration of the middle discharge waves by 1.5 (Figure 9a). The wide discharge waves follow by multiplying the middle discharge wave by 1.5 (Figure 9c).

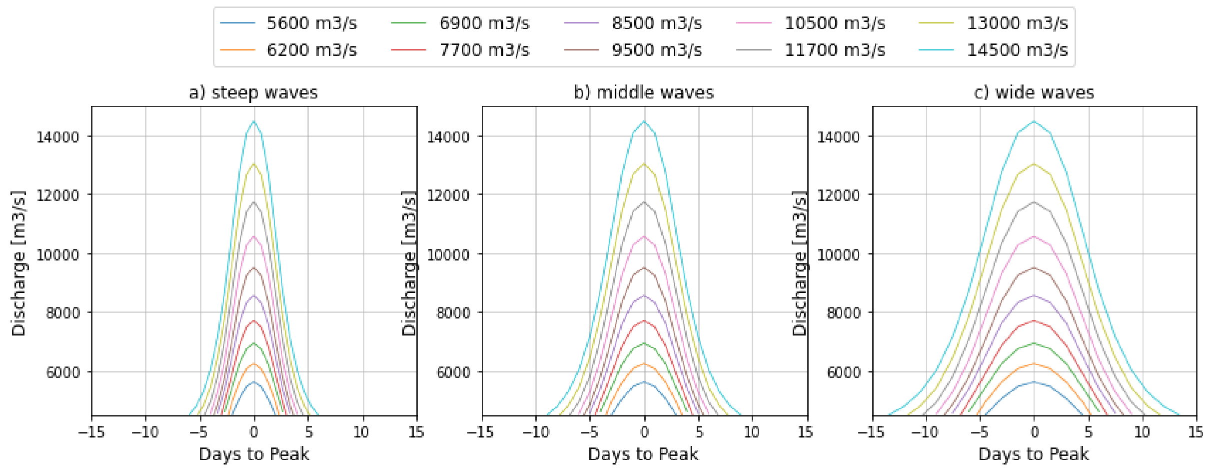

Figure 9 Input discharge waves with varying widths and peak discharges in the Rhine at Dornick. a) Steep waves, b) middle waves and c) wide waves

Two types of discharges are used as input for the Oude IJssel and Twentekanaal, high lateral inflow (Figure 7b and c) and the steady lateral inflow (Table 2). Since the focus is on the shape of the discharge wave in the IJssel, the timing will be kept constant on the reference timing (explained in section 3.2.2).

The water level in the IJssel in case of high lateral inflow is compared to the water level in the IJssel in case of the steady lateral inflow. The change in water level is determined for the skewed discharge waves and the discharge waves with varying widths for all peak discharges. The results of the skewed discharge waves are compared to the results of the symmetrical discharge waves. The results of the discharge waves with varying widths are compared to each other. The effect of the shape of the discharge wave in the IJssel is analysed at the three observation points (Figure 5).Overall, the results show whether the shape of the discharge wave in the IJssel affects the change in water level due to lateral inflow.

Table 5 overview of the scenarios modelled in section3.3.

Discharge wave in the Rhine	Lateral inflow	Timing
- Symmetrical shape - peak discharges from 5,600 m^3/s to 14,500 m^3/s	- High lateral inflow - Steady lateral inflow	Reference timing
- Shape skewed rightward - peak discharges from 5,500 m^3/s to 13,700 m^3/s		
- Shape skewed leftward - peak discharges from 5,500 m^3/s to 13,700 m^3/s		
- Steep shape - peak discharges from 5,600 m^3/s to 14,500 m^3/s		
- Wide shape - peak discharges from 5,600 m^3/s to 14,500 m^3/s		

4 Results

This chapter represents the results of the study. Section 4.1 shows the results of the analysis of the discharge waves based on when they took place, peak discharge, duration and shape. Section 4.2 gives the results for the change in timing. Section 4.3 shows the results for the change in shape of the discharge wave in the IJssel due to lateral inflow.

4.1 Analysis of the discharge waves

Data analysis resulted in 62 discharge waves for the Rhine, 88 discharge waves for the Oude IJssel and 52 for Twentekanaal. These discharge waves are analysed based on the season they took place, their peak discharge and duration and the shapes of the discharge waves.

4.1.1 Season

As expected, most discharge waves occurred during the high water season (Table 6). Discharge waves during high water season occur in various kinds of shapes, heights and durations (Figure 10a, c and e). Especially the waves in the Oude IJssel and Twentekanaal fluctuate significantly more than those in the Rhine. During low water season, the number of discharge waves is insufficient to discern a trend in the shape of discharge waves. There are no clear similarities between the waves that occurred during high water season and those that occurred during low water season.

Table 6 Number of discharge waves that occured during high water season (November to April) and during low water season (April to November)

	Rhine	Oude IJssel	Twentekanaal
High water season	54	79	46
Low water season	8	9	6
Total discharge waves	62	88	52

During high water season, the highest waves have a relatively short duration while the longest discharge waves tend to have a lower peak. Whereas during low water season, the highest and longest waves are the same (Figure 10d and f) or very comparable (Figure 10b). The difference in the origin of the water flow causes this appearance. During the high water season, the inflow of water is attributed to rainfall, melt water and saturated soils (Disse & Engel, 2001). During the low water season, the primary source of water flow is rainfall. Furthermore, increased temperatures lead to a higher evaporation rate, resulting in a lower soil saturation and larger storage buffer than in winter leading to a reduced quantity of water entering the river.

It is observed that the highest and longest discharge waves in the Rhine exhibit a higher peak discharge and longer duration during high water season compared to low water season. In contrast, the peak discharges in the laterals during low water season are similar to those observed during high water season. In the laterals the waterflow during the whole year is attributed to rainfall and saturated soils, resulting in high peak discharges throughout the whole year. Additionally, the catchment area of the laterals is much smaller than the Rhine, which makes the response time of the system shorter.

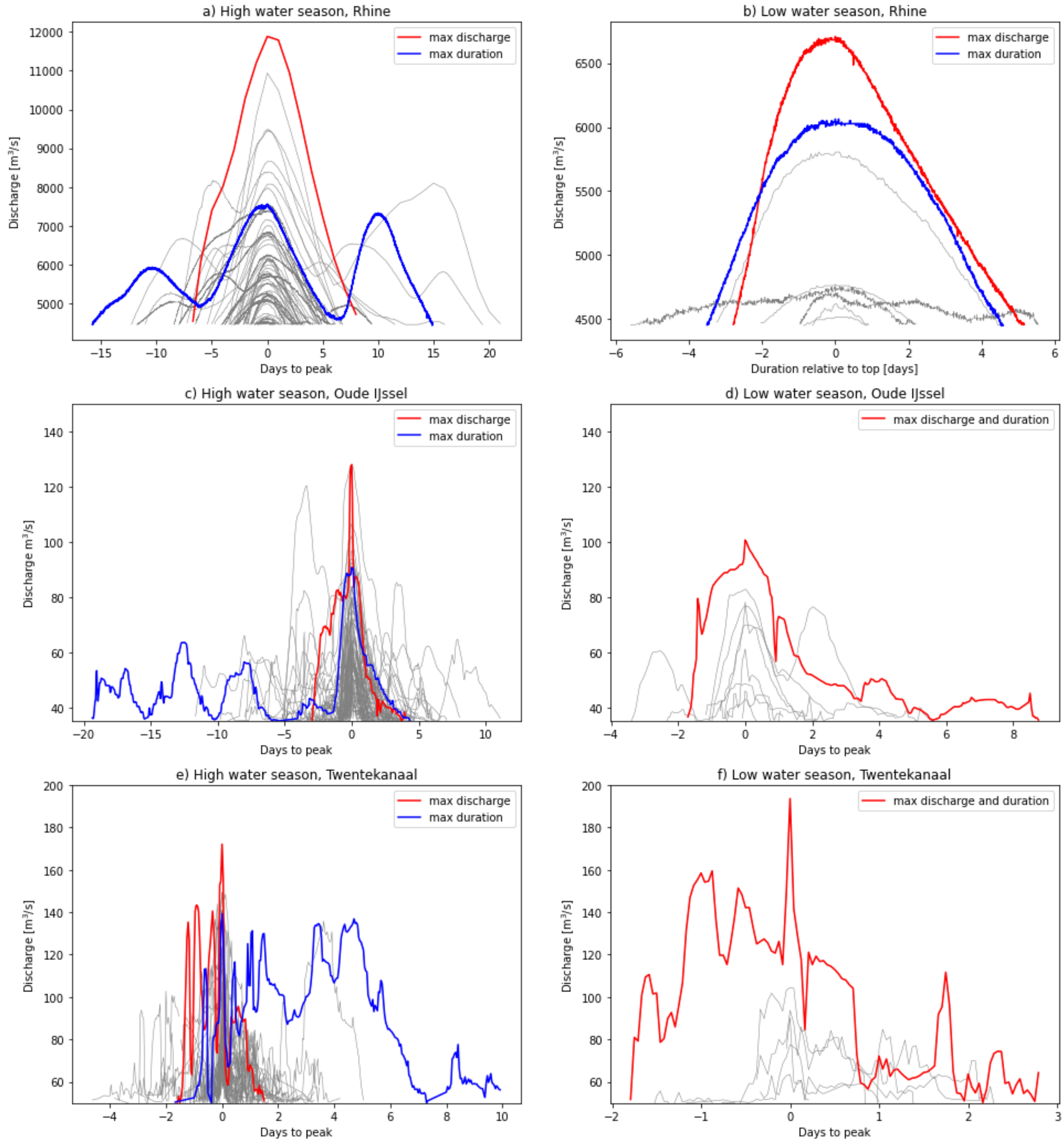

Figure 10 Separation of discharge waves between high and low water season for the Rhine, Oude IJssel and Twentekanaal. The discharge waves in blue represent the longest discharge waves and the ones in red represent the highest discharge wave.

4.1.2 Peak discharge and duration

Rhine

The spreading of peak discharge and duration shows that 75% of the 62 discharge waves in the Rhine at Lobith have a peak discharge lower than 6750 m^3/s and a duration shorter than 10 days and 6 hours (Figure 11a). The discharge waves are concentrated at lower values for the peak discharge and duration, which is reasonable because the return period for lower peak discharges is shorter than the return period of higher peak discharges. The orange 75% boundaries in Figure 11b show that peak discharges below this boundary tend to have a duration that is below its boundary as well. This figure shows their relation and the coefficient of determination (R^2) for the data from which can be concluded that there is a linear relationship between the peak discharge and duration of the discharge waves. The relationship is not very strong since the R^2 value is not close to 1, caused by outliers which were taken into account for the relationship.

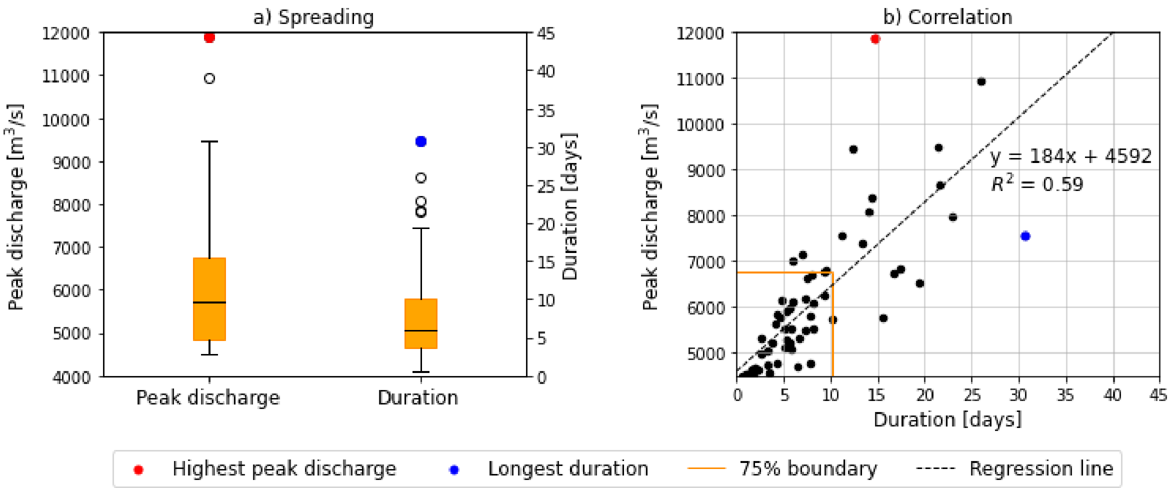

Figure 11 a) Spreading peak discharge and duration and b) correlation between peak discharge and duration for the Rhine

The red dots in Figure 11a and b represents the outlier with the highest peak discharge. This discharge wave occurred in January 1995, which is during the high water season (red in Figure 10a), and reached a peak of 11,885 m^3/s, corresponding to a return period of 80 years (Chbab, 2017). The duration of this discharge wave was almost 15 days, while according to the trendline, a duration of around 40 days would be expected. This extremely high peak discharge at Lobith was caused by the confluence of several peak discharges from laterals of the Rhine in Germany. The discharge from the sub-basins was high due to heavy rainfall and their peak discharges entered the Rhine around the same time (Van Hasselt et al., 1995).

the blue dots in Figure 11a and b represents the outlier with the longest duration. This discharge wave occurred in December 2023, which is during the high water season (blue Figure 10a), and lasted 32 days. The peak discharge was 7,500 m^3/s which corresponds to a return period of 3 years (Chbab, 2017). According to the trendline a peak discharge of 10,250 m^3/s would be expected, which is significantly higher. The long discharge wave was caused by an extremely long period of rainfall in large parts of the Rhine basin which caused saturated soils and increased discharges. Saturated soils in combination with periods of intensive rainfall caused the three individual peaks (Deltares, 2024b). Additionally, storm on the North Sea and IJsselmeer caused a delay in the discharge from the Rhine to the sea.

Oude IJssel

The spreading of peak discharge and duration shows that 75% of the 88 discharge waves in the Oude IJssel at Doesburg have a peak discharge lower than 76 m^3/s, with a return period of 1 year (Botterhuis & Klopstra, 2004), and a duration shorter than 6 days and 18 hours (Figure 12a). Similar as the Rhine, the discharge waves are concentrated at lower values for peak discharge and duration. Compared to the Rhine, more discharge waves have a peak discharge under the 75% boundary but a longer duration and vice versa. The relation and the coefficient of determination (R^2) show the correlation between the peak discharge and duration (Figure 12b). The low value for R^2 shows that the linear line does not fit the data points very well. It can be concluded that there is no clear trend between the peak discharge and duration in the Oude IJssel.

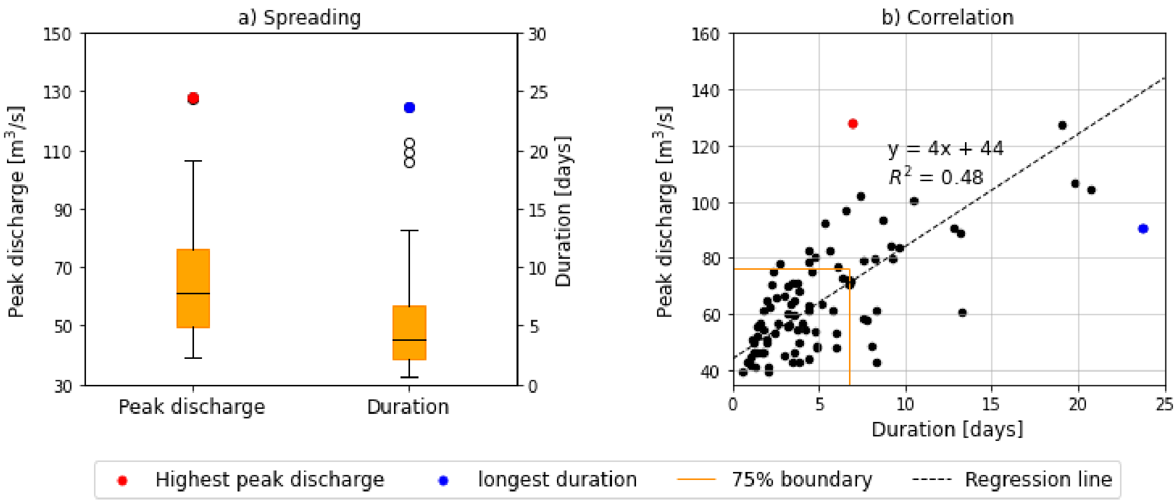

Figure 12 a) Spreading peak discharge and duration and b) correlation between peak discharge and duration for Oude IJssel

The red dots in Figure 12a and b represents the discharge wave with the highest peak discharge. This discharge wave occurred in January 2008, which is during the high water season (red in Figure 10c), and reached a peak discharge of 127 m^3/s, corresponding to a return period of 10 years (Botterhuis & Klopstra, 2004). The duration of this discharge wave was 7 days, while according to the linear trendline a duration of approximately 21 days would be expected. This peak discharge was attributed to a rainfall event of 660 mm in four days (KNMI, 2024).

The blue dots in Figure 12a and b represents the discharge wave with the longest duration. This discharge wave occurred in November 2023, which is during high water season (blue in Figure 10c) and lasted 23 days and 17 hours. The event had a peak discharge of 90 m^3/s, corresponding to a return period of 5 years (Botterhuis & Klopstra, 2004). This peak discharge is 30 m^3/s lower than would be expected according to the trendline. The long duration of the discharge wave was caused by a long period of rainfall and saturated soils. This discharge wave is a result of the same rainfall event as the longest discharge wave in the Rhine.

Twentekanaal

The spreading of peak discharge and duration shows that 75% of the 52 discharge waves in the Twentekanaal at Eefde have a peak discharge lower than 115 m^3/s and a duration shorter than 3 days and 4 hours (Figure 13a). Similar as in the Rhine and the Oude IJssel, the discharge waves are concentrated to the lower values for peak discharge and duration. The relation and coefficient of determination (R^2) value show the linear correlation between the peak discharge and duration, which is very weak since the R^2 value is very small. The wide spreading and poor correlation might be caused by the function of the Twentekanaal. Due to the locks that are situated in the canal, to facilitate shipping and water supply, the discharge is more controlled and will be different from a system without locks.

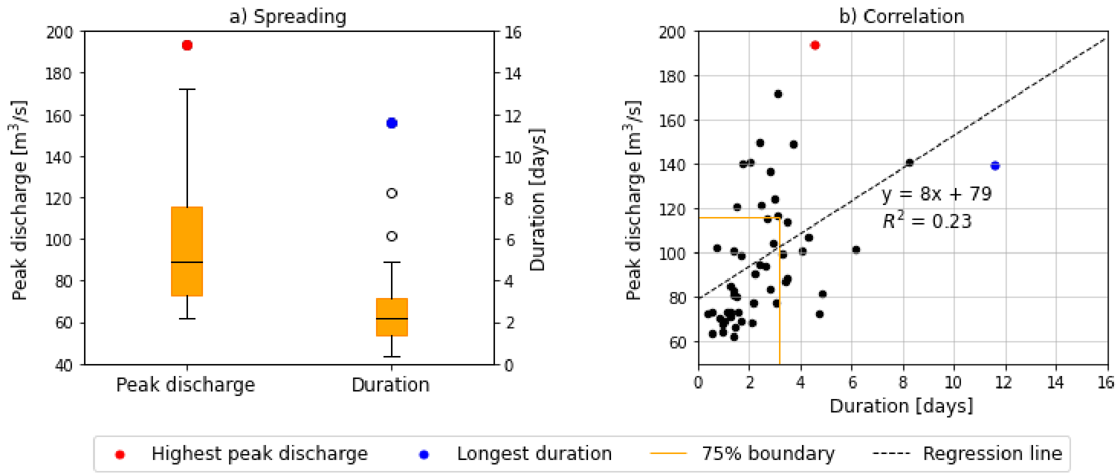

Figure 13 a) Spreading peak discharge and duration and b) correlation between peak discharge and duration for Twentekanaal

The red dots in Figure 13a and b represent the outlier with the highest peak discharge. This discharge wave occurred in August 2010, which is during low water season (red in Figure 10f), and reached a peak of 193 m^3/s. The duration of this discharge wave was 4.5 days, while according to the correlation, a duration of approximately 15 days would be expected. The high peak discharge was caused by extreme rainfall in the catchment area of the Twentekanaal (Vreugdenhil et al., 2010).

The blue dots in Figure 13a and b represent the outlier with the longest duration. This occurred in December 2023, which is during high water season (blue in Figure 10e), and lasted 11.5 days. The discharge wave features several peaks and attains a maximum height of 140 m^3/s. According to the correlation, a peak discharge of 170 m^3/s would be expected. As this event took place around the same time as the longest discharge wave in the Rhine and Oude IJssel, it was caused by extreme amounts of rainfall for a long period and saturated soils (KNMI, 2024). Due to the long period of rainfall, the IJssel had already high water levels which made it harder to discharge the water from the Twentekanaal to the IJssel.

4.1.3 Shape

Rhine

The skewness coefficient is calculated for 52 single-peak discharge waves in the Rhine (84% of all discharge waves in the Rhine), resulting in a maximum skewness coefficient of 0.98 and a minimum of -1.17. 41 discharge waves are characterized by a positive skewness coefficient, while 7 have a negative skewness coefficient and 4 approach zero. The discharge wave with the highest skewness coefficient shows the characteristic shape of a positively skewed distribution (Figure 14a), whereas the one with the smallest (most negative) skewness coefficient features a large mass on the left without a clear tail. The discharge wave with the skewness coefficient closest to zero, does not achieve full symmetry. The duration before and after the peak is different as well as the slope of the rising and falling part of the discharge wave.

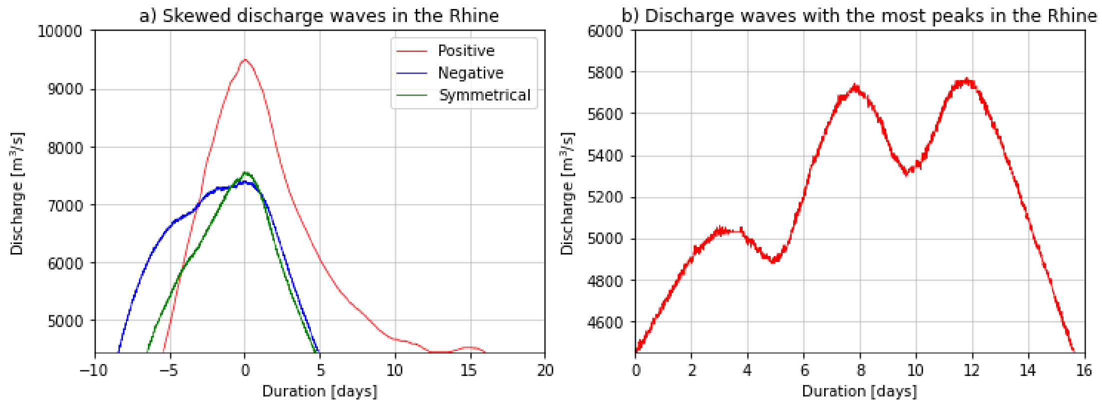

Figure 14 a) Skewed discharge waves and b) multiple peak discharge wave with the highest amount of peaks in the Rhine at Lobith

The remaining 10 discharge waves (16% of all discharge waves in the Rhine) contain multiple peaks. The maximum amount of peaks that occurred in one event is 3. Moreover, the minimum duration of 14 days surpasses the duration of 75% of all discharge waves (Figure 11a). The multiple peak discharge wave with the highest amount of peaks is shown in Figure 14b.

Oude IJssel

The skewness coefficient is calculated for 40 single-peak discharge waves in the Oude IJssel (45% of all discharge waves in the Oude IJssel). The calculation of the skewness coefficient results in a maximum of 1.67 and a minimum of -1.46. 26 discharge waves are characterized by a positive skewness coefficient, while 12 have a negative skewness coefficient and 2 approach zero. The discharge wave with the highest positive skewness coefficient shows the characteristic shape, although it has some fluctuations (Figure 15a). All 12 discharge waves with a negative skewness coefficient do not attain the typical shape and their peak discharge is below 55 m^3/s, which makes them irrelevant. The discharge wave with skewness closest to zero, has a comparable duration on both sides of the peak but is not completely symmetrical since the rising and falling part are not similar.

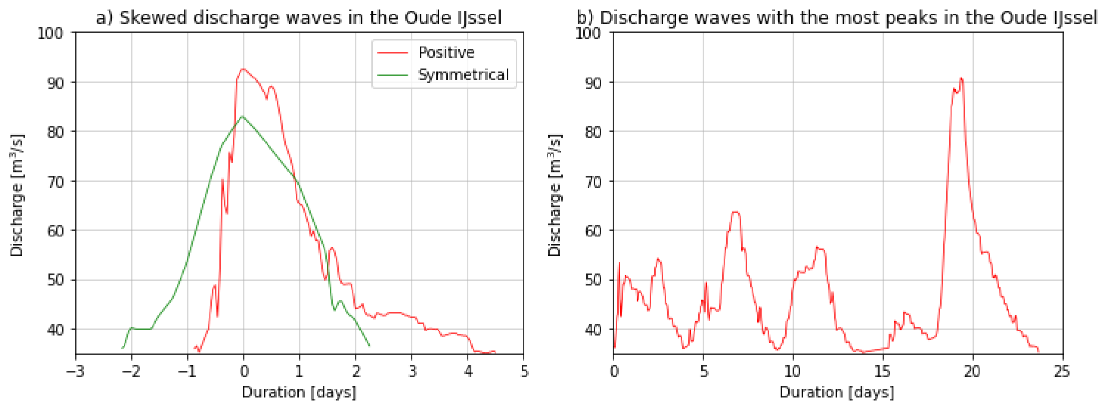

Figure 15 a) Skewed discharge waves and b) multiple peak discharge wave with the highest amount of peaks in the Oude IJssel at Doesburg.

The remaining 48 discharge waves (55% of all discharge waves in the Oude IJssel) contain multiple peaks of which 23 discharge waves have two peaks. The other 25 discharge waves have three or more peaks, with a maximum of five. The minimum duration of the discharge waves with several peaks is five days, equivalent to the average duration (Figure 12a). This shows that discharge waves with multiple peaks are not necessarily longer than those with one, which is different from the discharge waves in the Rhine. The multiple-peak discharge wave with the highest amount of peaks is shown in Figure 15b.

Twentekanaal

The skewness coefficient is calculated for 16 single-peak discharge waves (31% of all discharge waves in the Twentekanaal). The calculation results in a minimum skewness coefficient of -0.23 and a maximum of 1.86. 15 discharge waves are characterized by a positive skewness coefficient, while 1 has a negative skewness coefficient and none approaches zero. The discharge wave with the positive skewness coefficient shows the characteristic shape although it shows fluctuations (Figure 16a). The negative skewed discharge wave is different from the characteristic shape but does have a slightly longer tail on the left side.

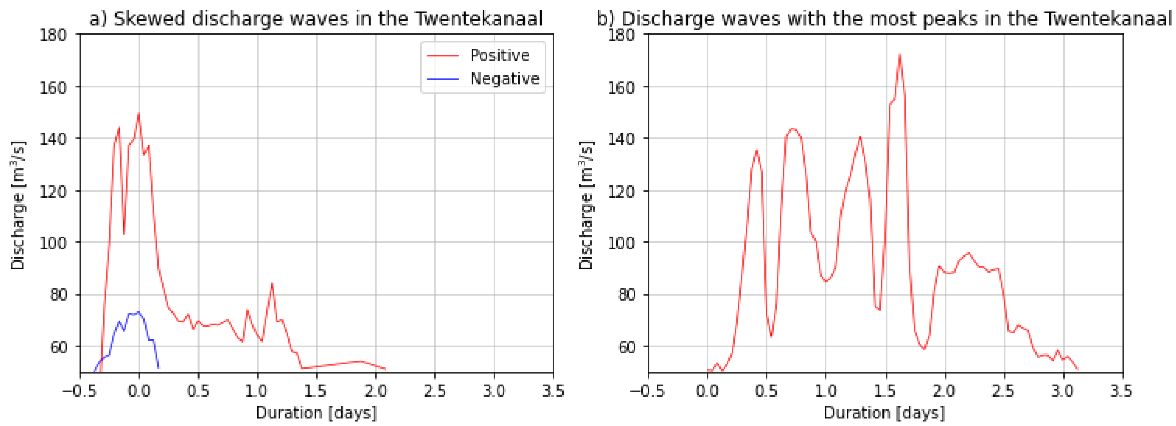

Figure 16 a) Skewed discharge waves and b) multiple peak discharge wave with the highest amount of peaks in the Twentekanaal at Eefde.

The remaining 36 discharge waves (69% of all discharge waves in the Twentekanaal) have multiple peaks. The number of peaks varies from 2 to 5, excluding small fluctuations. Their duration varies as much as the other discharge waves since the majority have several peaks. The multiple peak discharge wave with the highest amount of peaks is shown in Figure 16b.

Overall, the shape of the discharge waves in the Rhine are smoother than the discharge waves in the laterals. The skewed shapes are more clear than those in the laterals, since they have less fluctuations. The Rhine has the most discharge waves with one peak, and the discharge waves with multiple peaks are easy to define as the separate peaks are very clear. The discharge waves with multiple peaks have at most three peaks and their duration is significantly longer than the mean duration. Conversely, the discharge waves with multiple peaks in the laterals can have more than 5 peaks and their duration is comparable to the mean duration. A reason for this difference can be the size of the catchment areas. The smaller catchment areas of the laterals cause the rivers to react faster to rainfall, while the Rhine reacts slower. In addition, the Rhine has a much larger discharge, so small fluctuations caused by rainfall are not directly visible in the discharge waves. Another reason can be the fact that the discharge from the Oude IJssel and Twentekanaal are influenced by weirs and locks, resulting in more fluctuating discharges.

4.2 Timing

This section shows the results of the change in timing of the lateral inflow. First, the time difference between the discharge waves in the Rhine at Lobith, Oude IJssel at Doesburg and Twentekanaal at Eefde that occurred in the historical data is analysed. Then the effect of changing the timing of the lateral inflow on the water level in the IJssel is given. Finally, the effect of changing the timing of the lateral inflow on the shape of the discharge wave in the IJssel is shown.

4.2.1 Time difference between the discharge waves

The most common time difference is determined by subtracting the date of the peak in the Rhine at Lobith from the date of the peak in the Oude IJssel and Twentekanaal. The difference between the two laterals is also determined by subtracting the peak date of the Twentekanaal from the Oude IJssel. The result is shown in Figure 17. When Δt is negative it means that the peak of the Oude IJssel at Doesburg and Twentekanaal at Eefde is earlier than the peak of the Rhine at Lobith and in the case of the laterals, the Oude IJssel is earlier than the Twentekanaal.

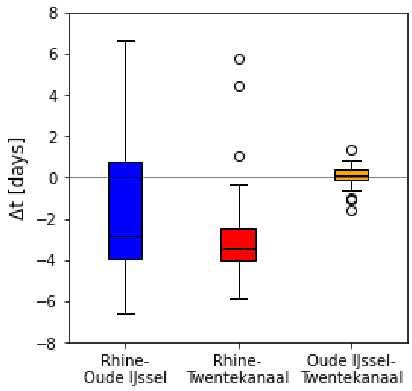

Figure 17 The difference in timing between the peak discharges of the Rhine and laterals. When the time difference is negative, it means that the peak of the first mentioned river is earlier

38 discharge waves in the Oude IJssel are matched to a discharge wave in the Rhine. The blue boxplot in Figure 17 shows that the median time difference is -3 days, meaning that the peak of the Oude IJssel at Doesburg is 3 days earlier than the peak of the Rhine at Lobith. The standard timing in Sobek is -3 days and 5 hours. This 5-hour time difference is partly caused by the travel time from Dornick to Lobith, since the standard timing is relative to Dornick and the observed timing in the historical data relative to Lobith. The travel time from Dornick to Lobith is approximately 3 hours, so the difference between the observed timing and the standard timing is only 2 hours. The travel time from Lobith to Doesburg is approximately 19 hours (Bod, 2021), so with the most common and standard timing the peak of the Oude IJssel enters the IJssel approximately 4 days before the peak of the Rhine is at Doesburg.

19 discharge waves in the Twentekanaal are matched to a discharge wave in the Rhine. The red boxplot in Figure 17 shows that the median time difference is -3 days and 11 hours, meaning that the peak of the Twentekanaal at Eefde is 3 days and 11 hours earlier than the peak of the Rhine at Lobith. The standard timing is -3 days and 10 hours. Including the travel time from Dornick to Lobith results in a difference of 2 hours between the observed timing in the historical data and the standard timing. The travel time from Lobith to Zutphen is approximately 25 hours (Bod, 2021). Therefore, with the most common and standard timing, the peak of the Twentekanaal enters the IJssel at Zutphen approximately 4 days and 12 hours before the peak of the Rhine is at Zutphen.

28 discharge waves in the Oude IJssel are matched to a discharge wave in the Twentekanaal. The orange boxplot in Figure 17 shows that the median time difference is -3 hours, meaning that the peak of the Twentekanaal at Eefde is 3 hours earlier than the peak of the Oude IJssel at Doesburg. In the standard timing this is -5 hours. The travel time from Doesburg to Zutphen is approximately 6 hours (Bod, 2021). Hence, with the most common timing, the peak of the Twentekanaal enters the IJssel 9 hours before the peak of the Oude IJssel is at Zutphen.

Overall, it occurs more often that a discharge wave in the Rhine is accompanied by a discharge wave in the Oude IJssel than by a discharge wave in the Twentekanaal. In 15 cases, discharge waves from the Rhine, Oude IJssel and Twentekanaal are matched. This is 39% of the matched discharge waves of the Oude IJssel and Rhine and 79% of the matched discharge waves of the Twentekanaal and Rhine. This shows that when there is a discharge wave in the Twentekanaal there is often a discharge wave in the Oude IJssel and Rhine as well. Conversely, when there is a discharge wave in the Oude IJssel, there it is more common that there is only a discharge wave in the Rhine and not in the Twentekanaal.

4.2.2 The influence of timing of lateral inflow on the water level in the IJssel

The effect of the timing of lateral inflow on the water level in the IJssel for various peak discharges in the Rhine at Lobith is evaluated. The water levels in the IJssel in the situation with high lateral inflow are compared to the water levels in the IJssel in the situation with steady lateral inflow, for different timings (reference, 1 day earlier, 2 days earlier, 1 day later, 2 days later).

At first, the change in water level due to lateral inflow for the reference timing along the IJssel for the lowest- and highest peak discharge in the Rhine at Dornick is shown in Figure 18. Overall, the lateral inflow from the Oude IJssel and Twentekanaal are affecting the water level along the whole length of the river. The change in water level for the lowest peak discharge in the Rhine is approximately 3 times higher than for the highest peak discharge in the Rhine. The increase in the change in water level due to the Twentekanaal is larger than due to the Oude IJssel, since the total volume of lateral inflow from the Twentekanaal is larger than that of the Oude IJssel. The smaller fluctuations along the river are caused by the river profile. At certain locations, the water level may remain within the main profile, whereas at other locations, it may already have reached the floodplains. When the water level is still in the main profile, the increase in water level due to lateral inflow is larger.

The water level with the higher Rhine discharge is decreasing between km 955 and km 970. This is a result of the inundation of the high water channel between Veessen (km 961) and Wapenveld (km 973). This high water channel will flow along the IJssel when the IJssel reaches a water level of 5.65 m +NAP at Veessen. Downstream of km 985 for peak discharge 5,600 m3/s and km 1000 for peak discharge of 13,000 m3/s, the increase in water level is decreasing fast. This can be caused by the fact that the water is reaching the lake, so it flows faster out of the river system. Another reason is that the water levels are affected by the Q(h) relations of the downstream boundary condition at Ketelbrug.

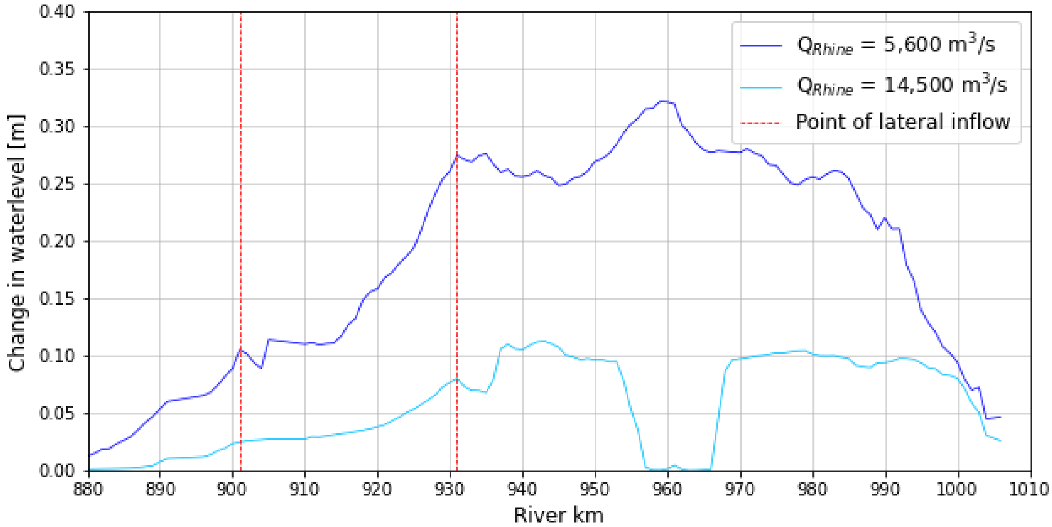

Figure 18 Change in water level due to high lateral inflow along the IJssel for a peak discharge in the Rhine at Dornick of 5,600 m³/s and 14,500 m³/s.

The water levels for all peak discharges in the Rhine in the situation with steady lateral inflow are given in Figure 19.

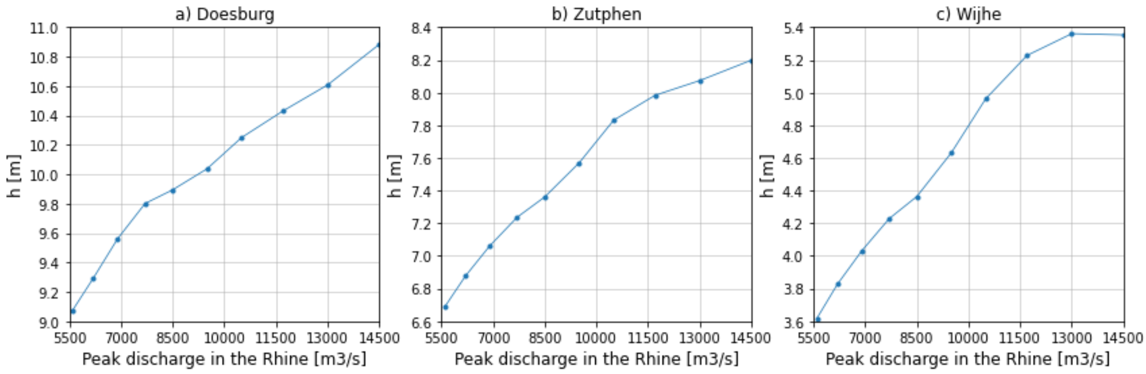

Figure 19 Maximum water levels at a) Doesburg, b) Zutphen and c) Wijhe for the different peak discharges in the Rhine in the situation of standard steady laterals

Doesburg

Figure 20a shows the change in water level at Doesburg relative to the water level in the situation with steady lateral inflow, which is shown in Figure 19a. The highest increase in water level is 17.3 cm and arises with a peak discharge of 6,900 m³/s in the Rhine. As expected, the reference timing, where the peak discharge in the IJssel and Oude IJssel confluence at the same time at Doesburg, resulted in the highest increase in water level at Doesburg. The timing of one day earlier and one day later show a similar increase in water level, which is logical given the symmetrical shape of the discharge wave in the IJssel. Conversely, the timing of 2 days later causes approximately 2 cm more increase than 2 days earlier.

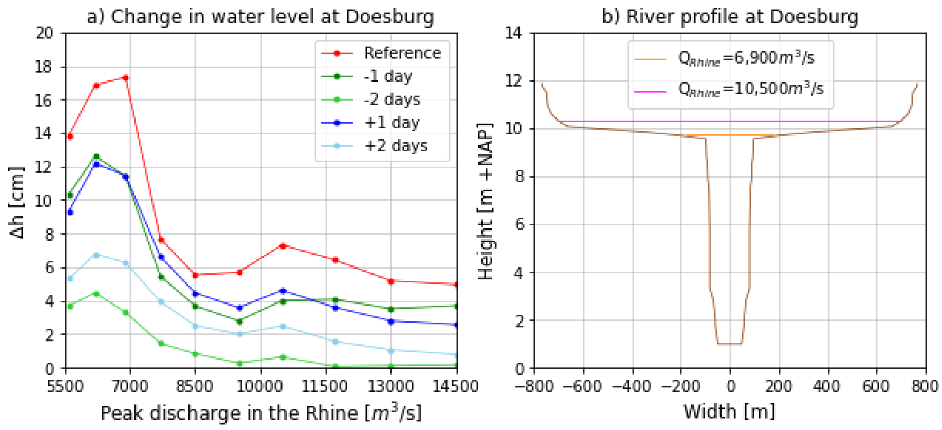

Figure 20 a) The change in water level at Doesburg caused by the timing of laterals for various peak discharges in the Rhine and b) the water levels in the river profile at Doesburg for a peak discharge of 6,900 m³/s and 10,500 m³/s in the Rhine.

The five different timings show a similar trend where the increase in water level is highest at a peak discharge of 6,900 m^3/s in the Rhine at Dornick. Until this discharge, the water level stays in the summer profile (orange line in Figure 20b). When the peak discharge in the Rhine at Dornick is increasing to higher values, the water in the IJssel will flow into the floodplains, resulting in a wider river profile and thus a smaller change in water level. Reaching a peak discharge of 10,500 m^3/s in the Rhine at Dornick, the change in water level is sightly increasing due to the river profile as well (pink line in Figure 20b). From this discharge the water level is reaching the embankments, and the river is not getting any wider. Overall, higher peak discharges in the Rhine at Dornick results in a higher water level, where the river profile is wider.

Zutphen

Figure 21a shows the change in water level at Zutphen relative to the water level in the situation with the standard steady laterals. The highest increase in water level is 27 cm and arises with a peak discharge of 5,600 m^3/s in the Rhine (orange line in Figure 21b). The timing that is causing the highest increase in water level is one day later than the reference timing, meaning that the peak discharge of the Oude IJssel is one day later at Doesburg than the peak discharge in the IJssel. However, the peak discharge in the IJssel is further downstream and now confluences with the peak discharge of the Twentekanaal. The travel time of the discharge wave from Doesburg to Zutphen is approximately 12 hours and the discharge wave from the Twentekanaal has to travel from Lock Eefde to the IJssel. All together this results in the peak discharge of the Twentekanaal entering the IJssel a few hours before the peak discharge of the IJssel at Zutphen. The timings of 1 and 2 days earlier cause smaller increase in water level, as the peak of the discharge wave in the IJssel is still further upstream.

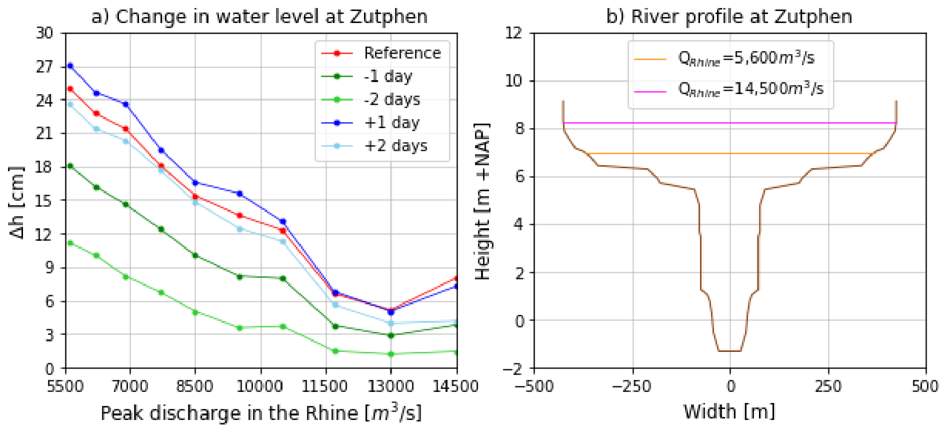

Figure 21 a) The change in water level at Zutphen caused by the timing of laterals for various peak discharges in the Rhine and b) the water levels in the river profile at Zutphen for a peak discharge of 5,600 m³/s and 14,500 m³/s in the Rhine.

The five different timings show a similar trend where the increase in water level is decreasing with increasing peak discharges in the Rhine at Dornick. Another cause is the shape of the river profile, which is becoming wider with a gentle slope. The change in water level at the highest peak discharge in the Rhine at Dornick is slightly increasing again as the water reaches the border of the floodplain (pink line in Figure 21b).

Wijhe

Figure 22a shows the change in water level at Wijhe relative to the water level in the situation with the standard steady laterals, which is shown in Figure 19c. The highest increase in water level is 28 cm and arises with a peak discharge of 5,600 m^3/s in the Rhine at Dornick (orange line in Figure 22b). The timing of lateral inflow resulting in the highest increase in water level is one day later than the reference timing, similar to Zutphen. This indicates that for locations downstream of the lateral inflow points, the influence of lateral inflow resembles the effect most downstream lateral, which in this case the Twentekanaal. The difference between the several timings is similar to the difference at Zutphen, because the discharge wave in the IJssel does not change due to lateral inflow between Zutphen and Wijhe.

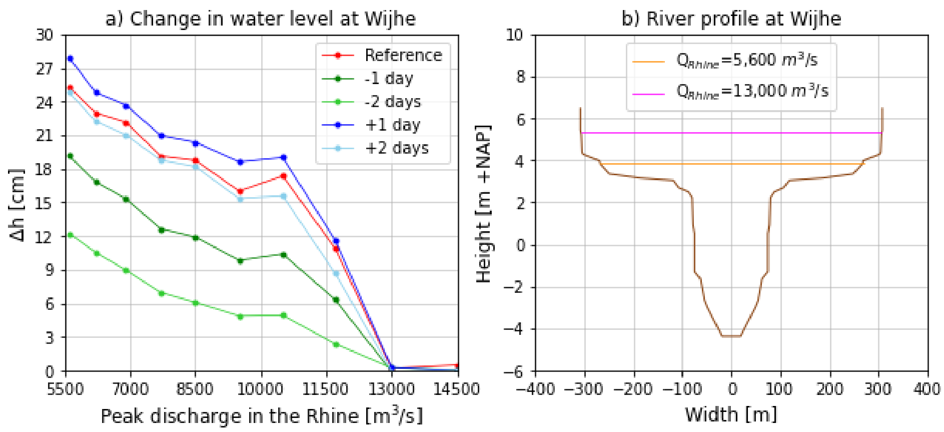

Figure 22 The change in water level at Wijhe caused by the timing of laterals for various discharges in the Rhine and b) the water levels in the river profile at Wijhe for a peak discharge of 5,600 m³/s and 13,000 m³/s in the Rhine.

The five different timings exhibit a similar trend over the increasing peak discharge in the Rhine at Dornick. Until a peak discharge in the Rhine at Dornick of 10,500 m3/s, the trend is very similar to that of Zutphen, since their amount of lateral inflow is the same and the shape of the river profiles are similar as well. The only difference is that at Wijhe the increase in water level is higher than at Zutphen which is caused by the smaller floodplains at Wijhe. When the discharge in the Rhine at Dornick becomes higher than 10,500 m^3/s, the change in water level at Wijhe is decreasing fast. At these discharges the high water channel Veessen-Wapenveld will be opened, which will result in less discharge in the IJssel at Wijhe, although the water level remains high (pink line in Figure 22b). The opening of the high water channel is also visible in Figure 19c, where the increase in water level stops at the discharge in the Rhine at Dornick of 13,000 m^3/s.

Overall, the highest increase in water level occurs at Wijhe, although it is just 1 cm more than at Zutphen. At Wijhe, both laterals have entered the IJssel, which results in more discharge than at Doesburg, where only the Oude IJssel has entered the IJssel. The floodplains at Wijhe are smaller than at Zutphen which results in slightly higher increases in water level. The reference timing only resulted in the highest increase in water level at Doesburg. This is as expected since the reference timing is based on the confluence of the discharge waves of the IJssel and Oude IJssel at Doesburg. At Zutphen and Wijhe, the timing of one day later than the reference timing resulted in the highest water levels. At this timing the peak of the Twentekanaal confluences with the peak of the IJssel at Zutphen. Since Wijhe is situated downstream of Zutphen, the dominant timing at Zutphen also results in the highest increase in water level at Wijhe.

4.2.3 The effect of timing of lateral inflow on the shape of the discharge wave in the IJssel

The effect of timing of high lateral inflow on the shape of the discharge wave in the IJssel is analysed at three locations for three different timings. The shape is compared to the shape of the discharge wave with the standard timing. Q(h) relation shows how the change in the shape of the discharge wave affects the water level.

Doesburg

Figure 23a, b and c show the change in the shape of the discharge wave at Doesburg for several timings of lateral inflow. Overall, the influence of the lateral inflow is clearly visible in all three scenarios. When the lateral inflow is timed before the reference timing, the increasing part of the discharge wave is steeper than that of the discharge wave with standard timing of lateral inflow. This results in a slightly increased and wider top. The highest increase in peak discharge occurred in case of the reference timing (64 m^3/s) which resulted in a steeper shape. When the laterals are timed 2 days after the reference timing, the shape of the discharge wave becomes wider on the decreasing part and the peak discharge remains similar. With all three adjusted timings, the start of the discharge waves is 2 days later than the start of the discharge wave with lateral inflow on the standard timing, since in case of the standard timing, the lateral inflow starts before the discharge wave from the Rhine is in the IJssel at Doesburg.

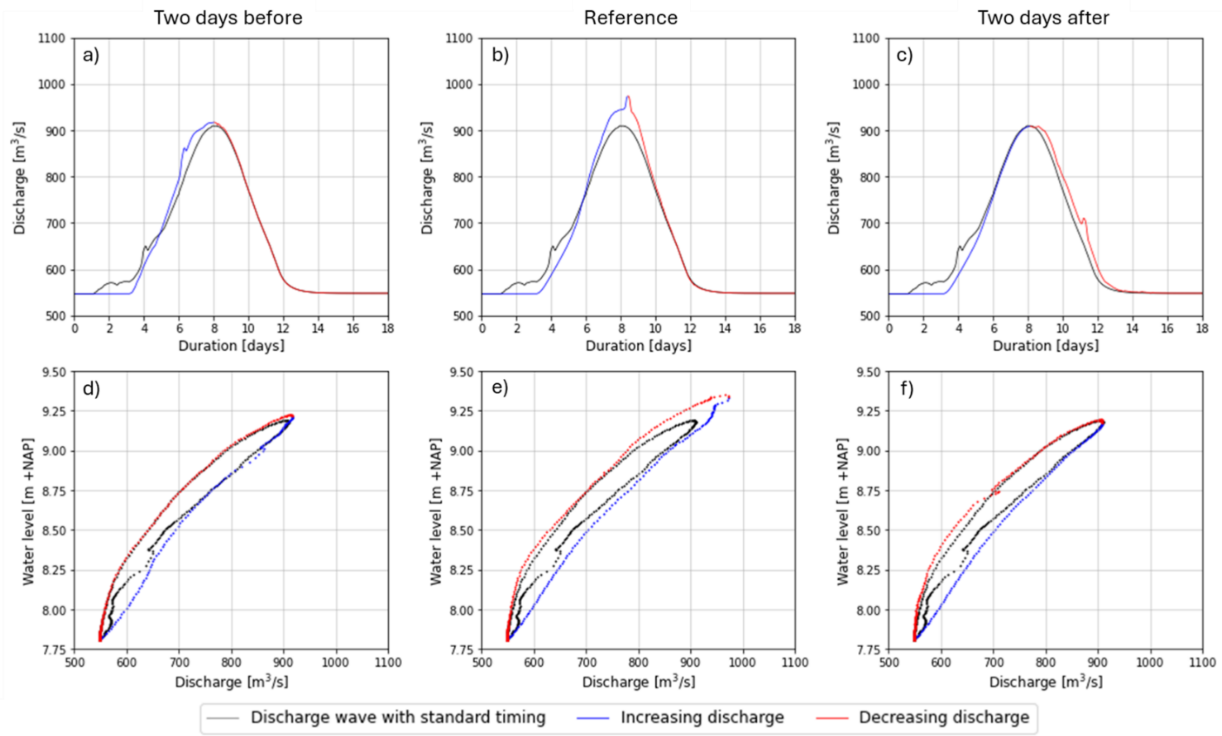

Figure 23 Change in the shape of the discharge wave at Doesburg for a) two days before the reference timing, b) the reference timing and c) two days after the reference timing and the accompanying Q(h) relations.

The Q(h) relations in Figure 23d, e, and f show that for the decreasing part of the discharge waves the water level is always higher for a given discharge. This phenomenon is called hysteresis. The timing of 2 days before the peak resulted in lower water levels at the start of the discharge wave and a slightly increase in maximum water level. The water level at discharges below 700 m^3/s is lower than the standard timing, as the there is no lateral inflow in that part of the discharge wave. With the reference timing, the higher discharge resulted in higher water level. At a discharge of 950 m^3/s, there is a steep increase in water level due to the lateral inflow. With increasing discharges the water level stays high until the discharge is decreased to 950 m^3/s again. The difference in water level between the increasing and decreasing discharge is larger than at the standard discharge wave, due to the lower water levels at the start of the discharge wave. When the laterals entered the IJssel 2 days after the reference timing, the water levels at the increasing part of the discharge wave are lower due to the absence of the lateral inflow, while at the decreasing part, the water levels are higher. From a decreasing discharge between 700 m^3/s and 600 m^3/s, the water level stays almost 10 cm higher than in case of the standard timing.

Zutphen

The discharge waves in Figure 24a, b and c show that the lateral inflow is even more visible than at Doesburg, due to the fluctuating shape of the high lateral inflow of the Twentekanaal. Although, the fluctuations are smaller in the adjusted timings than in case of the standard timing, since the laterals are more overlapping with the discharge wave in the IJssel. At both, two days before and two days after the reference timing, the discharge wave is becoming approximately 60 m^3/s higher. In case of the timing before the increasing part is becoming steeper while with the timing after, the decreasing part is becoming steeper. The reference timing resulted in a higher and steeper discharge wave with the highest increase in peak discharge, 181 m^3/s.

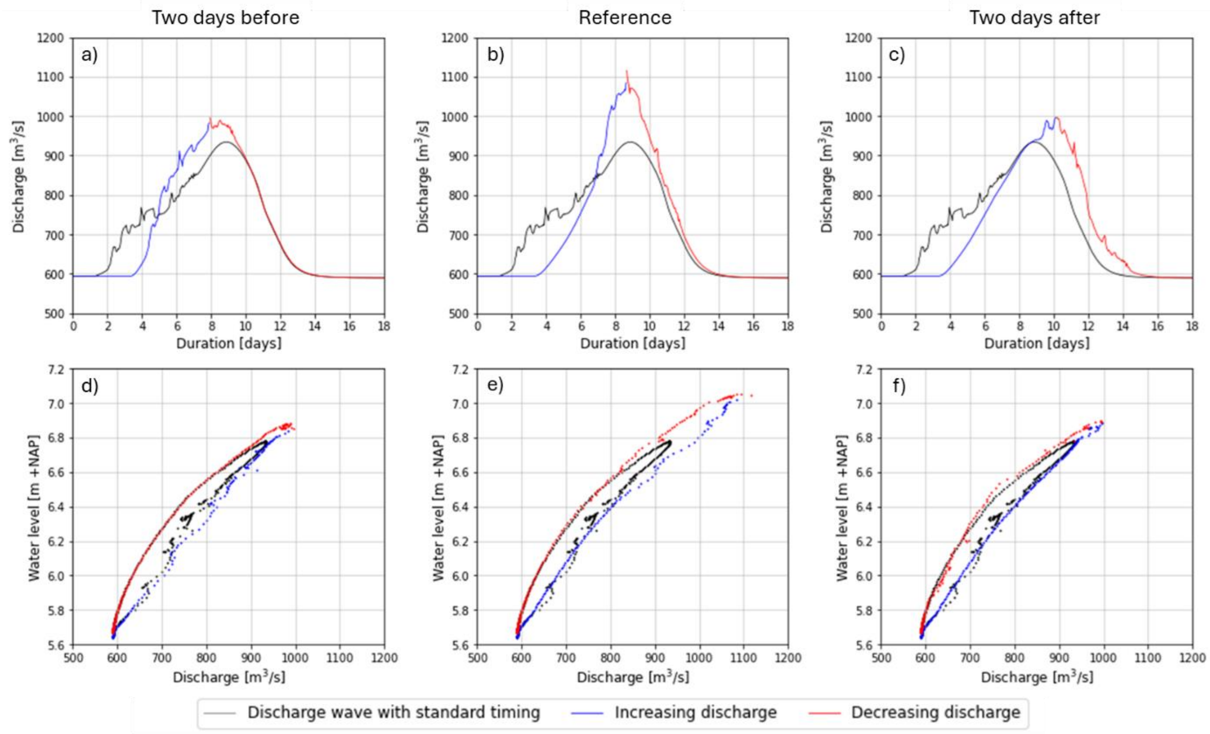

Figure 24 Change in the shape of the discharge wave at Zutphen for a) two days before the reference timing, b) the reference timing and c) two days after the reference timing and the accompanying Q(h) relations.

The fluctuating shape of the discharge wave from the Twentekanaal is also clearly visible in the Q(h) relation in Figure 24d, e, and f. The timing of 2 days before the reference timing results in lower water levels at the increasing part of the discharge wave and an increase in the maximum water level. The lateral inflow of the Twentekanaal joins the IJssel later than the standard timing, resulting in higher water levels at the peak discharge. The highest increase in peak discharge caused by the reference timing, resulted in the highest increase in water level as well. At an increasing peak discharge of 1050 m^3/s, the water level is increasing quickly and then stays high until the discharge is decreased to 1050 m^3/s again. The timing of 2 days after the reference timing shows that although the lateral inflow is later than the standard timing, the water level in the increasing part of the discharge wave is not much lower. The effect on the water level is mainly visible at the peak discharges and at the decreasing part of the discharge wave until a peak discharge of 700 m^3/s.

Wijhe

Figure 25 a, b and c show the influence of the laterals on the discharge wave in the IJssel at Wijhe. The fluctuations of the lateral inflow from the Oude IJssel and Twentekanaal are attenuated, but the increase in volume due to the laterals is still visible. At both, two days before and two days after the reference timing, the discharge wave is becoming approximately 60 m^3/s higher, similar to the increase at Zutphen. In both cases, the increasing part of the discharge wave is steeper than that of the standard timing, since the lateral inflow from the Oude IJssel and Twentekanaal is later than the standard timing in both cases. With the timing of two days after the reference timing, the decreasing part is steeper as well, resulting in a shorter and steeper discharge wave. The reference timing resulted in the highest increase in peak discharge of 131 m^3/s. The discharge wave starts later than the standard timing, resulting in a steeper increasing part. Due to the increase in peak discharge as well, the discharge wave becomes much steeper and more pointier than the discharge wave with standard timing.

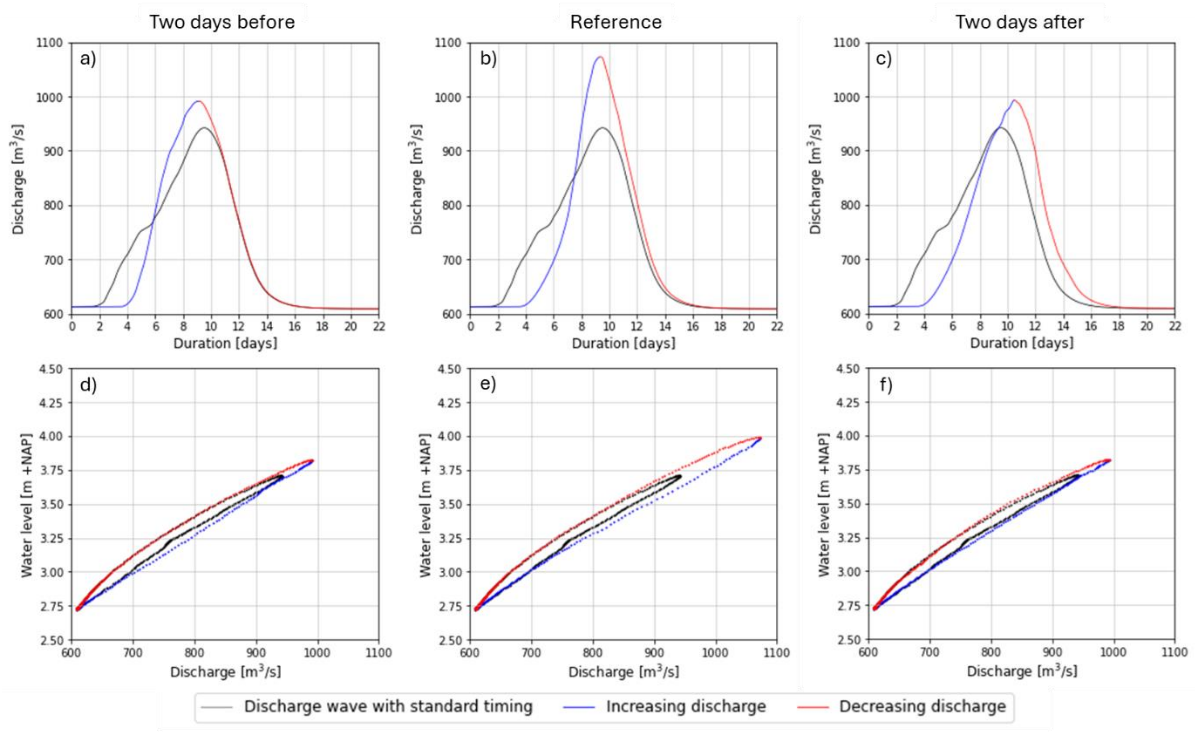

Figure 25 Change in the shape of the discharge wave at Wijhe for a) two days before the reference timing, b) the reference timing and c) two days after the reference timing and the accompanying Q(h) relations.

The Q(h) relation in Figure 25d, e and f show that the difference between the increasing and decreasing part of the discharge waves at Wijhe are smaller than at Doesburg and Zutphen. The kink at the increasing part of the discharge wave with standard timing, caused by lateral inflow, is not visible at the adjusted timings. This is because in the adjusted timings the lateral flow starts when the discharge wave in the IJssel started already, while with the standard timing the lateral inflow started before the discharge wave of the IJssel. The largest change is with all three timings visible at the highest peak discharges, which increased compared to the discharge wave of the standard timing. The water level increased along with the discharge, following the trend of the Q(h) relation of the standard timing.

Overall, the increase in peak discharge is highest at Zutphen for the reference timing. This is mainly caused by the total amount of lateral inflow, which is higher at Zutphen than Doesburg due to the inflow of the Twentekanaal. The slightly lower increase in peak discharge at Wijhe is caused by dissipation. Wave attenuation resulted in the disappearance of the fluctuations which are still visible at Zutphen. For all three locations, the timing of 2 days before and 2 days after the peak discharge resulted in a slightly increased peak discharge at Zutphen and Wijhe and wider peak of the discharge wave at all three locations. The reference timing resulted in a steeper, higher and shorter discharge wave.

The effect of the change in the shape of the discharge wave on the water level shows that the fluctuations due to lateral inflow are less with the adjusted timing than the in case of the standard timing. This is mainly caused by the fact that the lateral inflow starts later than in case of the standard timing. The hysteresis is smallest at Wijhe. Inactive storage causes higher hysteresis (Mishra & Singh, 1999), the river profiles at Doesburg and Zutphen have more inactive storage than the river profile at Wijhe. Additionally, At Doesburg and Zutphen the discharge waves are more dynamic than at Wijhe, due to the local changes caused by lateral inflow, which also is a cause of higher hysteresis (Mishra & Singh, 1999). Finally, the fluctuations in the Q(h) relations at Doesburg and Zutphen show the back water effect due to lateral inflow, which is not visible at Wijhe (Hidayat et al., 2011).

4.3 Shape

This paragraph shows the results of the effect of lateral inflow on different shapes of discharge waves in the IJssel. The effect on skewed shapes and on discharge waves with various widths are analysed.

Skewed shapes

The water level in the IJssel for skewed discharge waves with high lateral inflow will be compared to those with the standard steady lateral inflow. Figure 26 shows that various skewness of discharge waves in the Rhine with standard steady lateral inflow do not result in significant differences in the water level in the IJssel at Doesburg, Zutphen and Wijhe. The maximum water levels at Doesburg and Zutphen are similar for all three shapes, while at Wijhe the negatively skewed discharge wave results in lower water levels than the symmetrical and positively skewed discharge wave. However, the difference at Wijhe is very small.

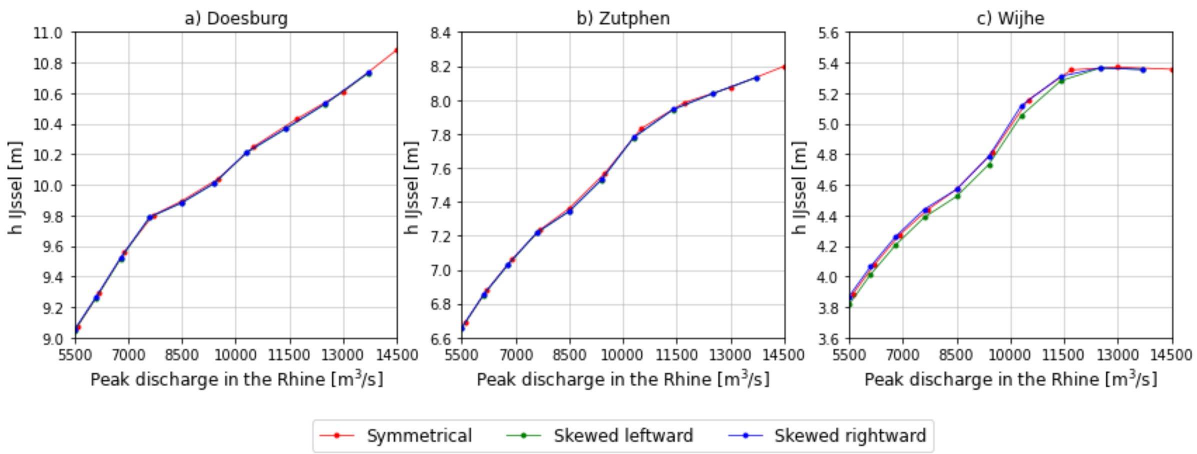

Figure 26 Maximum water levels in the IJssel at a) Doesburg, b) Zutphen and c) Wijhe for the different peak discharges and discharge shapes in the Rhine in the situation of standard steady laterals.

The high lateral inflow results in higher water levels than the standard steady lateral inflow. Figure 27 shows the change in water level due to the high lateral inflow compared to the maximum water levels in Figure 26. Overall, at all three locations the change in maximum water level shows the same trend for the three types of shapes. The trends are the same as in section 4.2.2 and are explained there as well.

At Doesburg (Figure 27a), the highest increase in water level is caused by the symmetrical shape at a peak discharge in the Rhine at Dornick of 6,900 m^3/s. The difference with the skewed shapes is almost nothing until a peak discharge in the Rhine at Dornick of 10,500 m^3/s. With higher discharges the discharge wave that is skewed negative results in a higher increase in maximum water level and the discharge wave that is skewed positive results in a smaller increase in maximum water level than the symmetrical shape. This difference may be caused by the difference in volume, but remains unclear.

At Zutphen (Figure 27b), the highest increase in water level is caused by the discharge wave in the IJssel that is skewed positive. The symmetrical and skewed negative discharge wave in the IJssel show very similar increase in maximum water levels. This suggests that if the discharge in the IJssel is rising quickly at Zutphen and extra lateral inflow reaches the river, this has more impact on the water level than when the discharge is increasing slowly. The quick increase in water level in combination with high lateral inflow can cause more backwater effect (Hidayat et al., 2011). At Zutphen this effect is larger than at Doesburg because the volume of the lateral inflow from the Twentekanaal is larger than the volume of the lateral inflow from the Oude IJssel.

At Wijhe (Figure 27c), the highest increase in water level is caused by the discharge wave in the Rhine that is skewed positive. This is similar to the results at Zutphen, so the highest increase with this shape may still be a result of the backwater effect at Zutphen as there is no lateral inflow at Wijhe. The discharge wave in the IJssel that is skewed negative results in a lower increase in water level than the other two shapes at Wijhe. The shape of the discharge waves is changed due to peak attenuation, which can result in difference influence of lateral inflow. From a discharge of 11,500 m^3/s there is no difference between the shapes of the discharge waves, due to the opening of the high water channel of Veessen-Wapenveld.

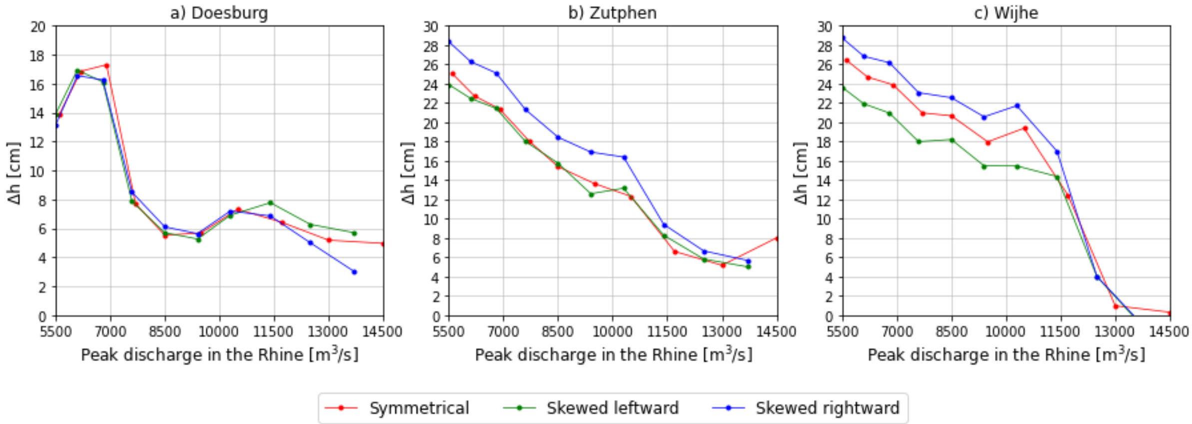

Figure 27 Change in maximum water level in the IJssel at a) Doesburg, b) Zutphen and c) Wijhe as a result of the high lateral inflow for the various shapes of discharge waves in the Rhine at Dornick.

Various widths

The water levels in Figure 28 show that even with standard steady laterals, the maximum water level in the IJssel is changing with the width of the discharge wave in the IJssel. At all three locations, the wide discharge wave results in the highest water level which is caused by the fact that the wide discharge wave has a higher total volume of water. At some peak discharges the difference in water levels between the three shapes is larger than at other peak discharges, this is a result of the width of the river profile at that specific water level. The difference between the shapes is smallest at Doesburg, since the river profile is there wider than at Zutphen and Wijhe.

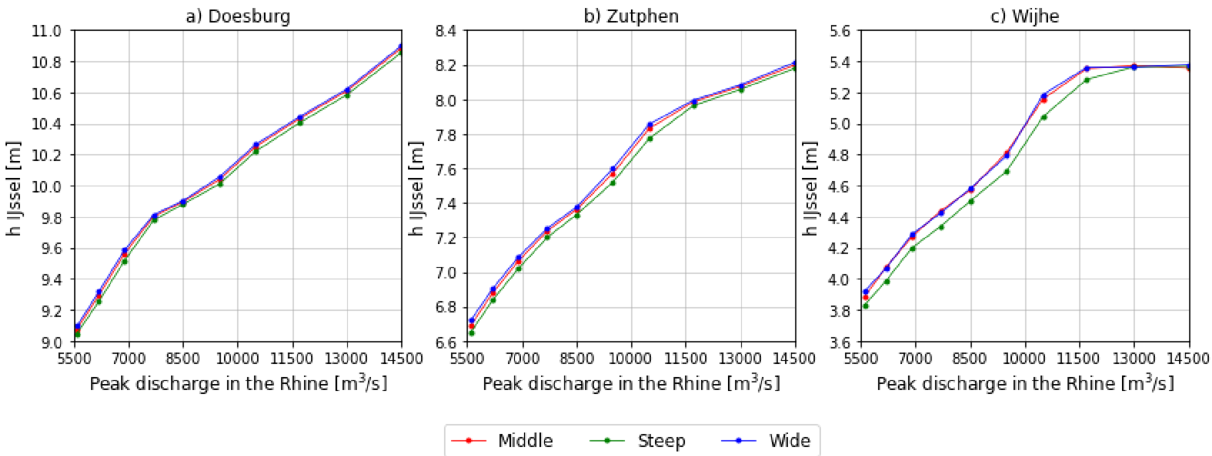

Figure 28 Maximum water levels at a) Doesburg, b) Zutphen and c) Wijhe for various widths of discharge waves in the IJssel and with standard steady lateral inflow.

Lateral inflow cand change the water level in the IJssel in different ways for the different widths. Figure 29 shows the increase in water level due to the high lateral inflow compared to the maximum water levels in Figure 28. The change in water level in Figure 29 follows roughly the same trend as in section 4.2.2 and section **Error! Reference source not found.** for all three locations and is explained in section 4.2.2.

At Doesburg (Figure 29a), the change in water level at two peak discharges stand out, 6,200 m^3/s and 9,500 m^3/s. In both cases, the lateral inflow resulted in the smallest increase in water level for the wide discharge wave. This is caused by the shape of the river profile. For example, in case of the peak discharge of 6,200 m^3/s, the maximum water level in case of the steep and middle wave is lower than the wide wave. At that water level, the river profile is smaller than at the water level of the wide wave, resulting in a higher increase in the maximum water level.

At Zutphen (Figure 29b), the change in water level at three peak discharges stands out, 6,200 m^3/s, 7,700 m^3/s and 9,500 m^3/s. In all cases the lateral inflow resulted in the highest increase in maximum water level for the middle wave. Similar to Doesburg, this is caused by the river profile. The river profile at Zutphen becomes wider in small steps (Figure 21b), which causes the difference in the increase in maximum water level at three peak discharges. The higher amount of discharge in the wide wave results in a higher water level where the river profile is wider, and thus the increase in water level lower.

At Wijhe, Figure 29c shows that the steep and the wide discharge waves both result in a lower increase in water level than the middle shape. Since Wijhe is situated downstream of the laterals, the influence of the lateral inflow shows a similar pattern as the influence of the lateral inflow at Zutphen. Additionally, peak attenuation may influence the water level.

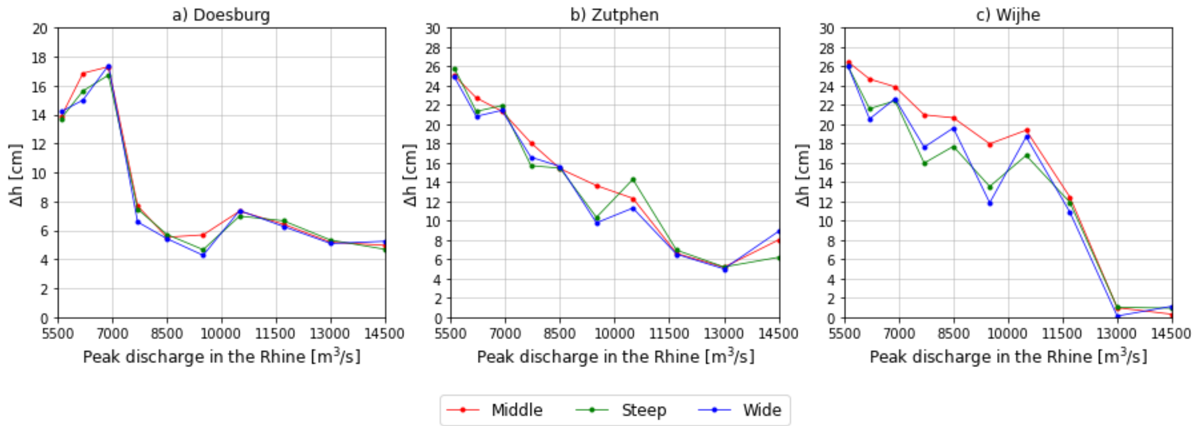

Figure 29 Change in maximum water level in the IJssel at a) Doesburg, b) Zutphen and c) Wijhe as a result of the high lateral inflow for the various widths of discharge waves in the Rhine .

Overall, high lateral inflow does have different effects on the water level for different shapes of discharge waves in the IJssel. The difference between Doesburg, Zutphen and Wijhe is mainly caused by the amount of lateral inflow, the distance from the lateral source and the river profile. According to Pol et al. (2006) the effect of the shape of the discharge wave is larger more downstream the river, which is visible in Figure 27, since the difference in change in water level between the shapes is larger at Wijhe than at Doesburg. The effect of the shapes is not as clear and more difficult to draw a conclusion on compared to the influence of the timing of the laterals in section 0. Moreover, these results are based on the reference timing for the lateral inflow. With other timings, the influence of lateral inflow on various shapes in the IJssel can be different.

5 Discussion

For this study, the influence of lateral inflow on the water level in the IJssel is determined by changing the timing of lateral inflow and the shape of the discharge wave in the IJssel. Historical discharge waves from the last 30 years are analysed based on their peak discharge, duration and shape. Changes in the timing are based on the moment of peak discharge in the Rhine at Dornick, Oude IJssel at Doesburg and Twentekanaal at Eefde. The changes in the shape of the discharge waves in the IJssel are based on theoretical discharge waves (GRADE) and discharge waves from the historical data. When the study would be repeated with similar discharge waves, the results will be similar.

5.1 Interpretation of results

Timing

The timing of confluence of the peak discharge of the laterals with the peak in the IJssel is an important factor for the influence of lateral inflow on the water level in the IJssel. When the peak discharge of the laterals enters the IJssel on the peak of the discharge wave in the IJssel, the increase in water level is highest and can locally reach up to a maximum of approximately 27 cm for the conditions considered in this study. This timing is the reference timing and occurs when:

- The peak of the Oude IJssel is approximately 1 day later at Doesburg than the peak of the Rhine at Dornick
- the peak of the Twentekanaal is approximately 2 days later at Zutphen than the peak of the Rhine at Dornick.

The difference with the most common timing in historical data and the standard timing in Sobek is approximately 4 days. From the analysis of the timing in the historical data resulted that the reference timing did occur in the past. The reference timing is comparable to the timing of the Geul during the flood in the Meuse in 2021 (De Bruijn & Slager, 2022). This shows that a similar event may occur in the IJssel.

Shape

The influence of high lateral inflow is different for various shapes of discharge waves in the IJssel. In this research, the skewness of the discharge waves resulted in a higher increase in water level than the width. This is mainly caused by the steep increase in discharge at the positively skewed discharge wave and total volume of water flowing through the river during a flood. Pol et al. (2006) showed that the hydrograph shape is an important variable which can affect the downstream water levels through peak attenuation effects. Three variables that can affect the water level are peak discharge, flood volume and peak curvature, where peak discharge is the most important. However, in this research the difference in change in water level between the different shapes is for all locations a maximum of 4 cm, making the shape of the discharge wave in the IJssel a less important factor than the timing.

Peak discharge in the Rhine at Lobith

The results of change in timing of the laterals and shape of the discharge wave in the IJssel showed that the increase in water level due to the lateral inflow is mainly dependent on the peak discharge in the Rhine at Dornick.. With increasing peak discharges in the Rhine the contribution of the lateral inflow becomes smaller due to wider river profiles. This shows that with lower peak discharges the same high lateral inflow has a larger influence on the water level. Hence, lateral inflow is more significant at lower discharges in the Rhine and can make a differences for navigation or the timing when the floodplains inundate. This can affect the evacuation of campsites in floodplains and whether ferries on the IJssel still can navigate or not. In these situations it is extra important to take lateral inflow into account while forecasting the water levels in the IJssel.

River profile

The results showed that the increase in water level due to high lateral inflow differs along the river. The IJssel is a river with changing river profiles along the river and in the cross section as well. At the wider river profiles the influence is smaller. Additionally, at some locations the floodplains inundate earlier than at other locations due to smaller main profiles and lower summer dikes, resulting in water in the wider part of the river profile and thus a lower increase in water level due to lateral inflow. So, the influence of lateral inflow is highly dependent on the location along the IJssel.

5.2 Limitation and application

1D model

The SOBEK 1D model used during this study, represents flow in only one direction, while in reality the river flow changes along the depth and width of the river. In the floodplains, more complex flow may occur and the 1D model can be insufficient to predict the exact changes in discharge and water levels because of the simplified computational schemes (Tayefi et al., 2007). The observation points downstream of the IJssel showed a much lower increase in water level due to lateral inflow than at Doesburg and Zutphen. The change in water level at Kampen is an example and showed a much lower increase in water level and did not show a clear trend with increasing peak discharged from the Rhine (Appendix I). This may have been affected by the downstream boundary conditions of the model and the simplification of the IJssel delta in the 1D model. In addition, the flow in one direction prevents water flowing from the IJssel to the Oude IJssel for water levels higher than 10 m +NAP, when the weir at Doesburg will be opened. Water flowing from the IJssel to the Oude IJssel may result in locally lower water levels in the IJssel and higher water levels in the Oude IJssel.

The lateral inflow in this study was based on historical data. For operational use, the discharge of the lateral inflow is not always available and needs to be predicted. In that case a dynamically coupled hydrologic and hydraulic model can provide greater utility. The hydrologic part models streamflow prediction based on precipitation and evaporation and the hydraulic part can simulate the river and floodplain hydraulics (Biancamaria et al., 2009).

Study area

The influence of high lateral inflow is dependent on the river basin, which makes is very case specific. The influence of lateral inflow was studied at the IJssel where two laterals can discharge a significant amount of water to the IJssel. The river basin of the IJssel is very flat and the river profile contains floodplains. When lateral inflow enters a river where the water already reached the floodplains, the effect of lateral inflow is smaller than when the water level is still in the main profile. The results of this study are specifically for the IJssel and may not be applicable to river basins that are not comparable to that of the IJssel. The Three Gorges reservoir, part of the Yangtze river basin in China, is a river basin that can have large lateral contributions. Unlike the IJssel, the Three Gorges reservoir is characterized by complex terrain and geomorphological features and contains many short and steep tributaries. These features cause rapid concentration which can reshape the discharge wave in the main river, or even generate flood waves (BaiWei et al., 2011). Another example of a basin with significant lateral inflow is the Ob river in Siberia. This is a large artic river which is frozen for large parts of the year. The main driver of lateral inflow in this basin is snow melt, which is different from the IJssel (Biancamaria et al., 2009). Comparison with these two river basins shows that steep tributaries, as in the Three Gorges reservoir, results in higher lateral inflow which causes a higher increase in water level. The source of lateral inflow is another factor that can influence the amount of lateral inflow, since both snowmelt and rainfall can cause rapid discharge, due to high temperatures or high intensity rainfall.

Lateral inflow

The discharge waves that are used as input for the high lateral inflow during the study have affected the results. As input for the high lateral inflow, a discharge wave for the Oude IJssel and Twentekanaal from the historical data is used. The selected discharge waves for the Oude IJssel and Twentekanaal do not have a similar peak discharge, so their effect on the water level in the IJssel cannot be compared to each other. However, historical data shows that the Twentekanaal reached higher peak discharges but the Oude IJssel had longer durations, so both laterals can give significant lateral inflow. Additionally, the shapes of the discharge waves are very specific for the event. The discharge wave analysis showed that the shapes of the discharge waves in the laterals can fluctuate a lot, so other shapes may lead to different results. Finally, it was assumed that both laterals had an extremely high peak discharge to simulate the most extreme effect. In the historical data, it occurred that they both had increased discharges but not that they were both extremely high. However, the flood in the Meuse in 2021 showed that lateral inflow for an extended period of time can result in influence on the water level as well, even though the peak discharge is not extremely high (De Bruijn & Slager, 2022).

The situation where only one lateral source has high lateral inflow is not researched and will give different results. When only the Oude IJssel has high lateral inflow, the effect at Doesburg would be similar to the situation where both laterals have high lateral inflow because the Twentekanaal confluences later with the IJssel than the Oude IJssel. In case of only high lateral inflow from the Twentekanaal, the increase in water level would be lower as the influence of the Oude IJssel is much lower.

Timing

The time difference between the peak discharge of the Oude IJssel and the peak discharge of the Twentekanaal was kept at a constant value of 5 hours. In reality, this time difference is not constant, since both laterals are fluctuating in their discharges and react fast to rainfall events in their basin. Additionally, the timing was adjusted such that the peak of the IJssel confluences with the peak of the Oude IJssel at Doesburg. This timing does result in the highest increase in water level at Doesburg but not necessarily at Zutphen. When the laterals will be timed such that they both confluence with the peak of the IJssel at their confluence, it may result in higher peak discharges. Additionally, there was focussed on the reference timing, where the peaks with high lateral inflow enter the IJssel at the same time as the peak of the IJssel is at their point of confluence. However, the lateral inflow of the Roer during the flood in the Meuse showed that when the peaks do not enter the main river at the same time, lateral inflow can have significant influence as well (De Bruijn & Slager, 2022).

6 Conclusions and recommendations

This chapter consists of the conclusion and recommendations following from this study. The conclusion answers the research questions and finally the main question. The recommendations include how to implement the study and if further research needs to be done.

6.1 Conclusions

First, the research questions is answered based on the results of the study. Finally, the main question is answered based on the answers on the research questions.

> *"What are potential shapes of discharge waves in the Rhine, Oude IJssel and Twentekanaal, during increased water levels?"*

The analysis of 30 years of data resulted in 62 discharge waves in the Rhine, 88 in the Oude IJssel and 52 in the Twentekanaal. Overall, the shapes of the discharge waves are highly varying. But there is a clear difference between the discharge waves in the Rhine and those in the laterals.

In the Rhine, most discharge waves occurred during high water season and were significantly higher and longer than those during low water season. The correlation between the peak discharge and duration showed that there is a linear relation, although the relation is weak. The shape of discharge wave that occurred most was the positively skewed wave. Discharge waves with several peaks had a maximum of 3 peaks.

In the Oude IJssel and Twentekanaal, more discharge waves occurred during high water season, but there is no significant difference between the season for peak discharge and duration. The correlation between the peak discharge and duration showed that there is a very weak linear relation. Most single-peak discharge waves had a positive skewness, however they were fluctuation more than the discharge waves in the Rhine. Additionally, the majority of the discharge waves had multiple peaks. The discharge waves with several peaks had a maximum of five peaks, although these peaks are harder to distinguish due to the fluctuations in the discharge waves of the Oude IJssel and Twentekanaal.

> *"What timing of confluence between the laterals and the IJssel results in the highest increase in water level due to lateral inflow in the IJssel?"*

Analysis of the most occurred timing in the historical data was resulted in the following time differences:

- The peak discharge in the Oude IJssel at Doesburg is 3 days earlier than the peak discharge in the Rhine at Lobith.
- The peak discharge in the Twentekanaal is 3 days and 11 hours earlier than the peak discharge in the Rhine at Lobith.

With this timing, the peak discharge of the laterals enters the IJssel before the peak discharge of the Rhine is in the IJssel. A discharge wave in the Twentekanaal and Rhine is often accompanied by a discharge wave in the Oude IJssel, while a discharge wave in the Oude IJssel and Rhine is less often accompanied by a discharge wave in the Twentekanaal.

Second, the timing that results in the highest increase in water level is the reference timing. With the reference timing, the peak discharge in the Oude IJssel at Doesburg is 1 day later than the peak discharge in the Rhine at Lobith, which results in both peaks at the same time at Doesburg. At Doesburg, this reference timing resulted in the highest increase in water level of approximately 17 cm with a peak discharge in the Rhine of 6,900 m^3/s. At both Zutphen and Wijhe, one day later than the reference timing resulted in the highest increase in water level of approximately 27 cm with a peak discharge in the Rhine of 5,600 m^3/s. The increase in water level is largest at Zutphen due to the amount of lateral inflow, since at Doesburg only the Oude IJssel entered the IJssel and at Zutphen the Twentekanaal entered the IJssel as well. Overall, the increase in water level is dependent on the peak discharge of the discharge wave in the Rhine, the location along the river and the amount of lateral inflow.

Finally, the effect of the timing of lateral inflow on the shape of the discharge wave in the IJssel is determined. At all three locations, the reference timing resulted in steeper (higher and shorter) discharge waves. The timing of two days before and two days after the reference timing resulted in slightly increased and wider peaks. The Q(h) relation shows hysteresis between the increasing and decreasing discharge. The hysteresis at Doesburg and Zutphen is larger than at Wijhe due to 1) inactive storage area, 2) dynamic discharge waves due to lateral inflow and 3) backwater effect.

> *"At what shape of discharge wave in the IJssel does lateral inflow result in the highest increase in water level in the IJssel?"*

The influence of high lateral inflow is different on various shapes of discharge waves in the IJssel. The change in water level for various shapes showed that the difference between the shapes was smaller at Doesburg than at Wijhe. This shows that the shape has more effect further downstream in the river profile (Pol et al., 2006). Additionally, the main factor that resulted in the difference in change in water level between the shapes was the total volume of the discharge wave in the IJssel. The total volume of the discharge wave determined the water level which affect the position of the water level in the river profile. As mentioned before, the river profile has a large impact on the change in water level due to lateral inflow. Overall, the difference in change in water level between the different shapes is for all locations a maximum of 4 cm, making the shape of the discharge wave in the IJssel a less important factor than the timing.

The answers of the research question can help to answer the main question:

"What influence does lateral inflow exert on the shape of the discharge wave in the IJssel?"

The influence of lateral inflow on the discharge wave in the IJssel is mainly determined by four variables: the timing of confluence of the peak discharges, the shape of the discharge wave in the IJssel, the peak discharge in the Rhine at Dornick and the river profile.

The highest increase in water level in the IJssel at Doesburg due to the timing of the lateral inflow occurs when the peak discharge of the Oude IJssel at Doesburg is 1 day later than the peak discharge of the Rhine at Dornick. The highest increase in water level in the IJssel at Zutphen and Wijhe occurs when the peak discharge of the Twentekanaal at Eefde is 2 days later than the peak discharge of the Rhine at Dornick. This timing differs 4 days from the most common timing following from the historical data, which makes the occurrence small. However this timing did occur in the past 30 years.

Additionally, the influence of lateral inflow on several shapes of discharge waves in the IJssel differs per shape of discharge wave in the IJssel. The effect of the shape of the discharge wave is mainly caused by the total volume of the discharge wave, the peak discharge and the peak curvature. The difference in change in water level between the shapes was only 4 cm, while for timing this difference was almost 15 cm, which makes the shape of the discharge wave less important than the timing.

Further, the peak discharge from the discharge wave in the Rhine has impact on the influence of lateral inflow. This is mainly due to the water level it causes. Higher peak discharges from the Rhine cause the water level in the IJssel to rise, resulting the water level reaching wider parts of the river profile. With wider river profiles the influence of lateral inflow is decreasing. This makes lateral inflow an important factor in case of lower peak discharges, as lateral inflow may then cause inundated floodplains.

Finally, the influence of lateral inflow differs along the IJssel due to the distance to the lateral source and the local river profile. Closer to the lateral source, the discharge wave in the IJssel becomes more dynamic, while further downstream the peaks caused by lateral inflow attenuate. The IJssel is a river with changing river profiles along the river, which results in lower increase in water level for wide profiles and a larger increase in water level for smaller profiles.

6.2 Recommendations

The high lateral inflow in this study will mainly occur due to high intensity rainfall events, which are likely to occur more often due to climate change. It is recommended to take into account discharge from the Oude IJssel and Twentekanaal during these types of events, while predicting water levels on the IJssel. The high lateral inflow based on historical data had the highest impact on slightly increased peak discharges in the IJssel. The lateral inflow may be less relevant for dike overflow but can make a difference in when floodplains will inundate. In some cases, floodplains need to be evacuated when they will overflow, so then the lateral inflow is important to take into account. An example is campsite in the floodplains. When floodplains tend to overflow, campsites need to be informed on time such that they can evacuate before the floodplains inundate.

The timing of the lateral inflow mainly determines the increase in water level due to high lateral inflow. From the research follows that the highest increase in water level occur when the peak of the laterals enters the IJssel when the peak of the IJssel is at their confluence point. It is recommended to avoid this timing by slowing down or fasten the peak discharge of the laterals when this timing might occur. Additionally, when measures on the Oude IJssel or Twentekanaal will be taken which might change the timing of the outflow on the IJssel, it is important to research the effect these measures have on the timing of confluence of the peak discharges.

For further research, it is recommended vary with the input for the lateral inflow. Some factors that can be interesting to take into account are the situation of high lateral inflow from only one lateral source. Thie occurs more often than that both lateral sources have high discharges and still have influence on the water level in the IJssel. Second, in this study both lateral sources had high peak discharges while the flood in the Meuse in 2021 showed that lateral inflow for an extended period of time with lower peak discharges can have significant influence as well (De Bruijn & Slager, 2022). It may be interesting to research the influence increased discharges for a longer duration, as these type of discharge wave occurred during the high water in the IJssel in 2023.

During the high water levels in the IJssel in 2023, the water level in the IJsselmeer was high as well. The high water levels in the IJsselmeer made it harder to drain the IJssel. This may have influenced the water level downstream in the IJssel. When high water levels in the IJsselmeer are combined with high lateral inflow, this may result in even more increase in water level in the IJssel due to the lateral inflow. The influence of high water levels in the IJsselmeer during high lateral inflow on the water level in the IJssel may be interesting to further research.

Bibliography

BaiWei, W., FuQiang, T., & HePing, H. (2011). Analysis of the effect of regional lateral inflow on the flood peak of the three Gorges Reservoir . *China Technological Sciences* .

Berends, K., Domhof, B., & Visser, T. (2022). *Pilot zesde generatie 1D SOBEK model voor de Rijn*.

Biancamaria, S., Bates, P. D., Boone, A., & Mognard, N. M. (2009). Large-scale coupled hydrologic and hydraulic modelling of the Ob river in Siberia. *Journal of Hydrology* , 136–150.

Bod, J. (2021). *Spreading of the runoff times in the Dutch Rhine delta*.

Botterhuis, T., & Klopstra, D. (2004). *Onderzoek afvoer Oude IJssel*.

Chbab, H. (2017). *Basisstochasten WBI-2017*.

De Bruijn, K., & Slager, K. (2022). *Wat als "de waterbom" elders in Nederland was gevallen?* .

Deltares. (n.d.). *SOBEK Suite: for integral water solutions*. Retrieved May 14, 2024, from https://www.deltares.nl/en/software-and-data/products/sobek-suite

Deltares. (2024a). *D-Flow 1D, User manual*.

Deltares. (2024b, January 9). *Terugblik hoogwaterpiek kerstvakantie 2023-2024*. https://www.deltares.nl/nieuws/terugkijken-op-hoogwaterpiek-kerstvakantie-2023-2024

Disse, M., & Engel, H. (2001). Flood events in the Rhine Basin: Genesis, influences and mitigation . *Natural Hazards* , 271–290.

Drents Overijsselse Delta. (2022). *Maatregelen voor een Delta met toekomst*.

Expertise Netwerk Waterkeren. (2007). *Leidraad rivieren*. Expertise Netwerk Waterkeren.

Havinga, H. (2016). *Visie op het rivierbeheer van de Rijn* .

Hegnauer, M., Beersma, J., Van Den Brink, H., & Partners, R. L. (2023). *Generator of Rainfall and Discharge Extremes for the Rhine Generator of Rainfall and Discharge Extremes for the Rhine Final report of GRADE-Rhine version 3.0*.

Hidayat, H., Vermeulen, B., Sassi, M. G., F. Torfs, P. J. J., & Hoitink, A. J. F. (2011). Discharge estimation in a backwater affected meandering river. *Hydrology and Earth System Sciences*, *15*(8), 2717–2728. https://doi.org/10.5194/hess-15-2717-2011

Kadaster. (n.d.). *Pdok*. Retrieved May 27, 2024, from https://app.pdok.nl/viewer/#x=160000.00&y=455000.00&z=3.0000&background=BRT-A%20Water&layers=

KNMI. (2024, May 10). *Dagwaarden neerslagstations*. https://www.knmi.nl/nederland-nu/klimatologie/monv/reeksen

Kundzewicz, Z. W., Ulbrich, U., Brücher, T., Graczyk, D., Krüger, A., Leckebusch, G. C., Menzel, L., Pinskwar, I., Radziejewski, M., & Szwed, M. (2004). Summer floods in central Europe - Climate change track? . *Natural Hazards* , 165–189.

Makaske, B., Maas, G. J., & va nSmeerdijk, D. G. (2008). The age and origin of the Gelderse IJssel. *Netherlands Journal of Geosciences*, *87*(4), 323–337.

Mishra, S. K., & Singh, V. P. (1999). Hysteresis-based flood wave analysis. *Journal of Hydrologic Engineering* , 358–365.

Moramarco, T., Barbetta, S., Melone, F., & Singh, V. P. (2005). Relating local stage and remote discharge with significant lateral inflow. *Journal of Hydrologic Engineering* , 58–69.

Pol, J. C., Kok, M., Barneveld, H. J., Morales-Napoles, O., & Schielen, R. M. J. (2006). *EVALUATION OF DESIGN HYDROGRAPH METHODS AND PROBABILISTIC METHODS FOR ESTIMATING DESIGN WATER LEVELS ON THE RIVER MEUSE*.

Rijkswaterstaat. (n.d.). *waterinfo* . Retrieved October 17, 2023, from https://waterinfo.rws.nl/#/nav/bulkdownload

Rijkswaterstaat. (2023a). *Twentekanaal* . https://www.rijkswaterstaat.nl/water/vaarwegenoverzicht/twentekanalen

Rijkswaterstaat. (2023b, October 9). *IJssel* . Rijkswaterstaat .

RURA-Arnhem. (2018). *Actualisatie beschrijving laterale toestroming Rijntakken*.

RURA-Arnhem. (2022). *Betrekkingslijnen Rijntakken versie 2022*.

Spiegel, M. R., & Stephens, L. J. (2007). *Theory and Problems of statistics* (4th ed.). McGraw-Hill Companies.

Task Force Fact-finding hoogwater. (2021). *Hoogwater 2021 Feiten en Duiding*.

Tayefi, V., Lane, S. N., Hardy, R. J., & Yu, D. (2007). A comparison of one- and two-dimensional approaches to modelling flood inundation over complex upland floodplains. *Hydrological Processes*, *21*(23), 3190–3202. https://doi.org/10.1002/hyp.6523

Van Der Veen, R. (2018). *Memo P180510R-1: Belangrijke beken Rijntakken*.

Van Hasselt, Van Everdingen, & & partners. (1995). *Druk op de dijken 1995*.

Van Zetten, R., Ten Brinke, W., Klijn, F., & Asselman, N. (2020). *Het verhaal van de Rijntakken* .

Vreugdenhil, H., Hakvoort, H., & Verhoeven, R. (2010). *Evaluatie regionale wateroverlast augustus 2010*.

Waterschap Rijn en IJssel. (n.d.). *meetgegevens*. Retrieved January 26, 2024, from https://waterdata.wrij.nl/index.php?wat=overzicht&type=alle

Appendix I

Influence of timing of lateral inflow on the water level at Kampen

Figure 22a shows the change in water level at Kampen relative to the water level in the situation with the standard steady laterals, which is shown in Figure 19c. The highest increase in water level is 13 cm and arises with a peak discharge of 13,000 m^3/s in the Rhine at Dornick (Figure 22b). The timing giving the highest increase is one day later than the reference timing, which means that the peak discharge of the Oude IJssel enters the IJssel at Doesburg one day later than the peak discharge in the IJssel is at Doesburg. This timing resulted in the highest increase in water level for all peak discharges in the Rhine at Dornick, since the reference timing is relative to Doesburg. The difference between the several timings is similar to the difference at Zutphen, because the discharge wave in the IJssel does not change due to lateral inflow between Zutphen and Kampen.

The five different timings exhibit a similar and highly fluctuating trend over the increasing peak discharge in the Rhine at Dornick. The increase in water level at peak discharges of 6,900 to 7,700 m^3/s in the Rhine at Dornick are almost as high as the increase in water level at a peak discharge of 13,000 m^3/s in the Rhine at Dornick. This is weird since at the higher peak discharges the contribution of lateral flow is lower and the river profile is wider (Figure 22b). Between a peak discharge of 7,700 and 9,500 m^3/s the increase in water level is decreasing, which is caused by the opening of the Reevediep. The Reevediep is an extra connection between the IJssel and the IJsselmeer to reduce the discharge in the IJssel.

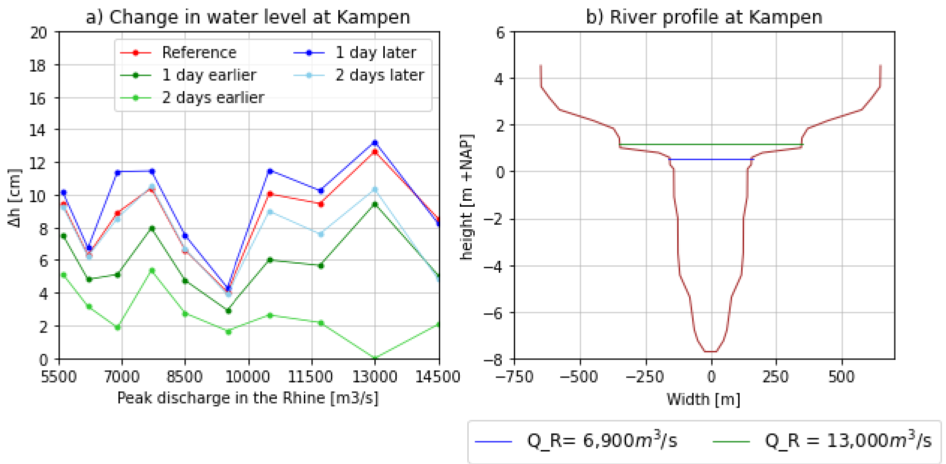

Figure 30 The change in water level at Kampen caused by the timing of laterals for various discharges in the Rhine and b) the water levels in the river profile at Kampen for a peak discharge of 6,900 m^3/s and 13,000 m^3/s in the Rhine

Influence of timing of lateral inflow on the discharge wave at Kampen

Figure 25 a, b and c show the influence of the laterals on the discharge wave in the IJssel at Kampen. The fluctuations of the lateral inflow from the Oude IJssel and Twentekanaal are not as clear anymore, but the increase in volume due to the laterals is still visible. At both, two days before and two days after the reference timing, the discharge wave is becoming approximately 50 m^3/s higher, similar to the increase at Zutphen. In both cases, the increasing part of the discharge wave is steeper than that of the standard timing. the timing of two days after the reference timing, the decreasing part is steeper as well, resulting in a shorter and steeper discharge wave. The reference timing resulted in the highest increase in peak discharge of 125 m^3/s.

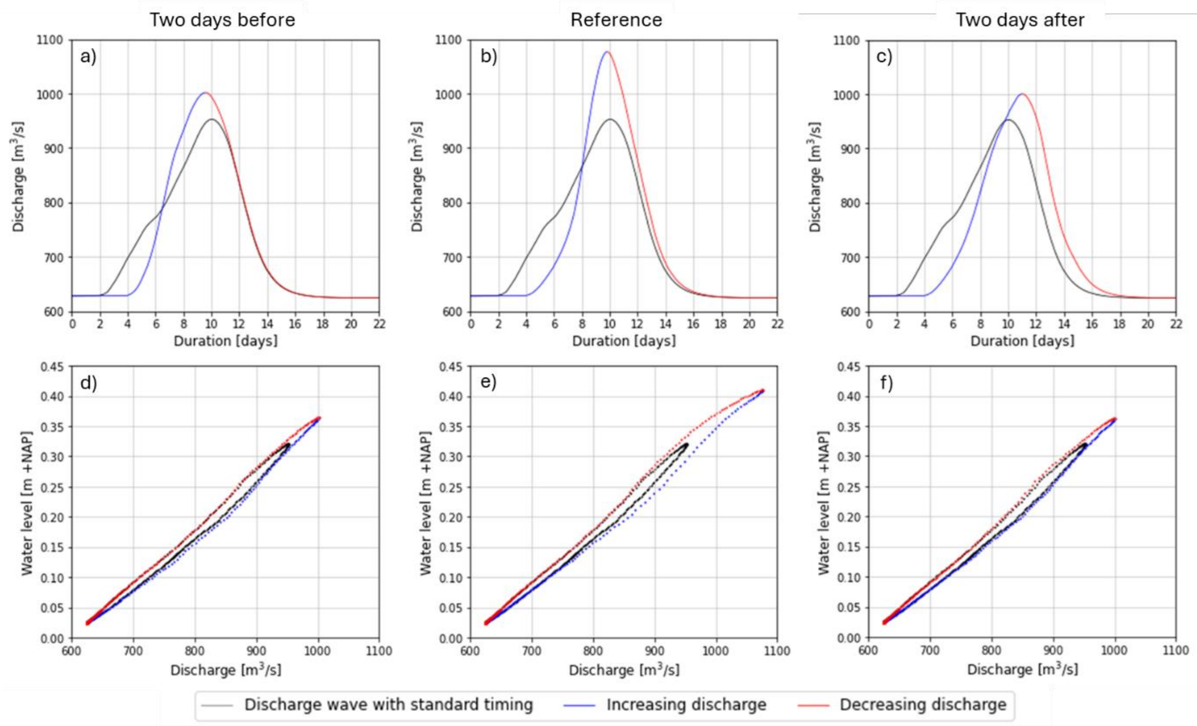

Figure 31 Change in the shape of the discharge wave at Kampen for a) two days before the reference timing, b) the reference timing and c) two days after the reference timing and the accompanying Q(h) relations

The Q(h) relation in Figure 25d, e and f show that the difference between the increasing and decreasing part of the discharge waves are smaller than at Doesburg and Zutphen. At both, two days before and two days after the reference timing, the increasing part of the discharge wave is slightly lower than the standard timing. The increase in peak discharge resulted in higher water levels as well, they do follow the same trend as the standard timing. The decreasing part on the timing 2 days before the reference timing is similar to the standard timing, while that of the timing two days after the reference timing is slightly higher until a discharge of 825 m^3/s. The Q(h) relation of the reference timing is lower than that of the standard timing in the increasing part. The increase in peak discharge resulted in higher water levels as well, although the increase in water level with discharge is not as fast as at the standard timing.

Influence of the shape of the discharge wave in the IJssel at Kampen

skewness

At Kampen (Figure 27c), the highest increase in water level is caused by the discharge wave in the Rhine that is skewed rightward. This is mainly the effect of the Twentekanaal at Kampen, since the results in section 4.2.2 showed that the Twentekanaal had the most visible influence at Kampen as well. The drop at a peak discharge in the Rhine of 12,500 m^3/s for the skewed waves is different than for the symmetrical wave, the reason for this is unclear.

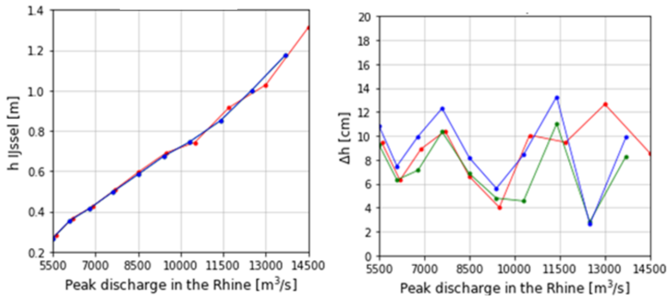

Figure 32 maximum water levels for skewed discharge waves with steady lateral inflow and the change in water level at Kampen due to high lateral inflow

width

At Kampen (Figure 29c), shows that there are almost no similarities between the peak discharges and the shapes of the discharge waves, especially at the higher peak discharges. The river profile may have influenced the differences, since the shape of the profile is changing a lot. Next to that, Kampen is more downstream than Zutphen and Doesburg, so dissipation influences the shape of the discharge waves as well. Finally, the Reevediep is influencing the discharge that flows along Kampen, which has impact on the water level. Additionally, since Kampen is more downstream of the IJssel, the downstream boundary condition can have influence on the results at Kampen.

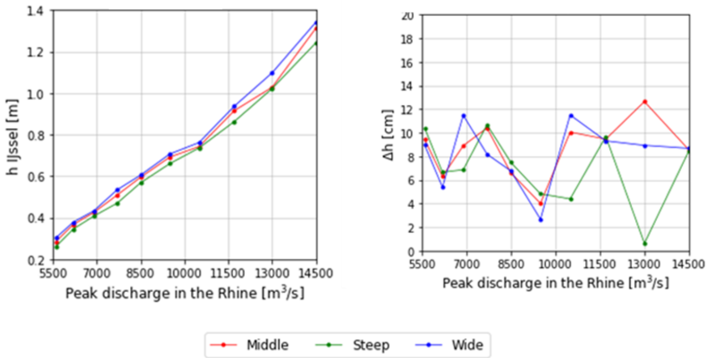

Figure 33 Maximum water levels for discharge waves with different widths with steady lateral inflow and the change in water level at Kampen due to high lateral inflow